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An intelligent active force control algorithm to control an upper extremity exoskeleton for motor recovery

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Abstract. This paper presents the modelling and control of a two degree of freedom upper extremity exoskeleton by means of an intelligent active force control (AFC) mechanism. The Newton-Euler formulation was used in deriving the dynamic modelling of both the anthropometry based human upper extremity as well as the exoskeleton that consists of the upper arm and the forearm. A proportional-derivative (PD) architecture is employed in this study to investigate its efficacy performing joint-space control objectives. An intelligent AFC algorithm is also incorporated into the PD to investigate the effectiveness of this hybrid system in compensating disturbances. The Mamdani Fuzzy based rule is employed to approximate the estimated inertial properties of the system to ensure the AFC loop responds efficiently. It is found that the IAFC-PD performed well against the disturbances introduced into the system as compared to the conventional PD control architecture in performing the desired trajectory tracking.

1. Introduction

Over the past two decades, the life expectancy of the elderly, particularly of 60 years and above has increased significantly [1]. The Malaysian Ministry of Health's annual report in 2011 stated that the Malaysia population between the age group of 0 to 18 years old suffers from both physical and cerebral palsy disabilities about 11% and 7%, respectively [2]. In addition, the report also highlighted that there is an upsurge of stroke patients at an average of approximately 300% annually. These statistics reflects the number of individuals that are diagnosed with such unsolicited disabilities that in turn deprives them of performing activities of daily living (ADL) [3]. However, through repetitive and continuous practice by means of rehabilitation therapy, the mobility of the involved limbs of the patients may be improved [3-5]. As the number of patient increases in the course of time, traditional rehabilitation methods are deemed costly as well as laborious, hence the need for viable alternatives to cater the demand [3-5].

One of the most prominent auxiliary techniques that have shown promising potential is the implementation of robotics. The use of exoskeletons may gradually eradicate the long hours of rehabilitation and consultation sessions consequently providing sufficient amount of time for the therapist to accommodate a larger pool of patients at any given time. These machines have demonstrated favourable results in facilitating the problem and has established confidence with the medical and physiotherapy fraternity with the existence of commercialised products and primarily the accomplishment of rehabilitating patients.

There are two distinct robots that commonly adapted to the upper limb rehabilitation namely end-effectors or exoskeletons. End-effector robots are reckoned to be less sophisticated than the exoskeleton system as the robots are not directly linked with human joints, hence the operation of end-effector robots is easier and less complicated to be manufactured. Conversely, the range of motions is restrained by the difficulty to distinguish correlated movements with associated mobility disorder. In preference to reconcile these limitations, exoskeleton robots consider the joints and perpetuate human figure into their system. The number of degree-of-freedom (DOF) in an entirely operational motion for the upper limb is said to be 9 [7]. Nevertheless, to regulate all of the DOF actuation requires the extensive inclusion of sternoclavicular, glenohumeral, elbow, wrist and fingers which is rather complicated for the system to deliver accurately.

Properties that should be considered for the human arm to be assign with the control strategy and mechanical principles are the adaptability, agility and robustness. In regards to the former, Human Machine Interface (HMI) process does elevate the reliability of the exoskeleton between the device and human operator. Conventional means of reconstructing human posture is through its dynamics [8-9]. The complexity of developing a consistent response between human and machine has indicated a more contemporary method of read signals from the motor cortex and transmitted to a controller, which is the neuromuscular and brain interaction that uses electromyography (EMG) and electroencephalogram (EEG) respectively [10-11].

