Proceedings of Mechanical Engineering Research Day 2018, pp. 297-298, May 2018

The control of an upper limb exoskeleton system for passive stroke rehabilitation: An active force control approach

A.P.P. Abdul Majeed[1,*], Z. Taha[1], M.A. Abdullah[1,2], I.M. Khairuddin[1,2], M.A. Zakaria[1]

[1)] Innovative Manufacturing, Mechatronics and Sports (iMAMS) Laboratory, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia.

[2)] Department of Mechatronics Engineering, International Islamic University Malaysia, Jalan Gombak, 53100 Kuala Lumpur, Malaysia.

[*]Corresponding e-mail: anwarmajeed@imamslab.com

Keywords: Rehabilitation; active force control; artificial intelligence

ABSTRACT – This paper examines the efficacy of a robust class control scheme namely active force control (AFC) on a two degrees of freedom upper limb exoskeleton system in performing typical rehabilitation trajectory on the shoulder and elbow joints. The dynamics of the system was attained via the Lagrangian principle. The ability of the Proportional-Derivative AFC (PDAFC) architecture optimized by means of fuzzy logic (FL) and artificial neural network (ANN) against classical PD in mitigating constant disturbance effect on the aforesaid joints were also evaluated. It was demonstrated from the simulation investigation that the PDANNAFC scheme triumphs against other schemes evaluated.

1. INTRODUCTION

Approximately 15 million people around the globe suffer from stroke annually. Stroke is a neurological disorder that is caused either by an interruption of blood flow to the brain or the bleeding of the brain. Stroke survivors are often left with complete or partial paralysis that affects their activities of daily living (ADL). Nonetheless, continuous passive motion activities have been reported to allow the survivors to regain their mobility [1,2]. The employment of robotics has been seen as a potential solution towards mitigating the drawbacks of conventional rehabilitation therapy [1-3].

AFC is a robust disturbance rejection controller that was initially proposed by Hewitt and Burdess [4] in the early eighties. This scheme has been demonstrated to be satisfactory with regards to its disturbance rejection ability in both simulation and experimental works on a number of different applications [3-6]. However, it is worth to note that the efficacy of the control scheme relies upon the appropriate estimation of the estimated inertial parameter, IN. Mailah and co-researchers [6,7] have employed different intelligent algorithms in estimating the aforesaid parameter.

The aim of the present study is to investigate the effectiveness of AFC scheme in mitigating disturbance effect that is non-trivial for rehabilitation application, notably owing to the unique anthropometric properties of different individuals. Fuzzy logic (FL) and artificial neural networks (ANN) is utilised in the ascertainment of the IN parameter in the study. The ability of the PDFLAFC, PDANNAFC and the classical PD scheme in performing a joint based trajectory tacking that mimics the flexion and extension therapy against constant disturbance of 30 N.m. at a speed of 0.375 rad/s on both the shoulder and elbow joints [8].

2. METHODOLOGY

The plant of the two degrees of freedom exoskeleton system examined is derived from the Euler-Lagrange formulation restricted to the sagittal plane. For the sake of brevity, the readers are referred to [9] for the detailed derivation as well as the numerical values of the relevant parameters considered in the present study. The heuristically attained PD gains for both the shoulder and elbow joints are 1000 and 90, respectively. The predefined trajectories selected is the movement of the limbs from 0° to 90° for a period of 45 seconds that complements a typical rehabilitation activity.

FL as well as ANN were utilised in acquiring the IN parameter in the present investigation. The Mamdani fuzzy inference system with three membership functions were found to be adequate in representing the evaluated system. Equation (1) is used to determine the IN parameter.

$$IN_i = IN_{\min,i} + x_i(IN_{\max,i} - IN_{\min,i}) \tag{1}$$

Where, the subscript i denotes the joints. The constant, x is varied between 0 to 1 by means of fuzzy logic. The upper and lower bounds i.e. IN_{max} and IN_{min} are determined by heuristic means to be $0.0001 \leq IN_1 \leq 0.02$ kg.m$_2$ and $0.0001 \leq IN_2 \leq 0.005$ kg.m$_2$, respectively. The joint angles, θ_1 and θ_2 are used as the crisp input, whilst x_1 and x_2 are used as the crisp output for the fuzzification process. The fuzzy rules developed are as follows, whilst Table 1 provides the linguistic values as well as its numerical range:

a) If θ_1 is S, then x_1 is XS
b) If θ_1 is M, then x_1 is XM
c) If θ_1 is B, then x_1 is XB
d) If θ_2 is S, then x_2 is XS
e) If θ_2 is M, then x_2 is XM
f) If θ_2 is B, then x_2 is XB

A single hidden layer ANN model with a network topology of 1-10-1 was utilised in the study. The activation function employed is the logsig activation function trained with the Levenberg-Marquardt training algorithm. The input of the ANN models is θ_1 and θ_2 whilst the output of the models is, x_1 and x_2, respectively that is in accordance to Equation (1). The 70:15:15 ratio is employed for the training, testing and validation of the models developed on a dataset of 241 points for both input and output data. The trajectory performance of the evaluated controllers is the root-mean-square-error (RMSE).

Table 1 The linguistic values and numerical range.

Linguistic Value	Numerical Range
Small (S)	0° to 22.5°
Medium (M)	22.5° to 67.5°
Big (B)	67.5° to 90°
Small (XS)	0 to 0.25
Medium (XM)	0.25 to 0.75
Big (XB)	0.75 to 1

3. RESULTS AND DISCUSSION

Figure 1 that depicts the tracking performance of evaluated controllers. It could be seen that PDAFC schemes are more superior in comparison to the classical PD scheme in mitigating the constant disturbance injected to both the shoulder and elbow joints. Moreover, it could be seen that the ANN based AFC scheme is slightly better in comparison to the FL based AFC scheme.

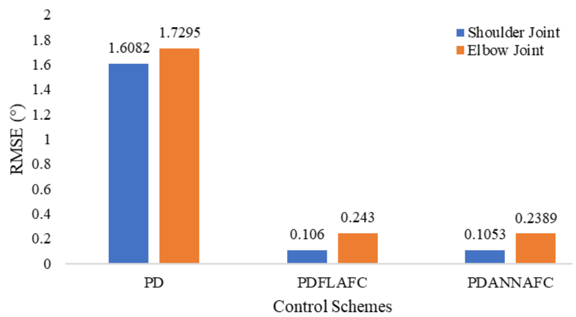

Figure 1 Tracking error performance.

The reduction of the RMSE provided by the PDANNAFC scheme against the classical PD is approximately 93 % and 86 % for the shoulder and elbow joints, respectively. This observation further suggests that the trajectory performance of the system is not compromised even in the event that disturbance is applied to the system that simulates the effect of a stroke patient upper-limb weight on the system.

4. CONCLUSION

It is apparent from the present investigation that the AFC scheme is able to mitigate the disturbance injected to the system. The PDANNAFC scheme appears to be better against the other control schemes tested, suggesting its potential employability for exoskeleton applications. Future study will explore the efficacy of the AFC scheme in real-time hardware experimentation.

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