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Natural Trajectory based FES-induced Swinging Motion Control

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***Abstract*— The use of electrical signals to restore the function of paralyzed muscles is called functional electrical stimulation (FES). FES is a promising method to restore mobility to individuals paralyzed due to spinal cord injury. FES induced movement control is a significantly challenging area, mainly emanating from various characteristics of the underlying physiological/biomechanical system. An approach of fuzzy trajectory tracking control of swinging motion optimized with genetic algorithm is presented. The results show the effectiveness of the approach in controlling FES-induced swinging motion. In this approach only the quadriceps muscle is stimulated to perform the swinging motion by controlling the amount of stimulation pulsewidth**

Keywords- Functional electrical stimulation, fuzzy logic, genetic algorithm, swinging motion, quadriceps, paraplegic.

I. INTRODUCTION

FES induced movement control is a significantly challenging area for researchers. The challenge mainly arises due to many obstacles in stimulating the paralyzed neuromuscular system, such as fatigue, time-varying and nonlinear properties of paralyzed muscles (Levy et al., 1990). Primarily due to the complexity of the system (nonlinearities, time-variation) practical FES systems are predominantly open-loop where the controller receives no information about the actual state of the system (Crago et al., 1996). In its basic form, these systems require continuous user input. Practical success of this open-loop control strategy is still, however, seriously limited due to the fixed nature of the associated parameters. Accurate control of FES-induced movement can be ensured with a suitable closed-loop adaptive control mechanism. Such approach has several advantages over open-loop schemes, including better tracking performance and smaller sensitivity to modelling errors, parameter variations, and external disturbances (Huq,2009).

Although conventional proportional, integral, derivative (PID) control is still the most widely adopted method in industry for various control applications due to its simple structure, ease of design, and low implementation cost, it might not perform satisfactorily if the system to be controlled is of highly nonlinear and/or uncertain nature. Classical closed-loop control algorithms have failed to provide satisfactory performance and are not able to guarantee stability, a desired property of the controlled system (Jezernik et al, 2004).

Many control strategies have been developed to provide enhanced reproducibility of muscle response, including model reference adaptive control (Bernotas et al., 1987), fixed-parameter feedback control (Abbas, 1991), and sliding mode control (Jezernik et al., 2004). Model-reference adaptive control does not need a precise model of the musculoskeletal system, but the control performance is satisfactory only when the closed-loop bandwidth is restricted by appropriate choice of reference model parameters (Hatwell et al., 1991). Fixed parameter feedback control involves the construction of a precise mathematical model that describes the dynamic behaviour of the controlled musculoskeletal system. As muscle is very complex, fixed-parameter feedback control techniques have only enjoyed limited success (Chang et al., 1997). Jezernik et al. (2004) used sliding mode FES control to regulate knee joint angle and tested this on six neurologically intact subjects and two untrained paraplegic subjects. Good tracking of a desired knee joint trajectory was achieved, but this could only be applied to mathematical model based plant. The overall model of the plant being considered is a multi-input-multi-output (MIMO) nonlinear model consisting of nonlinear lumped parameters comprising passive joint viscoelasticity and active muscle properties and segmental dynamics (Ibrahim et al., 2010).

On the other hand, fuzzy logic control (FLC) has long been known for its ability to handle complex nonlinear systems without the need for a mathematical model. FLC is the fastest growing soft computing tool in medicine and biomedical engineering (Teodorescu et al., 1999). This paper presents the development of strategies for swinging motion control by controlling the amount of stimulation pulsewidth to the quadriceps muscle of the knee joints. The knee joint model developed in Matlab/Simulink, as described in (Ibrahim et al., 2010), is used to develop the FLC based on reference trajectory derived from passive oscillation to control the knee joint movement. The FLC output is the controlled FES stimulation pulsewidth signal which stimulates the knee extensors providing torque to the knee joint. The swinging movement is performed by only controlling stimulation pulsewidth to the

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knee extensors to extent the knee and then the knee is left freely to flex in the flexion period.

II. MATERIALS AND METHOD

The role of simulation was to design, test, and optimize the control strategies, thus reducing time-consuming trial and error adjustments during human experiments.

