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SMC Scheme for FES Aided Restoration of STS Movement in Paraplegics

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Abstract: Application of electrical signals for reviving movement functions previously disabled due to diseases or accidents is popularly known as functional electrical stimulation (FES). FES over the years have showed improvement capability in movement restoration, gait rehabilitation and therapy. Annual rise in neurological disorder subjects without same occurring in terms of FES based support devices are worrisome. It could be that more refinement is required to pass clinical stages. Control systems used have been continuously improved in order to meet up with the challenge. The study presents the sliding mode (SM) controller for FES induced sit-to-stand (STS) movement restoration in paraplegics. It can also be applied to other forms of maneuvers and applications. The controller shows robustness in reducing perturbations related and superior tracking ability. Ease of implementation in relation to intelligent methods and presence of mathematical model making advanced analysis easier. The linearized model was used to obtain the PID gains and were utilized for the controller gains using the nonlinear. It was further used as the basis for determining the SM controller parameters. Hence, the sliding mode control (SMC) method have portrayed improved tracking and robustness ability for the FES-aided STS movement revival in paraplegics. The study is novel in the sense such contributions have never been explored for FES induced STS movement restoration application. Therefore, it is expected with further investigations that it might help towards attaining clinical acceptance.

Keywords: Movement function restoration, Sit-to-stand movement, functional electrical stimulation, paraplegia, PID control, sliding mode control

1. Background Information

Loss of movement functions could be restored to a certain extent using a specialized form of electrical signals. The technique is at the present time popularly known as Functional Electrical Stimulation (FES). The causes of impaired movement could be due to ill health or catastrophe. As a result interference of the normal functioning of the nervous system result. Examples of such conditions are: stroke, spinal cord injury (SCI), cerebral palsy, drop foot and so on. Paraplegic refers to a subject that has loss of movement functions in the lower limbs only [1-4].

FES was identified as a technique that helps not only for restoration of movements in patients with nervous systems failure but also assist in therapy and rehabilitation. There are so many forms of researches going on to assist individuals with such disorders, but until now only a few devices are available. The reason might be due to additional refinements required owing to the sensitive nature of the condition. Another issue is the continuous rise of such cases (number of subjects with neurological disorders that affect their movement abilities) [5-9].

Control systems were one of the subject areas playing important role in providing improvements. There are in existence proposed control techniques for the systems [2, 10-12]. In order to make things easier, the different control systems can be grouped into three: linear, intelligent and nonlinear control schemes. In the linear approach, the systems are strictly considered to be linear and time-invariant. It is opposite in the nonlinear approach. Although the intelligent approach is also nonlinear, for simplicity systems with high level of intelligence incorporated most especially in the controller design are kept in this group. An important factor was the inability to obtain mathematical models of such systems which may hinder easiness of carrying out analysis on the systems which are sometimes essential during controller designs.

Reducing velocity and accelerations at terminal points during sit-to-stand (STS) and stand-to-sit movements using FES assistance was targeted in the work of Dolan et al. [13]. Control system was developed

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using the switching curve approach and was tested using single paraplegic subject. The parameters were reduced and the load on the shoulder was also reduced. In a similar vein, Yu et al. [14], conducted a study were three approaches were looked into. The open loop, on-off feedback, and PID control techniques. Results, however, indicate the superiority of their performances in the opposite manner they are mentioned. In the work of Poboroniuc [15] effort was made to improve the proportional integral derivative PID control approach which requires sensor of improved accuracy for good performance. An upgraded version of knee extension control scheme was proposed. Although it indicates better performance, more exploration is needed.

A self-adaptive fuzzy with learning reinforcement control approach was developed by Davoodi and Andrews [16]. Reduction of terminal velocities and loading of shoulders were the major concerns. The work was completely simulation. The work was further extended [17], and the genetic algorithm was utilized to optimize the parameters of the control system.

