City University eJournal of Academic Research (CUeJAR)
e-ISSN : 2682-910X
CUeJAR Homepage: https://www.city.edu.my/CUeJAR

The Development of an Adaptive Controller Algorithm for Human Arm Trajectories Control in the Rehabilitation Process

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Abstract

Rehabilitation process usually utilised the therapist skill in manoeuvring patient hand movement with their hand in the correct posture. The problem with the use of hand assisted movement exercises showed inconsistency in every movement. Hence a robot arm assisted movement are introduced to eliminate this problem. A modelling based on the Proportional Integral Derivative (PID) and Feedback Error Learning (FEL) are used to model the robotic arm movement with respect to the humanoid properties and can be evaluated by simple rehabilitation exercises. The main goal of this paper is to development of a 2-Degree of Freedom (2-DOF) humanoid robotic arm algorithm with the introduction of an adaptive controller utilising OCTAVE software. The concept is based on a basic mathematical model of a composite pendulum with 2 segments that mimic the human upper arm and forearm. The 2-DOF dynamic equations using the Lagrangian and Euler-Lagrange equations were extracted and solved using Euler's method. The algorithm showed learning of the required torque needed in carrying out the rehabilitative task of the desired Position Control via Specific Trajectory (PCST), through feedback control, and using it as the feed-forward torque in different test motions. The mean absolute error with respect to the expected upper arm motion after 30 trials showed a decrease from 0.01 to 0.0074469, and the motion of the forearm from 0.028 to 0.007163. This decrement in mean absolute error is consistent with the human arm's adaptive control concept known as the FEL with an increased number of trials.

1. Introduction

Rehabilitation procedures are based on psychological evaluation techniques that can be conducted by the recovery facility therapist. Physiotherapy care is one of the comprehensive preparation programs for the recovery and enhancing the patient's physical activity. The length of the therapy session is reduced because of the shortage of the therapist available. Such problems resulted in the insufficient time and resources to obtain the optimum result in each session. In utilizing assistive technologies such as human-robotic arms as a substitute for human therapy in rehabilitation, the length of the training session can be increase and reduce the number of therapists needed per case. The robot arm is described as an assistive system capable of imitating the motions of the human arm in action. In the development of humanoid robotic arm, this will mimic individual actions in such a manner that it can be applied to support the recovery phase.

There are various types of assistive devices in the current technology which can help the rehabilitation process. First device known as the exoskeleton that have greater range of movement and complex design suited for use in hospitals and research labs. It is suitable for

CUeJAR
Received: 17th January 2023
Revised: 15th February 2023
Accepted: 5th March 2023

patients with severe disability. Second device is an operational devices which are less complex, end-effector and suitable for use by patients with moderate disability (Mehrholz et al., 2015). However, these two approaches require a mathematical description of the musculoskeletal system. Due to the high complexity of such system and the simplifications typically assumed to derive the models, the applicability of these approaches for clinical purposes is limited. Additionally, there are a need to determine a large number of parameters, which represent a time-consuming and difficult to reproduce task in a clinical environment.

Hence to reduce the large numbers of parameter required to model the rehabilitation process, a movement known as flexion-expansion of the elbow is introduced (Fu et al., 2015). Flexion-extension movement as depicted in Figure 2.1 showed that, flexion consists of rotating the forearm towards the arm at a maximum angle of 150°, while extension consists of rotating the arm in the opposite direction, at an angle of 10° (Morrey et al., 2017).

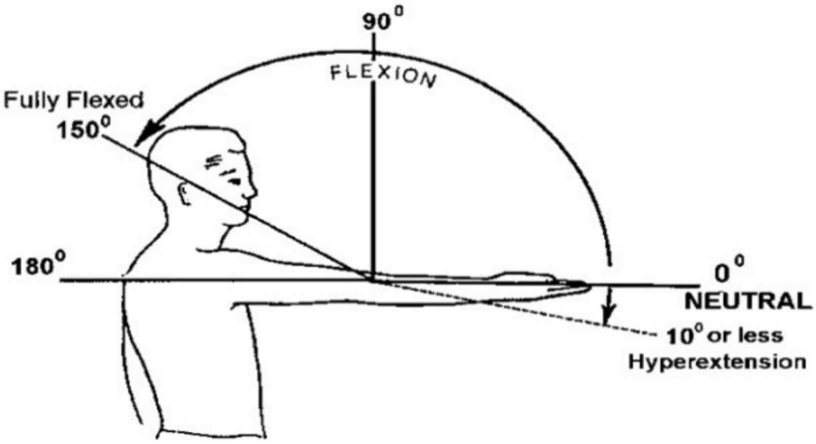

Figure 2.1: Flexion-extension of the elbow (Georgiana & Andrea 2017)

The movement of the flexion-extension of the elbow can be simplified as the double compound pendulum movement as shown in Figure 2.2. The angle between each extremity and the vertical is the generalised coordinates that describe the device configuration. These angles are labelled at a distance between θ_1 and θ_2 as shown in the figure. An illustration of the arm's double-pendulum method, the centres of the inertial ellipsoids are located at the body segments' centres of mass. Pendulums have played a major role in the development of dynamics pendulums, which have significant applications in gravimeter and inertial navigation. The pendulum is a rigid structure, suspended from a fixed position, which is offset toward the body's centre of mass. If all the mass is assumed to be concentrated at a point, the obtain an idealised single pendulum.