Exoskeleton developers have a different way of producing the system, customarily depending on the set of objectives for rehabilitating the patients' disorder. Therefore, various type of methods that relates to the number of DOF used and the control strategies established. For instance, NEURO employed a bio-stimulated controller known as the lambda model for its 2 DOF exoskeleon [12]. Similarly, a 3 DOF Robotic Exoskeleton by Rahman et. al. integrate PD control and neuro-fuzzy based biological control for passive and active mode respectively [13]. RUPERT IV exoskeleton with 5 DOF actuation compensates the high nonlinearity of the Pneumatic Muscle Actuator (PMA) and the user's limb with an iterative learning controller to ensure adaptability from various patients is considered. ExoRob deploys nonlinear sliding mode control and nonlinear torque control exoskeleton system on its 7 DOF exoskeleton [14]. SUEFUL-7 is an EMG controlled 7 DOF exoskeleton and implements the fuzzy-neuro control method. The angle of the forearm and the wrist activates the mixture between fuzzy and adaptive neural network controllers [15].

This study investigates the efficacy of a simple and robust control technique viz. IAFC-PD in performing joint tracking of a two DOF upper limb exoskeleton system subjected a number of different type of disturbances. The system is developed with an aim to rehabilitate the flexion/extension of the elbow as well as the adduction/abduction of the shoulder joint in the sagittal plane. The intelligent mechanism chosen is fuzzy logic to address the crude means of approximating the estimated inertial matrix of the AFC loop. The performance of the proposed scheme will also be compared with a conventional PD controller under the same operating conditions of the former. To the best of the authors' knowledge, this study is novel as the proposed control strategy has yet been employed in any upper limb exoskeleton system.

2. Upper Extremity Dynamics

The upper-extremity dynamics of both the human limb and robotic exoskeleton are modelled as rigid links joined by joints as depicted in figure 1. The two-link model is restricted along the sagittal plane by assuming seamless human-machine interaction. This model is a rather simplistic model as it ignores the frictional elements that act on both the exoskeleton and human joints as well as other unmodelled dynamics.

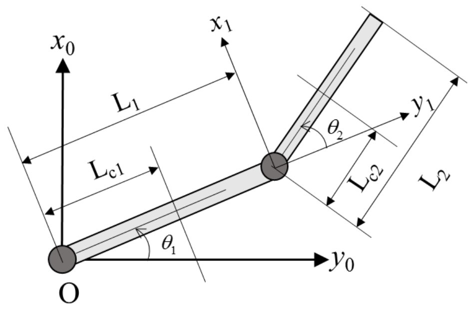

Figure 1. A two-link manipulators that represents the upper extremity.

The subscripts 1, and 2 in figure 1 indicates the parameters of the first link (upper arm), and the second link (forearm), respectively. L is the length segments of the limb and the exoskeleton; L_c is the length segments of the limb as well as the exoskeleton about its centroidal axis and θ is the angular displacement of the links. The Newton-Euler formulation is employed in deriving the equation of motions for the upper-extremity dynamic system. The coupled nonlinear differential equations may be written as [16]

$$\boldsymbol{\tau} = \mathbf{D}(\theta)\ddot{\theta} + \mathbf{C}(\theta,\dot{\theta}) + \mathbf{G}(\theta) + \boldsymbol{\tau}_d \tag{1}$$

where $\boldsymbol{\tau}$ is the actuated torque vector, **D** is a two by two inertial matrix of the limbs and exoskeleton, **C** is the Coriolis and centripetal torque vector, **G** is the gravitational torque vector whilst $\boldsymbol{\tau}_\mathbf{d}$ is the external disturbance torque vector. The following equation that represents the system can be derived as follows

$$\tau_1 = D_{11}\ddot{\theta}_1 + D_{12} + C_{11}\dot{\theta}_1 + C_{12}\dot{\theta}_2 + G_1 + \tau_{d1} \tag{2}$$

$$\tau_2 = D_{21}\ddot{\theta}_1 + D_{22} + C_{21}\dot{\theta}_1 + C_{22}\dot{\theta}_2 + G_2 + \tau_{d2} \tag{3}$$

where

$$D_{11} = m_1 L_{c1}^2 + I_1 + m_2\left(L_1^2 + L_{c2}^2 + 2L_1 L_{c2}\cos\theta_2\right) + I_2 \tag{4}$$