Previdi et al. [18], proposed a nested controller using the linear and nonlinear control schemes. It was aimed at improving stability. Although improvement was observed stability was only guaranteed for a small range of muscular contractions. The model predictive controller was proposed by Espanjani and Towhidkhah [19] in order to make an improvement in robustness. Results were encouraging, but the study is limited to simulations and high computational time requirement.

Scholars have the opinion that the linear control approach might fit well for the system under consideration [14, 20, 21]. Mathematical models are not readily available when using the intelligent control methods. Although popular with promising results in FES control, but lack of the model could deprive it of subjecting the control proposed to scrutiny. Nonlinear control methods could be harnessed, apart from the availability of models, they present models that are a closer replica of the real ones and also have well established and simplified theories.

The sliding mode control (SMC) was explored for the FES induced STS movement. It was applied to other tasks of FES with relative success. Hence, it is expected to yield similar or better results for the scenario considered (FES induced STS movement).

Organization of the paper was such that it comprises of four sections. The background information, modelling and control, results and discussions and the summary of the study. The first section was an introduction, which was followed by the section that briefly gave an explanation on the FES aided STS model and how the control system was achieved. The third section was short explanations on the results obtained and finally was the conclusion section which gave the winding-up remarks.

2. Modelling and Control

The FES is used to restore the STS movement ability due to the loss of function in paraplegics in the study. The quadriceps are stimulated and this results in torque produced at the knee joints which facilitate the movement. The controller was used to make the process more optimal/efficient (stimulation rate) with respect to the desired trajectory. It also has the capability of reducing the effects of disturbances which could either be internal or external. In the study, internal disturbances are considered. Effects of tremor and spasm were used as disturbances to the system. As they are well characteristics affecting subjects with nervous system disorders.

A mathematical model of the FES induced STS movement was proposed. It was obtained using both direct and the Euler-Lagrange method. The same model resulted when the two different techniques were applied. A simple model was developed after which the SMC was designed. The study was an initial phase of a research and it was expected to give an insight into a more general situation later. A similar approach was used by Vette et al. [22-29], but for FES assisted continuous standing.

2.1 STS model

In this present study, a simplified model of FES induced STS movement was developed using the Euler-Lagrange method. Figure 1 shows the simplified FES assisted movement. The feet are assumed to be fixed and the trunk. The movement is caused by extension of the knee joint and the angle increases as indicated in the figure; hence, at full extension ideally becomes straight and is zero by convention. The parameters were obtained from the paraplegic subject (P3) in the works of Ferrarin and Pedotti [30]. Anthropometry, as described in the works of Winters [31] was used to determine other necessary variables.

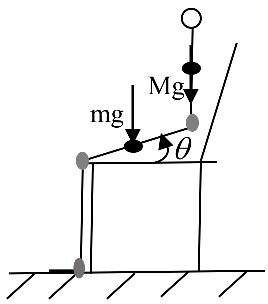

Fig. 1 Simplified STS model

$$\tau = A\ddot{\theta} + B\cos\theta\tau \tag{1}$$

$$A = ML^2 + ml^2 + I_M + I_m \tag{2}$$

$$B = MgL + mgl \tag{3}$$

$$\ddot{\theta} = \tau(1/A) - (B/A)\cos\theta \tag{4}$$

Where: θ is the knee angle, $\ddot{\theta}$ is the angular acceleration of the knee angle, the masses of the thigh m and parts of the body above the thigh M were 8.5kg and 57.63kg respectively, L is the length of the thigh and l

length of the center of mass of the thigh and were 0.4361m and 0.2472 respectively. I_m and I_M are the moments of inertia of the thigh and that of the parts of the body above the thigh respectively. And they were 0.4kgm^2 and 5.8488kgm^2 respectively. The acceleration due to gravity g is 9.81m/s^2 and τ is the knee torque.

