The Control of an Upper-Limb Exoskeleton by Means of a Particle Swarm Optimized Active Force Control for Motor Recovery

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Abstract—**The modelling and control of a two degree of freedom upper extremity exoskeleton for motor recovery is presented in this paper. The dynamic modelling of the upper arm and the forearm for both the anthropometric based human upper limb as well as the exoskeleton was attained via the Euler-Lagrange formulation. A proportional-derivative (PD) architecture is employed to assess its effectiveness in performing joint-space control objectives namely the forward adduction/abduction on the shoulder joint and the flexion/extension of the elbow joint. An intelligent active force control (AFC) optimised by means of the Particle Swarm Optimisation (PSO) algorithm is also integrated into the aforesaid controller to examine its efficacy in compensating disturbances. It was established from the simulation study that the PD- PSOAFC performed notably well in catering the disturbances introduced to the system whilst maintaining its excellent tracking performance as compared to its pure classical PD counterpart.**

Keywords— **Active force control, Particle swarm optimisation, Robust, rehabilitation, Trajectory tracking control.**

I. Introduction

Over the past couple of decades, the life expectancy amongst the ageing has increased steadily around the globe [1]. Approximately 8.3% of Malaysia's population is well over 60 years old [1]-[2]. The number of stroke patients as reported in the 2013 Malaysian Ministry of Health's annual report, demonstrated an average increase of threefold annually [3]. Furthermore, it was also reported in the 2011 report, that 11% and 7.2% of Malaysians between the age of an infant to 18 years old are affected by physical and cerebral palsy disabilities [2]. It is not uncommon for people that fall into the aforesaid figures are affected by complete or partial loss of motor control of the upper-limb which essentially affects their activities of daily living [4].

It has been established from the literature that through continuous and repetitive rehabilitation activities, these individuals may regain their mobility [4]–[7]. Nonetheless, it is worth to note that conventional rehabilitation therapy is often deemed to be laborious and costly which in turn limiting the patient's rehabilitation activities [4]–[6]. Owing to the increasing demand for rehabilitation coupled by the shortcomings of conventional rehabilitation therapy has led the research community to address the aforementioned issues through the engagement of robotics [4], [5], [8], [9]. It is hypothesised that the use of exoskeletons may progressively eliminate the long hours of consultation as well as rehabilitation sessions and subsequently accommodate more patients.

The control strategies developed over the years with respect to rehabilitation robotics reported in the literature can be classified into four main classes, viz. position tracking control, bio-signal, impedance and force control based control as well as adaptive control [10]. As previously mentioned, one's mobility may well be further developed through repetitive and continuous exercise on the impaired limb. This form of training is of particular importance, especially in the early stage of rehabilitation whereby passive mode is required, and this therapy may be achieved through positional or joint based trajectory tracking control.

Hitherto, a number of control strategies have been employed with regard to positional or joint based trajectory tracking control for the upper limb exoskeleton system i.e. Proportional-derivative (PD) controller [11]-[12], nonlinear sliding mode control (SMC) [13]-[14], modified non-linear computed-torque control [15] as well as intelligent based controller such as fuzzy-based PD [16] amongst others. The objective of the study is to examine the tracking performance of a robust control scheme viz. a hybrid proportional-derivative particle swarm optimised active force control (PD-PSOAFC) that is to some extent oblivious to the presence of disturbances of a two DOF upper limb exoskeleton system. The performance of the proposed controller is then compared to a classical pure PD controller by exciting the same form of disturbance into both systems. To the best of the authors' knowledge, the study is novel as the proposed controller has yet been utilised in any upper limb exoskeleton system.

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II. Upper limb dynamics

Figure 1 illustrates the upper limb dynamics of the human limb and exoskeleton are modelled as rigid links joined by joints (bones). The two-link model restricted to the sagittal plane is a rather conservative system as the human-machine interaction is presumed smooth. Furthermore, it is noteworthy to mention that the frictional elements, as well as other unmodelled variables, are disregarded.