$$D_{12} = D_{21} = m_2 L_1 L_{c2}\cos\theta_2 + m_2 L_{c2}^2 + I_2 \tag{5}$$

$$D_{22} = m_2 L_{c2}^2 + I_2 \tag{6}$$

$$C_{11} = -m_2 L_1 L_2\left(2\dot{\theta}_2\right)\sin\theta_2 \tag{7}$$

$$C_{12} = -m_2 L_1 L_2 \dot{\theta}_2 \sin\theta_2 \tag{8}$$

$$C_{21} = m_2 L_1 L_2 \dot{\theta}_1 \sin\theta_2 \tag{9}$$

$$C_{22} = 0 \tag{10}$$

$$G_1 = \left(m_1 + m_2\right) g L_1 \cos\theta_1 + m_2 g L_2 \cos\left(\theta_1 + \theta_2\right) \tag{11}$$

$$G_2 = m_2 g L_2 \cos\left(\theta_1 + \theta_2\right) \tag{12}$$

where m is the combination of both masses, whilst I is the mass moment of inertia of the exoskeleton as well as the limbs, respectively, and g is the gravitational constant taken as 9.81m/s^2. The antropometric human limb parameters that are taken from [17]. The remaining relevant parameters are provided in section 4.

3. The Proposed Controller

3.1. Active Force Control

Hewit and Burdess [18] introduced the AFC control strategy in the early eighties, proposed a more comprehensive system that is primarily based on the principle of invariance and the classic Newton's second law of motion. The system was further extended by Mailah and fellow researchers through introducing intelligent mechanisms to approximate the inertial matrix of the dynamic system to activate the compensation effect of the controller on a number of different application [19-22]. A detailed description of the AFC method by means of crude approximation may be found in [19], whilst the conventional PD structure in [16]. Figure 2 illustrates the proposed IAFC-PD proposed in the study.

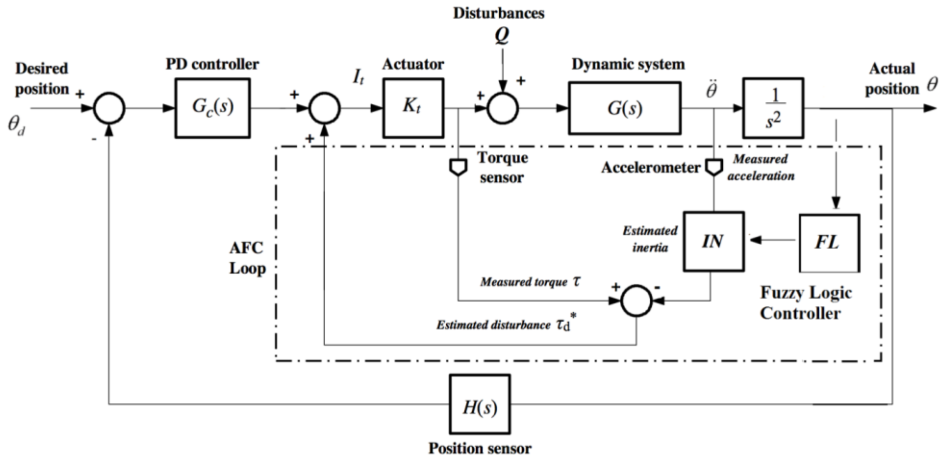

Figure 2. The proposed IAFC-PD control scheme for the exoskeleton system.

3.2. Fuzzy Logic Control

Lotfi Zadeh founded the notion of fuzzy logic (FL) in the mid-sixties. A fuzzy controller is an intelligent control architecture that is capable of performing smooth interpolation between hard boundary crisp rules [23]. FL stems from the use of linguistic variables where true and false logic is used. In this study, FL is used to compute the constant, x that is governed by the respective joint angles (joint angle 1 is represented by q1 in figure3). The constant x that varies from 0 to1 is multiplied with an initial guess of the estimated diagonal inertial matrix (**IN**) to obtain the suitable diagonal **IN** for an effective activation of the AFC mechanism as illustrated in figure 3.