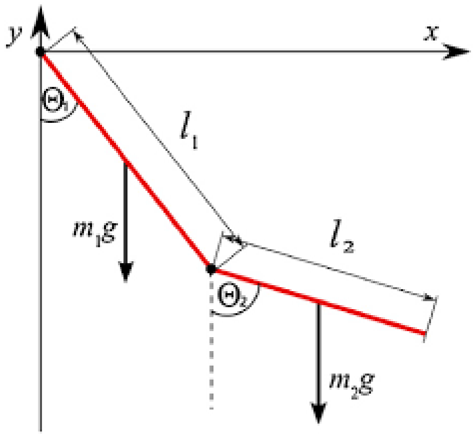

Figure 2.2: Schematic of Double Compound Pendulum

The coordinate of the upper arm is the centre of mass from the centre of rotation of the elbow shown in Figure 2.3 and it is labelled as x_1 and y_1 while the coordinate of the forearm labelled as x_2 and y_2. The upper arm and forearm are known to be a longitudinal entity without a wrist joint. By combining the upper arm and forearm, the resulting centre of mass for the segment is obtained and is located at the elbow. The size of each ellipsoid is dependent upon the segment's mass and inertial tensor. The dimensions of each ellipsoid are determined as the moments of tensor inertia along the major and minor axes and as the mass of the section.

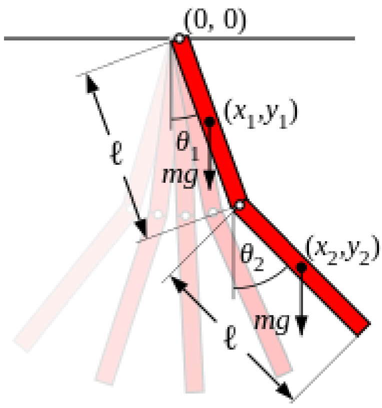

Figure 2.3: Double Compound Pendulum

Theories of motor control involve the development of reflexive, automatic, adaptive, and voluntary movements, and the development of efficient, synchronised, goal-directed body movement within the nervous system involving multiple body systems (input, output, and central processing) and multiple levels. Several textbooks and researchers suggest the implementation of a Motor Control system model that combines the concepts of neurophysiology, biomechanics and motor learning which learning solutions based on the patient, role, and environmental interaction. When designing the strategies in order to enable the patients to achieve the objectives, it is important to be aware of the effects of this relationship between the mission and the environment (Sanyal & Goswami 2014).

Therefore, Proportional-integral-derived controller (PID) is used for the efficient operation of the robot arm. Two PID controllers needed since upper arm and forearm are mutually related. PID controller has the optimum control dynamics including zero steady state error, fast response no oscillations and higher stability. It also the most adopted controllers in the industry due to the good cost and given benefits to the industry. Many nonlinear processes can be controlled using the well-known and industrially proven PID controller.

The controller that uses the Feedback Error Learning (FEL) scheme is also a hybrid controller. The feed forward controller is realised by an Artificial Neural Network (ANN), which uses feedback controller outputs as signals to learn the inverse dynamics of controlled objects. It also applies the FEL controller to monitor the redundant musculoskeletal structures.

This paper aim is to develop an effective system that can help patients to flex or extend their arms. By performing bilateral movement training, the arm motor function of the damaged limb of the patient may be enhanced due to the plasticity of the human brain (Cauragh et al., 2007). By developing 2-Degree of Freedom (DOF) humanoid robotic arm algorithm with the introduction of an adaptive controller in order to replicate the properties of the human arm. In order to accomplish this aim, the objectives are defined as follows; first is to develop 2-DOF humanoid robotic arm algorithm simulation model in OCTAVE, and second is to analyse the system developed by the torque and load required by the system to mimic the rehabilitation exercise. OCTAVE software is used to develop the algorithm. Deriving and solving 2-DOF double compound pendulum dynamic equation to reflect as human arm properties. Modelling humanoid properties in the system by the addition of additive controller which are PID and FEL. The evaluation of overall result is done by assigning simple rehabilitation exercise to the model.