A. *Model of Knee Joint*

The shank-quadriceps dynamics are modelled as the interconnection of passive and active properties of muscle model and the segmental dynamics. The total knee-joint moment is given by (Ferrarin, 2000):

$$M_{\mathrm{i}} = M_a + M_{\mathrm{g}} + M_{\mathrm{s}} + M_{\mathrm{d}} \tag{1}$$

where M_a refers to an active knee joint moment produced by electrical stimulation, M_s is the knee joint elastic moment and M_d is the viscous moment representing the passive behaviour of the knee joint. In this research the $M_{\mathrm{i}} - M_g$ is represented by equation of motion for dynamic model of the lower limb while M_{a} and $M_s + M_d$ are represented by a fuzzy model as active properties of quadriceps muscle and passive viscoelasticity respectively. A block diagram of the knee joint model consisting of active properties, passive viscoelasticity and equations of motion of the lower limb is shown in Fig. 1. The active joint moment is added with the passive joint moment as an input (torque) to the lower limb model and this will produce the knee angle as the output.

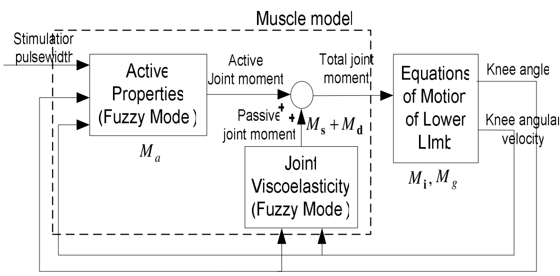

Figure 1. Schematic representation of the knee joint model

A schematic diagram of the lower limb model is shown in Fig. 2, where q_2 = shank length, r_1 = position of centre of mass (COM) along the shank, r_2 = position of COM along the foot, θ_1 =knee angle and θ_2 =ankle angle. The leg movements were described as a double pendulum with constant ankle angle. Hence, the motion dynamics can be represented in a simpler form. The gravitational (M_{g}) moment is represented by:

$$M_g = m_1 g \cos\theta_1 r_1 + m_2 g \cos\theta_1 q_2 \tag{2}$$

The inertial (M_{i}) moment is represented by mathematical model of the lower limb based on Kane's equations as follows:

$$M_i = -m_2 q_2 \dot{\theta}_1{}^2 r_2 - I_1 \ddot{\theta}_1 - m_1 r_1{}^2 \ddot{\theta}_1 - m_2 q_2^2 \ddot{\theta}_1 \tag{3}$$

where, m_1 = shank mass, m_2 =foot mass, I_1 = moment of inertia about COM, $\dot{\theta}_1$ =knee velocity, $\ddot{\theta}_1$ =knee acceleration, g =acceleration due to gravity.

The anthropometric inertia parameters of the subject's lower limb were optimised based on passive pendulum test as described in (Ibrahim et al., 2010), and these are shown in Table 1.

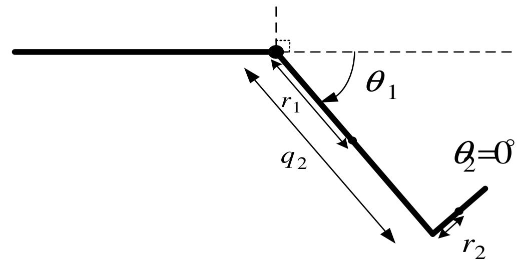

Figure 2. Lower limb model

TABLE 1. ANTHROPOMETRIC DATA OF SUBJECT

Parameter	Value
Shank length (m)	0.43
Foot length (m)	0.068
Position of COM of shank (m)	0.22
Position of COM of foot (m)	0.035
Foot Mass (kg)	0.95
Shank Mass (kg)	3.5
Moment of Inertia (Nm^2)	0.36

The knee joint model input is the stimulation pulsewidth as would be delivered by an electrical stimulator in reality. Thus a complete model of knee joint developed is utilized as platform for simulation of the system and development of control approaches.

B. *Controller Development*

In this study, the focus is on the design and evaluation of fuzzy logic control using GA optimisation.

1. Reference trajectory

Compromising with the natural dynamics of the plant in the control of movement to produce a desired outcome is a good choice as considered in (Williamson, 1998). Perhaps the feature is most prominent within natural movements, performed by human or animals, as is suggested by the ‘minimum torque-change’ model of voluntary human arm movement (Uno et al., 1989). The choice of the reference trajectory with a view to overcome some drawbacks of the trajectory based closed-loop FES control, viz. poor tracking and oscillating response (Huq, 2009). Therefore a reference trajectory for the knee joint obtained from observing the subject’s passive oscillation from the pendulum test.