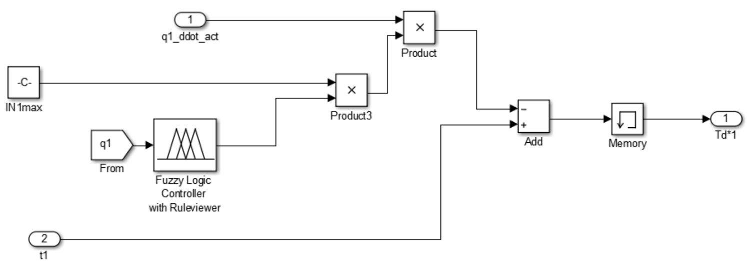

Figure 3. The IAFC Simulink block.

4. Simulation

In this study, MATLAB and Simulink were utilised. Furthermore, the Fuzzy Logic Toolbox embedded in MATLAB was also used to design the Fuzzy Logic Controller. The fuzzy inference system used in the study is based on Mamdani model [24]. Other parameters related to the human arm and controller are as follows:

Upper-limb parameters:
Limb and exoskeleton lengths: $L_1 = 0.34$ m, $L_2 = 0.25$ m;
Centre of mass: $L_{c1} = 0.17$ m, $L_{c2} = 0.\ 125$ m;

Limb masses: m_{limb1} = 1.91 kg, m_{limb2} = 1.22 kg;
Exoskeleton masses: m_{exo1} = 0.34 kg, m_{exo2} = 0.25 kg;

Mass moment of inertia of limb: I_{limb1} = 0.2374 kg.m^2, I_{limb2} = 0.0873 kg.m^2;
Mass moment of inertia of exoskeleton: I_{exo1} = 0.0131 kg.m^2, I_{exo2} = 0.0052 kg.m^2;

Controller parameters:
Controller gains (obtained heuristically):
K_{p1} = 2 000, K_{d1} = 150;
K_{p2} = 800, K_{d2} = 50;

Diagonal elements of the initial estimated inertia matrix:
$\mathbf{IN}_1$ = 0.2935 kg.m^2, $\mathbf{IN}_2$ = 0.0743 kg.m^2.

Simulation parameters:
Integration algorithm: ode2 (Heun)
Simulation start time: 0.0
Simulation stop time: 10 sec
Fixed-step size: 0.001

The membership functions employed in the study are illustrated in figures 4 and 5 below.

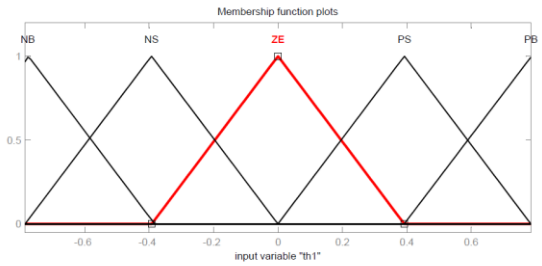

Figure 4(a). The membership function for the shoulder joint, θ_1.

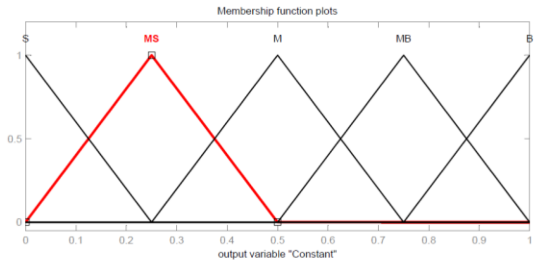

Figure 4(b). The membership function for constant 1, x_1.