2. Methodology

This chapter will start with the deriving and solving the dynamic equation of the double compound pendulum to reflect the mimic human arm. After the derivation method, the simulation code will be written in the OCTAVE software to implement the derivation into it. Then the code will be run with the value of initial and final position of xy-rotation, and number of trials inserted by the user. The process will be repeated after the results obtain satisfy with the FEL and verify with the simple rehabilitation process. The result from the simulation then will be analyse and discuss in the next chapter.

2.1 Mathematical Modelling

The double compound pendulum consists simply of two compound pendulums connected at the top of both pendulum and traveling along a straight line. Movement on the first pendulum will be like a regular pendulum, but movement on the second pendulum will influence overall motion. The angle between the two arms is used to measure the force that opposes the acceleration. The mass is distributed through the length, hence the angle between two arms is used to calculate moment of Inertia (Georgiana & Andrea 2017), the statistical models for each limb can be interpreted to be the following (Abdul-Sater et al., 2014) as depicted in Figure 3.1. Double part of the compound pendulum on a 3-D axis, which is similar to the human upper arm and forearm; (a) at rest position; (b) the forearm rotates along the z-axis around the x-y plane with $\theta_2 = 45°$ and stays at rest; (c) both the upper arm and the forearm rotates along the z-axis around the x-y plane with $\theta_1 = 45°$ and $\theta_2 = 135°$.

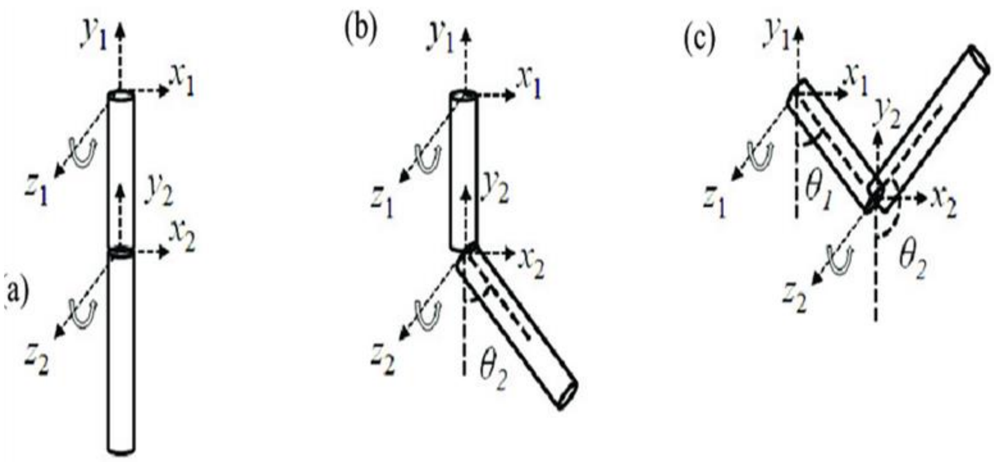

Figure 3.1: The movement double compound pendulum mimic forearm movement

Mass is distributed through the length, hence the angle between two arms is used to calculate moment of Inertia. The dynamics of a double segment compound pendulum is governed by a set of coupled nonlinear equations. The centre of mass for each limb (upper arm and forearm) depends on the mass distribution of each segment. The statistical models for each limb can be extracted from the following:

$$x_1 = l_1 \, sin(\theta_1) \quad (3.1)$$

$$y_1 = -l_1 \, cos(\theta_1) \quad (3.2)$$

$$x_2 = l_1 \, sin(\theta_1) + l_2 \, sin(\theta_2) \quad (3.3)$$

$$y_2 = -l_1 \, cos(\theta_1) - l_2 \, cos(\theta_2) \quad (3.4)$$

Apply from equations (3.1) until (3.4) to the upper arm and forearm, x and y coordinates respectively as mathematical model. Differentiate equation from (3.1) until (3.4) in order to achieve their corresponding velocity.

$$\dot{x}_1 = l_1\dot{\theta}_1 \, cos(\theta_1) \quad (3.5)$$

$$\dot{y}_1 = l_1\dot{\theta}_1 \, \sin(\theta_1) \quad (3.6)$$

$$\dot{x_2} = l^1\dot{\theta}_1 cos(\theta^1) + l_2\dot{\theta}_2 cos(\theta_2) \quad (3.7)$$

$$\dot{y_2} = l_1\dot{\theta}_1 \sin(\theta_1) + l_2\dot{\theta}_2 \sin(\theta_2) \quad (3.8)$$

Lagrangian, L, of a dynamical system is a function that summarises the dynamics of a particular system. Natural form is defined as the total kinetic energy, K, of the system minus its total potential energy, P.