2. Fuzzy Controller Tuning

Tuning a control loop refers to the adjustment of its control parameters to the optimum values for the desired control response. A major problem in the not so widespread use of fuzzy logic (FL) is the difficulty in designing of membership functions (MFs) to suit a given problem. A systematic procedure for choosing the vector of parameters that specify the MF is still not available. Given such plant model in the control loop, conventional stability analysis and tuning techniques are of no use. Consequently the tuning process of FL controller was suitably formulated as optimization procedure using genetic optimization techniques. Piecewise linear triangular MFs are used, because of their simplicity and efficiency with respect to computability. The FL controllers were optimized involving 73 decision variables or parameters. A breakdown of optimized parameters of the fuzzy system is as follows:

i. 45 parameters relating to the triangular MFs, (3-element vector that determines the break points for each MF).
ii. 25 weighting factors that are to be applied to the rule between 0 and 1 for all rules.
iii. 3 parameters associated with the scaling factors of the three fuzzy state vectors relating them to the normalized universe of discourse used by the inference method.

3. Design of the Natural Swinging Motion Fuzzy Logic Control Strategies

An outline of the natural swinging motion FLC is shown in Figure 3. Error is defined as difference between the desired trajectory and measured joint angle. The Mamdani-type fuzzy controller will regulate the stimulation pulsewidth according to the error and derivative of error. The control problem is to design a fuzzy controller such that the knee joint tracks the desired trajectory as closely as possible at all times in spite of the uncertainties and non-linearities present in the system.

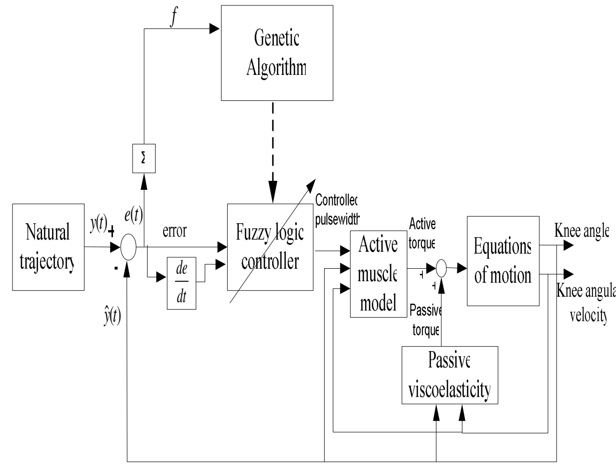

Figure 3. GA optimization of fuzzy controller

The GA is based on natural selection and population genetics theory (Goldberg, 1989). This evolutionary algorithm is chosen because the search space is large and complex. The advantages of the GA approach are that it is robust, searches many points simultaneously, and is able to avoid local optima that traditional gradient descent algorithms might get stuck in (Jan, 2008). Optimization of the FL controller using GA is shown in Figure 3. The automatic optimization is implemented in MATLAB with GA Toolbox.

The objective of GA optimization process is to minimize the error between the desired trajectory and actual knee angle. The error is defined as:

$$e(t) = y(t) - \hat{y}(t) \tag{4}$$

where $y(t)$ is the desired trajectory and $\hat{y}(t)$ is the actual knee angle. The ‘goodness of fit’ of the identified model is determined using the objective function by minimizing the MSE:

$$f = \left\{ \frac{\sum_{i=1}^{N} \left(y(t) - \hat{y}(t) \right)^2}{N} \right\} \tag{5}$$

III. RESULTS AND DISCUSSION

A. Tuning of the Controller

A new method comprising a GA and unconstrained MF overlap to automatically design fuzzy controllers is presented. . The automatic GA optimization process was set to generate up to 100 generations of solutions. Population size of GA was set to 50 and crossover and mutation probabilities were 0.8 and 0.001 respectively. The best solution was kept and the rest were discarded until there was no significant change in the mean square error (MSE) observed after the 85th generation. The computation time taken by the GA to converge was 18 minutes and the minimum MSE achieved was 1.07°. The optimized weighting factors of all the fuzzy rules for the controller are contained in Table 2 in their corresponding cells. Figure 4 shows the optimally shaped input and output MFs of the fuzzy controller.

TABLE 2: FLC RULE TABLE WITH OPTIMIZED WEIGHTING FACTORS FOR THE RULES.