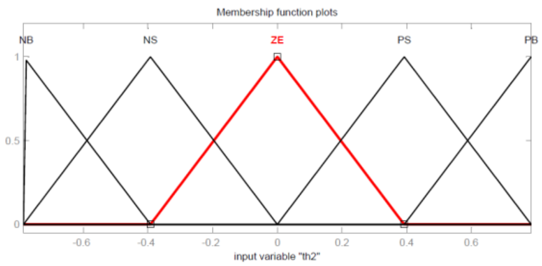

Figure 5(a). The membership function for the shoulder joint, θ_2.

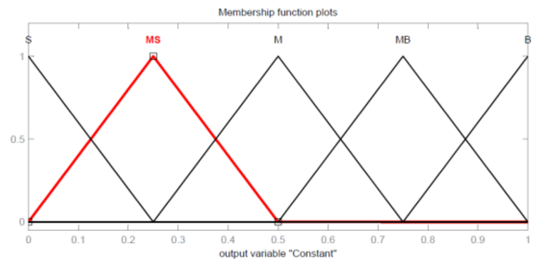

Figure 5(b). The membership function for constant 2, x_2.

5. Result and Discussion

Figures 6 to 8 illustrate the results obtained in this study. The results exhibit the efficacy of the proposed controller performing the trajectory of a sinusoidal input with an amplitude of 45° (0.7855 rad) on both the elbow and shoulder joints by subjecting the system to three distinct conditions viz. without disturbance (figure 6), a constant disturbance with an amplitude of 100 N.m. (figure 7) and a harmonic disturbance with an amplitude of 500 and frequency 1 rad/s (figure 8).

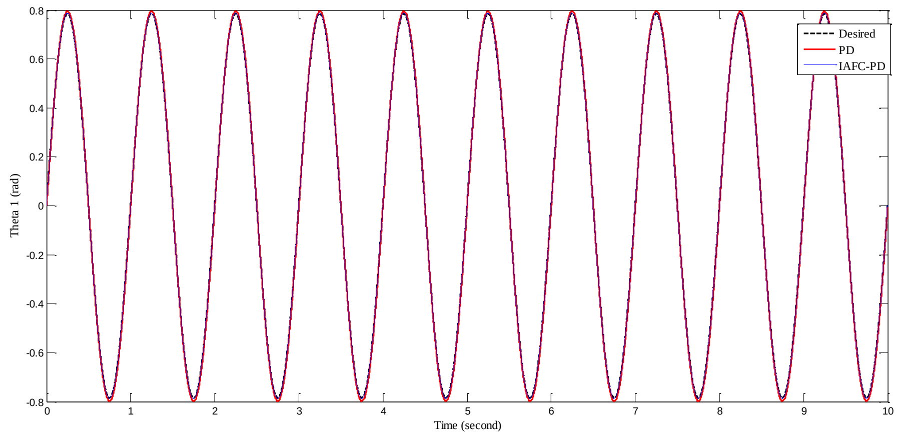

Figure 6 (a). Result of joint 1 angle trajectory without any disturbance.

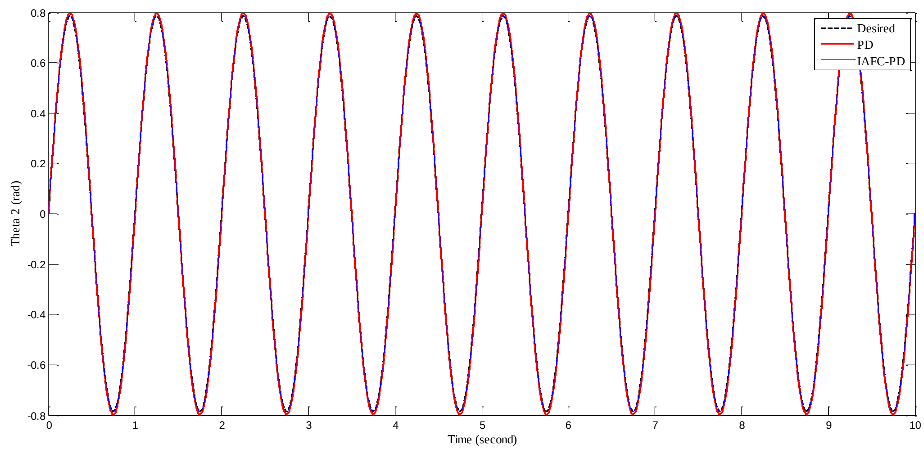

Figure 6(b). Result of joint 2 angle trajectory without any disturbance.