$$L = K - P \tag{3.9}$$

Then, substitute from equation (3.5) until (3.8) into (3.10):

$$K = K_E + K_R \tag{3.10}$$

$$K = \frac{1}{2}m(v)^2 + \frac{1}{2}I(\dot{\theta})^2$$

$$K = \left(\left[\frac{1}{2}m_1(\dot{x_1} + \dot{y_1})\right] + \left[\frac{1}{2}m_2(\dot{x_2} + \dot{y_2})\right]\right) + \left(\left[\frac{1}{2}I_1(\dot{\theta}_1)^2\right] + \left[\frac{1}{2}I_2(\dot{\theta}_2)^2\right]\right)$$

Substitute equation (3.2) and (3.4) into (3.11)

$$P = mg \tag{3.11}$$

$$P = m_1 g y_1 + m_2 g y_2$$

Substitute equation (3.10) and (3.11) into equation (3.9):

$$L = \left(\frac{1}{2}m_1 l_1 \dot{\theta_1}^2 + \frac{1}{2}m_2\left[\left(l_1{}^2\dot{\theta_1}^2\right) + l_2\dot{\theta}_2 + 2l_1 l_2\cos(\theta_1 - \theta_2)\right]\right) + [(m_1 + m_2)gl_1\cos\theta_1 + m_2 g l_2\cos\theta_2] \tag{3.9}$$

If the Lagrangian of the system is known, the equations of motion of the system which be obtained by direct substitution. From this Lagrangian's substitution we can express it into Euler-Lagrange equation. Equation shows that formula of Euler-Lagrange is written as follows:

$$\frac{\delta L}{\delta \theta_1} - \frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\theta}_1}\right) = 0 \tag{3.13}$$

The Euler-Lagrange equation for the coordinate θ_1 are:

$$\frac{\delta L}{\delta \dot{\theta}_1} = m_1 l_1{}^2\dot{\theta}_1 + m_2 l_1{}^2\dot{\theta}_1 + m_2 l_1 l_2 \dot{\theta}_1 \cos(\theta_1 - \theta_2)$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta \dot{\theta}_1}\right) = (m_1 + m_2)l_1{}^2\ddot{\theta}_1 + m_2 l_1 l_2 \ddot{\theta}_1\cos(\theta_1 - \theta_2) \tag{3.14}$$

$$\frac{\delta L}{\delta \theta_1} = -m_2 l_1 l_2 \dot{\theta}_l \dot{\theta}_2 \sin(\theta_1 - \theta_2) - (m_1 + m_2)g l_1 sin\theta_1 \tag{3.15}$$

Substitute equation (3.14) and (3.15) into (3.13)

$$(m_1+m_2)l_1{}^2\ddot{\theta}_1+m_2l_2\ddot{\theta}_2 co\,s(\theta_1-\theta_2)-m_2l_1l_2\dot{\theta}_2\sin(\theta_1-\theta_2)\cdot(\dot{\theta}_1-\dot{\theta}_2) + m_2l_1l_2\dot{\theta}_1\dot{\theta}_2\sin(\theta_1-\theta_2)+m_2l_1l_2\dot{\theta}_2\sin(\theta_1-\theta_2)-(m_1+m_2)gl_1sin\theta_1 = 0$$

$$(m_1+m_2)l_1{}^2\ddot{\theta}_1+m_2l_2\ddot{\theta}_2 co\,s(\theta_1-\theta_2)-m_2l_1l_2\dot{\theta}_2\sin(\theta_1-\theta_2)+(m_1+m_2)gl_1sin\theta_1 = 0$$

$$(m_1+m_2)l_1{}^2\ddot{\theta}_1=m_2l_2\ddot{\theta}_2 co\,s(\theta_1-\theta_2)-m_2l_1l_2\dot{\theta}_2\sin(\theta_1-\theta_2)+(m_1+m_2)gl_1sin\theta_1 \quad (3.16)$$

The Euler-Lagrange equation for the coordinate θ_2 are:

$$\frac{\delta L}{\delta\dot{\theta}_2}= m_2l_2{}^2\dot{\theta}_2+m_2l_1l_2\dot{\theta}_1\cos{(\theta_1-\theta_2)}$$

$$\frac{d}{dt}\left(\frac{\delta L}{\delta\dot{\theta}_2}\right)=m_2l_2{}^2\ddot{\theta}_2+m_2l_1l_2\ddot{\theta}_1\cos(\theta_1-\theta_2)-m_2l_1l_2\dot{\theta}_1sin(\theta_1-\theta_2)\cdot(\dot{\theta}_1-\dot{\theta}_2)$$
(3.17)

$$\frac{\delta L}{\delta\theta_1}=m_2l_1l_2\dot{\theta}_l\dot{\theta}_2\sin(\theta_1-\theta_2)-m_2gl_2sin\theta_2 \quad (3.18)$$