		Derivative of Error				
		NB	NS	ZO	PS	PB
Error	NB	ZE (0.38)	ZE (0.03)	ZE (0. 49)	NS (0.05)	LO (0. 59)
	NS	ZE (0.82)	ZE (0.49)	VL (0. 64)	LO (0.26)	ME (0.37)
	ZO	ZE (0.42)	VL (0. 49)	LO (0. 33)	ME (0.25)	HI (0.59)
	PS	VL (0.76)	LO (0. 53)	ME (0. 82)	HI (0.82)	HI (0.47)
	PB	LO (0.79)	ME (0. 22)	HI (0. 42)	HI (0.64)	HI (0.46)

NB=Negative big, NS=Negative small, ZO=Zero, PS=Positive small, PB=Positive big, ZE=Zero, VL=Very Low, LO=Low, ME=Medium, HI=High

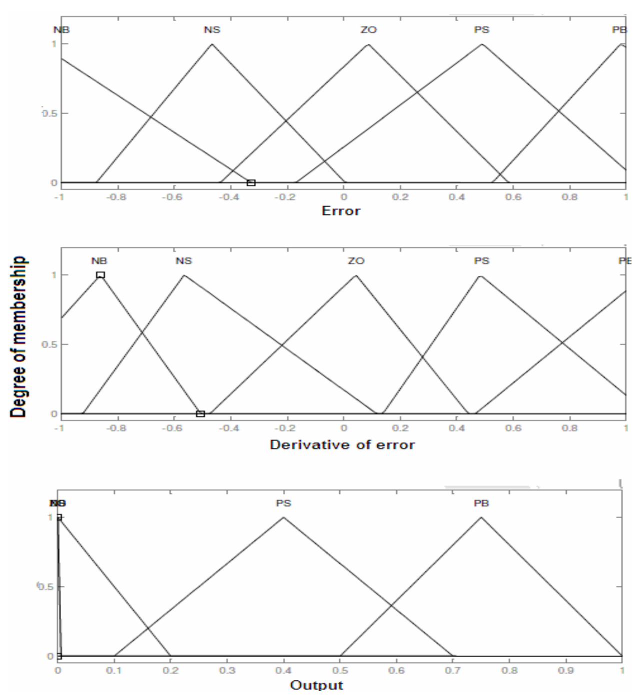

Figure 4. Optimised MFs of the fuzzy controller

B. *Controllers Tracking*

The computer simulation test of the designed swinging motion FLC was performed to track the desired trajectory. The test was initiated with 220µs amplitude with 0.15s burst durations of stimulation pulse for the first cycle of swing gait before controller took action. The simulation was carried out using Matlab/Simulink as a platform. The control was performed in stimulation course of 100 cycles. The first 10 cycles of the controller's performance can be seen in Figure 5. It can be noted that this fuzzy controller achieved the objective; to track the trajectory and thus maintain a steady swinging of the lower limb. The error between desired trajectory and actual response of the knee joint was less than 1° for the first 10 cycles.

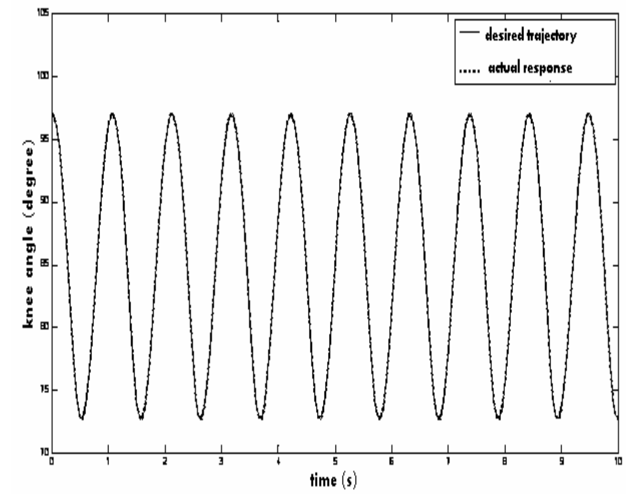

Figure 5. Controlled swinging leg

IV. CONCLUSION

FES induced movement control is a difficult task due to the highly time-variant and nonlinear nature of the muscle and segmental dynamics. In this study, the natural trajectory based swinging motion control is developed. The controller is designed to track the trajectory based on natural dynamics of the paraplegic's leg segment. In these approaches, the fuzzy logic controller is optimized using genetic optimization technique. Hence this fuzzy controller achieves the main objective; to track the trajectory and maintain a steady swinging of the lower limb. Future work will investigate the performance of the control approach in a practical environment.

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