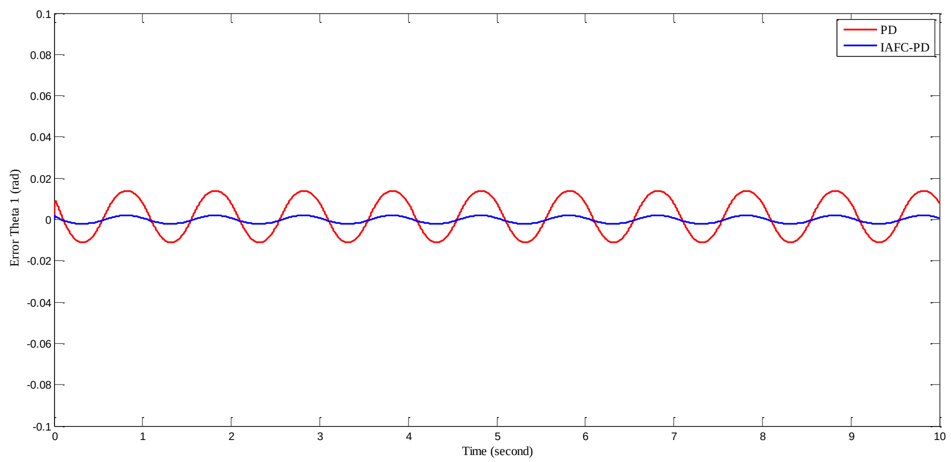

Figure 6(c). Tracking error of joint 1 without any disturbance.

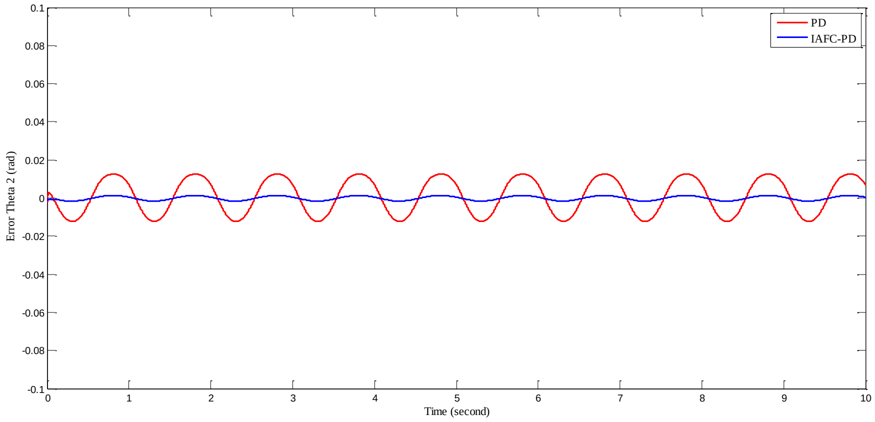

Figure 6(d). Tracking error of joint 2 without any disturbance.