Substitute equation (3.17) and (3.18) into (3.13)

$$m_2l_2{}^2\ddot{\theta}_2+m_2l_1l_2\ddot{\theta}_1\cos(\theta_1-\theta_2)-m_2l_1l_2\dot{\theta}_1{}^2\,sin(\theta_1-\theta_2)+m_2l_1l_2\dot{\theta}_1\dot{\theta}_2\sin(\theta_1-\theta_2)-m_2l_1l_2\dot{\theta}_1\dot{\theta}_2\sin(\theta_1-\theta_2)+m_2gl_2sin\theta_2=0$$

$$m_2l_2\ddot{\theta}_2+m_2l_1\ddot{\theta}_1\cos(\theta_1-\theta_2)-m_2l_1l_2\dot{\theta}_1{}^2\sin(\theta_1-\theta_2)+m_2gl_2sin\theta_2=0$$

$$m_2l_2\ddot{\theta}_2=m_2l_1\ddot{\theta}_1\cos(\theta_1-\theta_2)-m_2l_1l_2\dot{\theta}_1{}^2\sin(\theta_1-\theta_2)+m_2gl_2sin\theta_2 \quad (3.19)$$

To obtain the path of angular displacement for the upper arm and the forearm, the dynamic equations of $\ddot{\theta}_1$ and $\ddot{\theta}_2$ can be solved. These equations can be solved using a numerical method.

Euler's method, as shown in the equation (3.20), is chosen because of its strength in this algorithm.

$$\theta(t+1) = \theta(t) + \dot{\theta}(t) \cdot dt \tag{3.20}$$

2.2 Modelling Humanlike Properties

A particular control strategy that humans exert when carrying out a task is known as the FEL strategy. The FEL controller can also be applied to control the redundant musculoskeletal systems. In this paper, mimicking the humanlike behaviour when moving the arm from one position to another for example during rehabilitation task, a Position Control via Specific Trajectory (PCST) task is introduced. The 2-DOF system will receive the desired initial and final position for both upper arm and forearm, based on the equation (3.21) (Sanyal & Goswami 2014):

$$\theta(t) = \theta_1(\theta f - \theta i) \cdot (10 \cdot t^3 - 15 \cdot t\text{^}4 + 6 \cdot t^5) \tag{3.21}$$

To generalise the calculations, estimated anthropometric human arm data is required for the execution of the algorithm in MATLAB. The parameter for the human upper arm and forearm is derived from current literature as shown in Table 3.1.

Table 3.1: Parameter for 2-DOF robotic arm

Arm segment	Range of Length (m)	Range of Mass (kg)
Upper arm	0.250 - 0.290	1.794 – 1.950
Forearm	0.150 – 0.373	0.930 – 1.354

2.4 PD Feedback Controller with PCST

PCST task is known as trajectory generation and control. A trajectory is defined not only by the destination for the system to move to, but also by continuous intermediate locations through which the system must pass, en route to the destination. The required torque to compensate this error is generated by a conventional Proportional-Derivative (PD) feedback controller. For both upper and forearm arms, as seen in equations (3.22) and (3.23).

$$(m_1 + m_2){l_1}^2\ddot{\theta}_1 = m_2 l_2 \ddot{\theta}_2 cos(\theta_1 - \theta_2) - m_2 l_1 l_2 \dot{\theta}_2 \sin(\theta_1 - \theta_2) + (m_1 + m_2) g l_1 sin\theta_1 - FB_1 \tag{3.22}$$

$$m_2 l_2 \ddot{\theta}_2 = m_2 l_1 \ddot{\theta}_1 \cos(\theta_1 - \theta_2) - m_2 l_1 l_2 {\dot{\theta}_1}^2 \sin(\theta_1 - \theta_2) + m_2 g l_2 sin\theta_2 - FB_2 \tag{3.23}$$

$$FB(t) = P \cdot e(t) + D.\dot{e}(t) \tag{3.24}$$

Feedback (FB) is a piecewise torque generated by the controller to compensate for the error that occurred during each trial and regulated by equation (3.24). Figure 3.2 shows the block diagram description for this PD feedback controller that is applied to the nonlinear 2-DOF arm model framework.