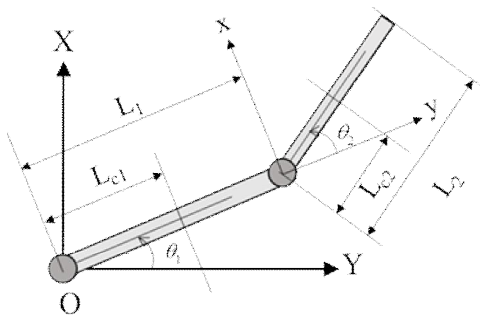

Fig. 4 The two-link manipulator that mimics the human upper limb

The parameters of the upper arm and the forearm illustrated in Figure 1 are represented by the subscripts 1 and 2, respectively. The joint position of the shoulder and elbow is also depicted in the figure. L is the length segments of the limb; L_c is the length segments of the limb about its centroidal axis and θ is the angular position of the limbs. The equation of motions for the non-linear dynamic system is derived by means of the Lagrangian. The following vector form expresses the upper-extremity dynamics of the coupled nonlinear differential equations

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix}=\begin{bmatrix}D_{11} & D_{12}\\ D_{21} & D_{22}\end{bmatrix}\begin{bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\end{bmatrix}+\begin{bmatrix}C_{11} & C_{12}\\ C_{21} & C_{22}\end{bmatrix}\begin{bmatrix}\dot{\theta}_1\\ \dot{\theta}_2\end{bmatrix}+\begin{bmatrix}G_1\\ G_2\end{bmatrix}+\begin{bmatrix}\tau_{d1}\\ \tau_{d2}\end{bmatrix} \quad (1)$$

where **τ, D, C, G** and $\boldsymbol{\tau_d}$ denote the actuated torque vector, the 2 × 2 inertia matrix of the human limb and the exoskeleton, the Coriolis and centripetal torque vector, the gravitational torque vector and the external disturbance torque vector, respectively. The readers are referred to [17] for the detail components of the above vector formulation.

III. Control architecture

A. Active Force Control

Hewit and Burdess initially proposed the concept of AFC in the early eighties, and it is established on the principle of invariance and Newton's second law of motion [18]. Mailah et al. have improved the effectiveness of the aforementioned control scheme by integrating artificial intelligent techniques in estimating the inertial matrix of the dynamic system that essentially activates the compensation effect of the controller [19]–[28]. Furthermore, the robustness of this method has also been well demonstrated in various applications both numerically as well as experimentally [22],[23],[26]-[28].

The torque generated is governed by the classical PD control law, typically expressed as [17]

$$\tau = K_p(\theta_d - \theta) + K_v(\dot{\theta}_d - \dot{\theta}) \quad (2)$$

where, $\dot{\theta}_d$ and $\dot{\theta}$ are the desired and present angular velocities, respectively, θ_d and θ are the desired and present positions, respectively, whilst K_p and K_d are the proportional and derivative constants, respectively. In the study, the controller gains were assumed to be appropriately tuned by heuristic means.

To eliminate the actual disturbances τ_d, the estimated disturbance torque τ_d* has to be calculated and is given by the following equation

$$\tau_d^* = \tau - \mathbf{IN}\,\ddot{\theta} \quad (3)$$

where **IN** is the estimated inertial matrix, whilst τ and $\ddot{\theta}$are the measured applied control torque acceleration signal, respectively. The value of **IN** may be expressed in the following form

$$[\mathbf{IN}] = [\mathbf{D}] \quad (4)$$

where only the diagonal terms of **D** are considered. The off-diagonal terms of the matrix are ignored as it has been demonstrated that the cross-coupling term may be disregarded [18]. The acceleration, as well as the actuated torque of the lower limbs, were also assumed to be perfectly modelled (i.e. the noises from sensors are also totally neglected) in this particular study. A graphical representation of the PSOAFC scheme with the PD controller applied to the exoskeleton is illustrated in Figure 2. The PD-PSOAFC control scheme is only activated upon the engagement of the AFC loop. The system is driven by