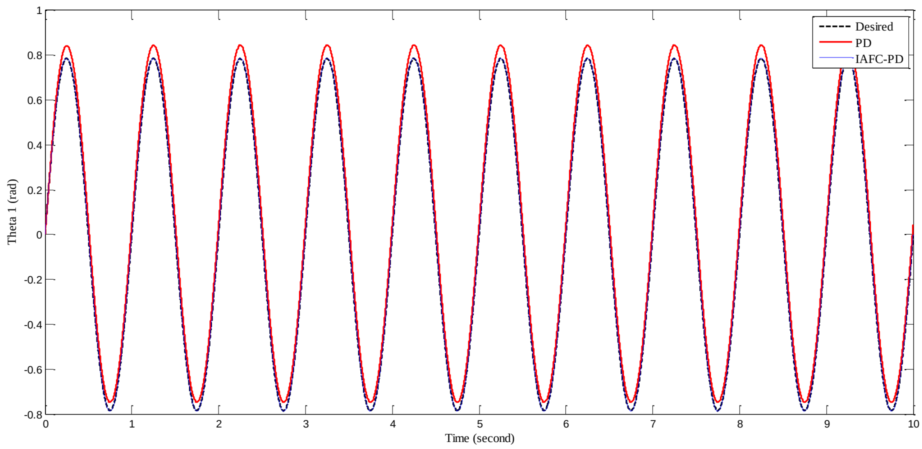

Figure 7(a). Result of joint 1 angle trajectory with a constant disturbance of 100 N.m.

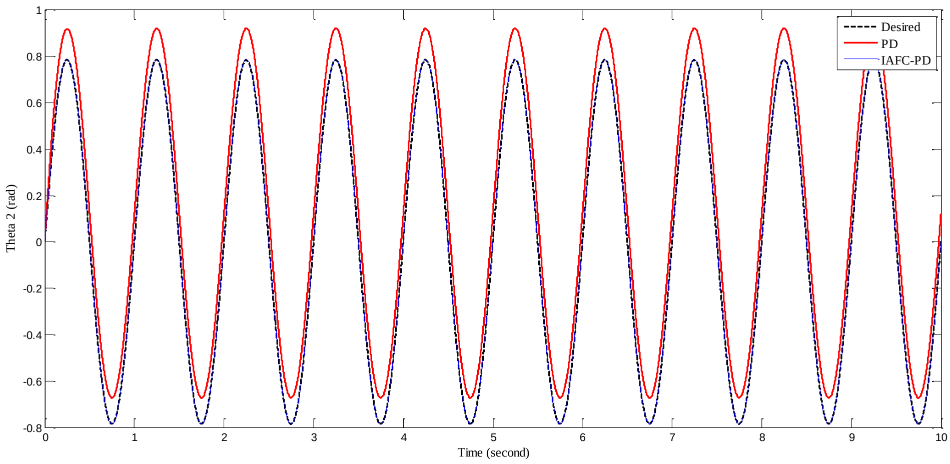

Figure 7(b). Result of joint 2 angle trajectory with a constant disturbance of 100 N.m.

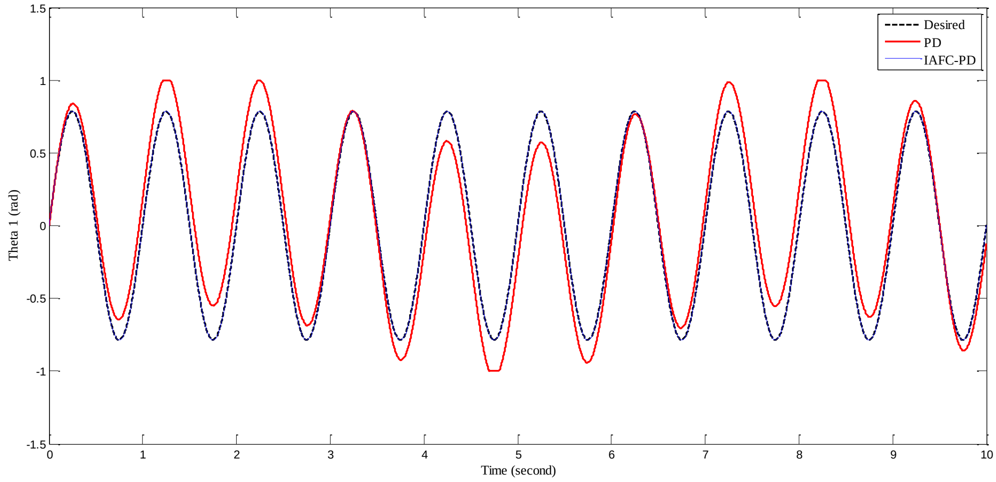

Figure 8(a). Result of joint 1 angle trajectory with a harmonic disturbance of 500 N.m.