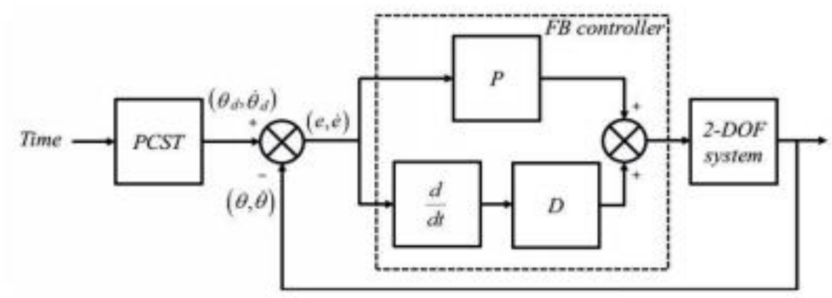

Figure 3.2: Block diagram of Proportional-Derivative (PD). PCST is a designated motion planner that provides the desired position and path.

2.5 PD Feedback and Feed forward Controller with PCST

The algorithm's efficiency is further increased with the addition of a feed forward function. The controller slowly determines the torque needed to execute the operation. In subsequent motions the torque generated by the feedback controller will be used as feed forward torque during each trial. The algorithm that is used as feed forward controller for both upper arm and forearm is listed below with equations (3.25) and (3.26).

$$(m_1 + m_2){l_1}^2\ddot{\theta}_1 = m_2 l_2 \ddot{\theta}_2 cos(\theta_1 - \theta_2) - m_2 l_1 l_2 \dot{\theta}_2 \sin(\theta_1 - \theta_2) + (m_1 + m_2) g l_1 sin\theta_1 - FB_1 - FF_2 \quad (3.25)$$

$$m_2 l_2 \ddot{\theta}_2 = m_2 l_1 \ddot{\theta}_1 \cos(\theta_1 - \theta_2) - m_2 l_1 l_2 {\dot{\theta}_1}^2 \sin(\theta_1 - \theta_2) + m_2 g l_2 sin\theta_2 - FB_2 - FF_2 \quad (3.26)$$

Based on equations (3.25) and (3.26), FF is the torque of feed forward used to execute the process in the subsequent (t+1) trial, which the FB input controller received from the torque, at trial t. The feed forward controller gain which determines how much feedback torque to use as feed forward is defined by the feed forward, below shown in equation (3.27). Figure 3.3 showing the control strategies Feedback Error Learning (FEL).

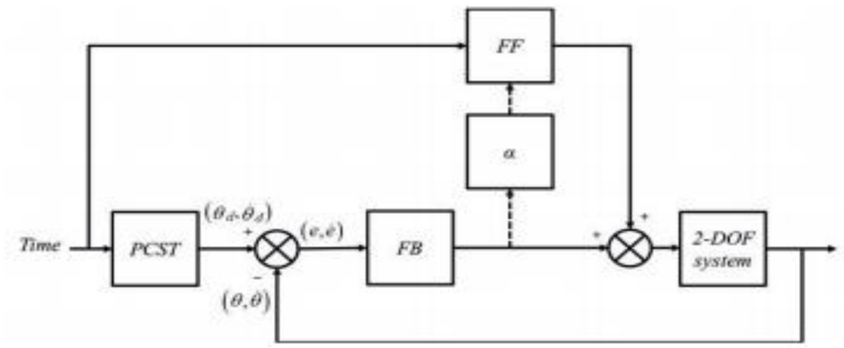

Figure 3.3: The adaptive controller scheme block diagram representation which is a mixture of input and feed forward interface.

3. Result and discussion

After successfully run the algorithm with a minimum number of 30 trajectories, the response for the upper arm and forearm showed a significant result. The responses of the upper arm as shown in Figure 4.1, where the trajectory of the arm response acquired (solid line) and the desired trajectory (dashed line) set by the PCST are in line with each other. This result showed that the algorithm able to follow the correct trajectory of the upper arm and with the increase number of the trajectory, the precision increase with lower number of mean error.

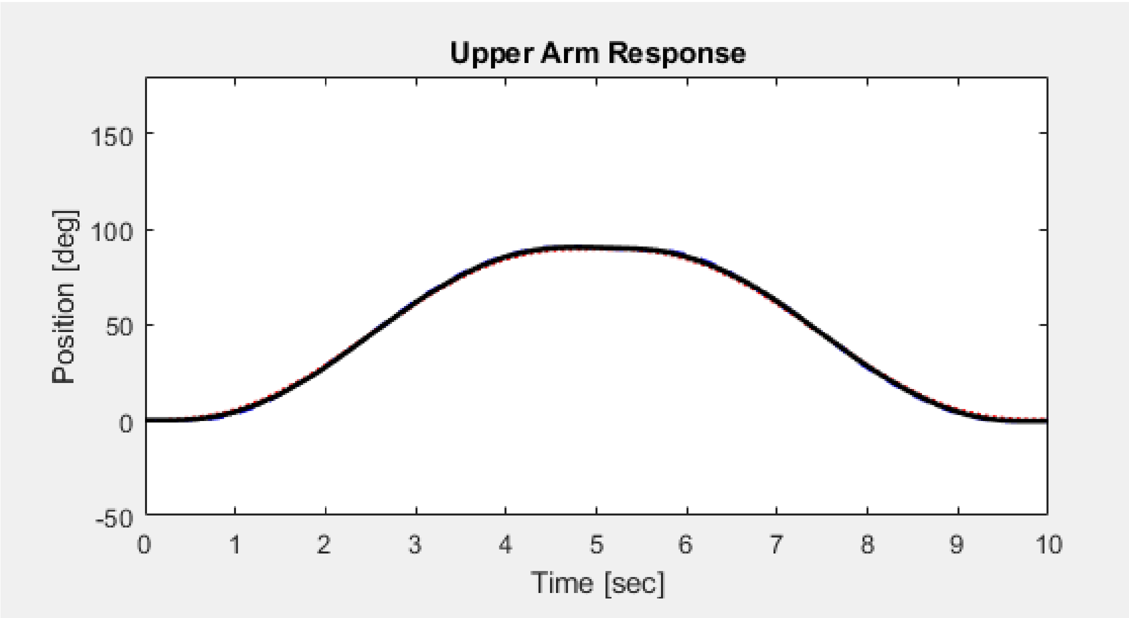

Figure 4.1: Upper arm response after minimum 30 number of trajectories.

The trajectory of the and forearm response is shown in Figure 4.2. A significant result between the trajectory acquired (solid line) and the trajectory desired (dashed line) set by PCST are in line with each other. This signify that the response from the algorithm acted according to the desired trajectory. Both the upper arm and forearm trajectory can follow the desired trajectory as set in the PCST. Based on this finding, the algorithm able to follow the required trajectory with minimum error while maintaining the response movement position.

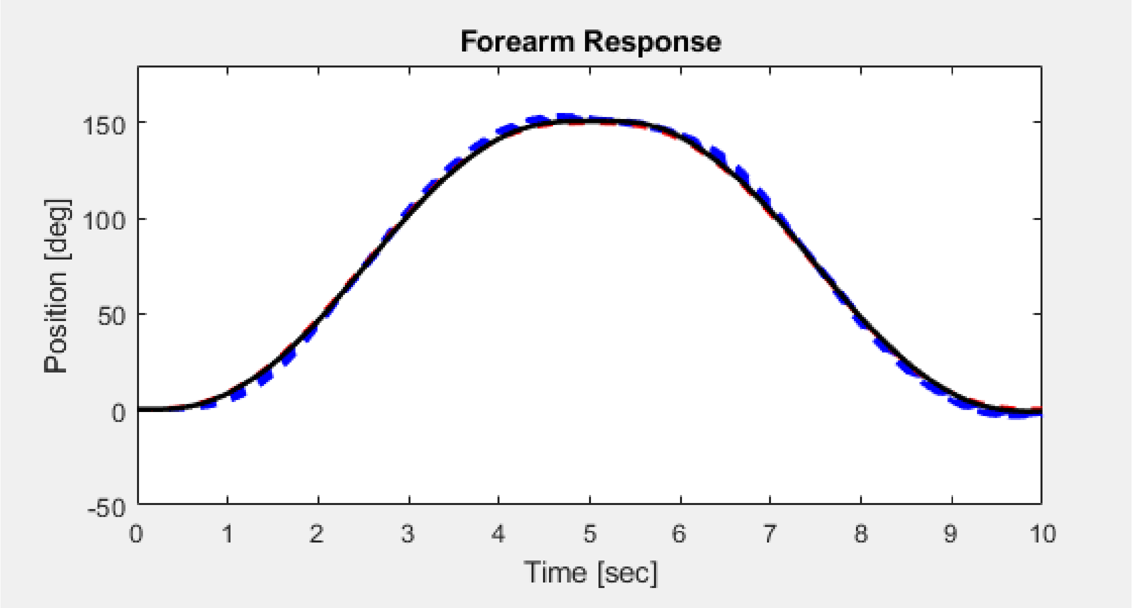

Figure 4.2: Forearm response after minimum 30 number of trajectories.

The movement and trajectory of the upper arm and forearm showed good result and are inline with the required trajectory, hence the next step is to assess the error by both upper arm and forearm. For the same PCST activity repeated for 30 trajectories trials are used in the algorithm. During the exercise session in the algorithm, a decrease in error for the combination of input and feed forward control indicates a decrease in error at the end of the simulation for both the upper arm and forearm are present. Initial absolute mean errors during the first trial for both the upper arm and forearm were 0.01 and 0.028 as shown in Figure 4.3. After 30 numbers of trials, the absolute mean error reduces to 0.0074469 and 0.007163 for upper arm and forearm respectively, as the exercise proceeded after 30 trials. This showed a reduction of 25.53 % and 74.42 % in both upper arm and forearm error response. This means that the algorithm displayed learning and adaptive learning. Properties to accomplish the aim of performing the desired PCST mission.