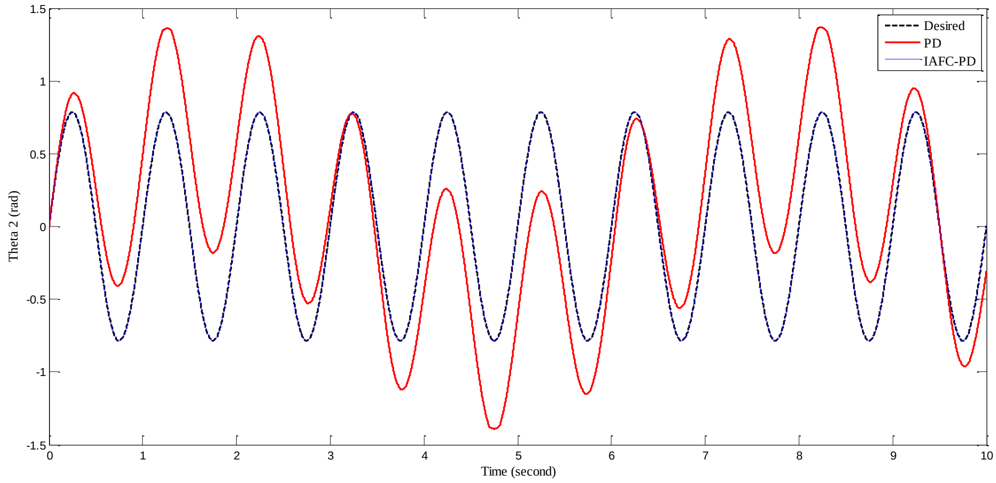

Figure 8(b). Result of joint 2 angle trajectory with a harmonic disturbance of 500 N.m.

Table 1. Summary of joint root mean square tracking error ($error_{RMS}$).

	Elbow joint, θ_1 $error_{RMS}$ (mrad)		Shoulder joint, θ_2 $error_{RMS}$ (mrad)	
Disturbance Type	PD	PD-IAFC	PD	PD-IAFC
None	9.728	1.485	9.210	1.077
Constant (100 N.m.)	48.761	1.485	123.584	1.078
Harmonic (500 N.m.)	170.809	1.486	429.327	1.080

The root mean square error ($error_{RMS}$) of both joints are listed in Table 1. It is apparent that the IAFC-PD control scheme provides the best trajectory tracking for both joints with and without the influence of any form of disturbances. The conventional PD control strategy manage to track the joint trajectories well without the presence of disturbance, however performs poorly with the onset of disturbance as illustrated in figures 8 to 9. The proposed control scheme manage to achieve the desired trajectory tracking with an $error_{RMS}$ of approximately 0.2% and 0.14% for the elbow and shoulder joints, respectively. It is interesting to note that, the results obtained from the IAFC-PD suggest that the control strategy is indeed robust and would bode well in practical application as the unmodelled dynamics shall be treated as a form of disturbance.

6. Conclusion and Future Work

It can be concluded from the study that the proposed IAFC-PD performs exceptionally well even under the influence of external disturbances. The conventional PD control strategy provides satisfactory tracking performance without the presence of disturbance, nonetheless, suffers significantly upon the inclusion of disturbance. The study further implies the effectiveness of the proposed controller for the early stage of upper limb rehabilitation. Further investigation may be carried out by subjecting the system to other form of disturbances as well as incorporating other intelligent methods (neural network, GA, etc.) in acquiring the suitable estimated inertial matrix.

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