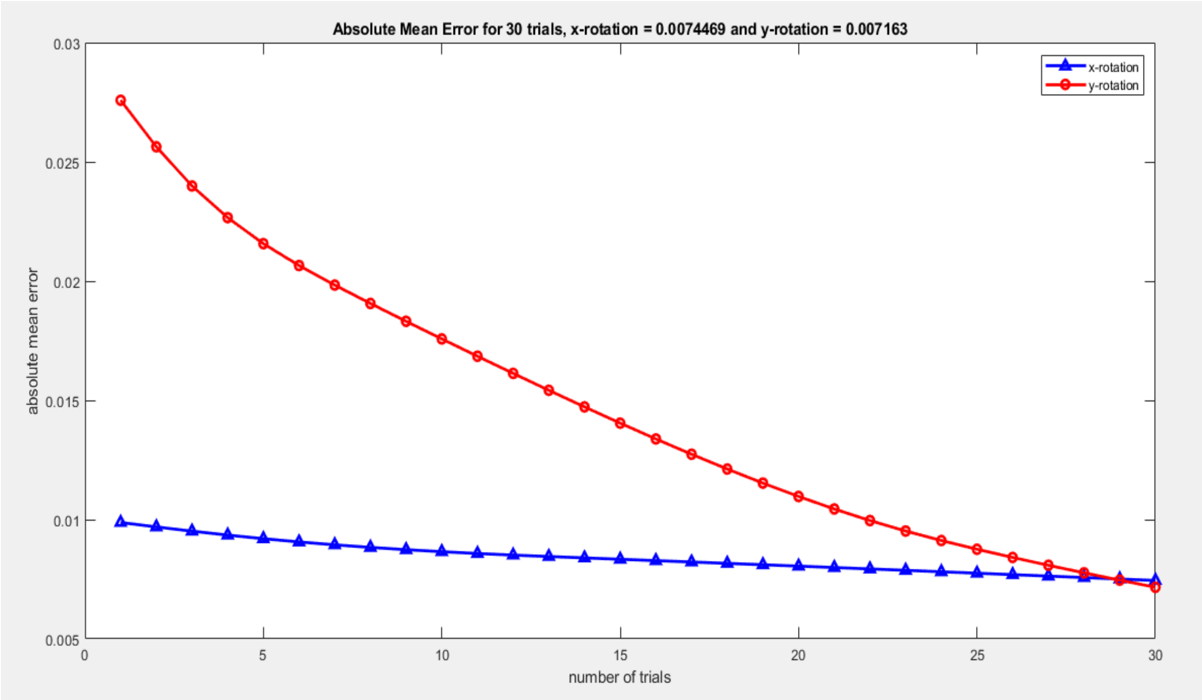

Figure 4.3: Comparison of error progression when both controllers are feedback control and control strategy for FEL.

The algorithm learns the desired trajectory after 30 repeated tests of the PCST task by taking the information of the necessary torque required from the feedback controller and feeding it into the device as a feed forward torque by a gain, α value in the subsequent test. The benefit of this control strategy is that the algorithm pre-emptively defines the amount of torque required to perform the task designated. This is the algorithm's learning component, which is consistent with the human control technique known as FEL, where a human learns from past 'errors' in order not to repeat them in similar tasks afterwards.

4. Conclusion

A model of human motor control based on Feedback Error Learning (FEL) was successfully developed. Its development combines anatomical knowledge, biomechanics, and kinematics. A distinct feature of this algorithm is the 2-DOF mathematical model used as the core element. Approach to the use of mathematical concepts, Lagrangian and Euler Lagrange equation. Both equations used to achieve the dynamic equation of mimicry of the upper arm and the forearm segments of the human arm.

In comparison to having to manually modify and change the controller gain parameters, the ability of the algorithm to learn and adapt its trajectory in order to achieve the desired task objective is also in addition to that. Therefore, when performing tasks, the algorithm succeeded in displaying human-like properties, allowing researchers to better understand the adaptive properties and strategies for human motor control. While this algorithm is designed to fit the human upper arm and forearm, it is also possible to implement the algorithm for other applications, such as robotic finger rehabilitation devices (Gomi & Kawato 1993).

However, to refine the algorithm until it can be implemented on an actual robot, the algorithm needs to be further improved. Based on the simulation results, the stability analysis of the controller parameters needs to be the focus in the next step of this research. Therefore, the typical transfer function that relates to the relationship between input and output must be defined further. Also, the convergence range of the parameters used can be achieved by using alternative methods of control analysis should be consider to help improve the algorithm.

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