2.2 Controller design

Fig. 2 shows the block diagram of the control system of the FES induced STS movement in paraplegics. Where; reference is the desired trajectory of the knee angle during the FES induced STS movement, the position is the actual knee angle during FES aided STS manoeuvre, the plant is the paraplegic subject, θ_d is the disturbance caused by a combination of spasm and tremor and U is the control signal.

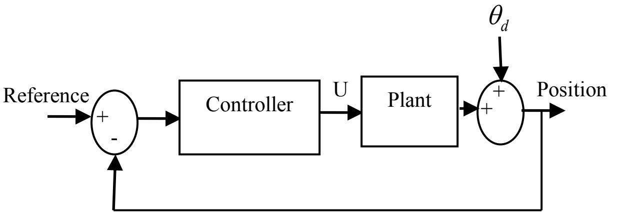

Fig. 2 Block diagram of the FES induced STS movement.

The sliding mode controller was designed using the steps described below. From (1) the plant could be written as shown in (5).

$$u(t) = A\ddot{\theta}(t) + B\cos\theta(t) \tag{5}$$

The sliding mode function is given as shown in (6) such that c is greater than zero; in order meet the Hurwitz criterion.

$$s(t) = ce(t) + \dot{e}(t) \tag{6}$$

Errors in the position (tracking error), velocity and acceleration were as given by (7), (8) and (9) respectively.

$$e(t) = \theta_d(t) - \theta(t) \tag{7}$$

$$\dot{e}(t) = \dot{\theta}_d - \dot{\theta}(t) \tag{8}$$

$$\ddot{e}(t) = \ddot{\theta}_d(t) - \ddot{\theta}(t) \tag{9}$$

$$\dot{s}(t) = c\,\dot{e}(t) + \ddot{e}(t) \tag{10}$$

Substituting (9) and (5) in (10) and making u (t) the subject of the formula. And also choosing the constant rate reaching law to govern the sliding manifold (11) was obtained.

$$u(t) = A(c\,\dot{e}(t) + \ddot{\theta}_d(t) - \eta\,\mathrm{sgn}(s)) + B\cos(\theta(t)) \tag{11}$$

Equation (11) gives the control law using the SMC scheme.

3. Results and Discussion

Fig. 3 shows the desired knee trajectory, response with linear and nonlinear models using the PID controller. The parameters obtained using the linear model was used for the nonlinear model. And it can be seen that they fit well for the case of the nonlinear model.

Fig. 4 portray the desired knee trajectory, response with PID controller and SM controller. It can be seen that the later controller has better tracking performance. The tracking errors were close to about degrees maximum and close to zero degrees respectively.

Fig. 5 indicates the disturbance signal used to perturb the system, the desired knee trajectory, and the trajectory when corrupted with the disturbance. Even though in reality the desired trajectory and disturbances are separated, but the plant sees the combination as the desired input. The disturbance was obtained from the works of Lynch et al. [21, 32, 33]. It is an effort to represent the combined effects of the tremor and spasm as portrayed in their publications. The tremor and spasm are undesired phenomena associated with neurologically impaired subjects.

Fig. 6 show the desired trajectory, the system controlled using the PID and the sliding mode (SM) under perturbations. It can be seen that the system was more robust with the SM controller. It shows close to zero rejection of the disturbance with the SMC, while more significant with the PID controller.

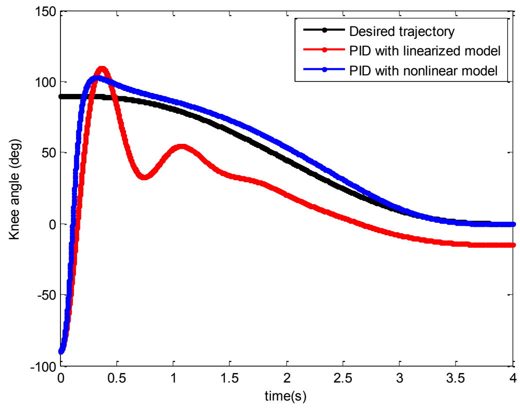

Fig. 3 The response of the system with linear and nonlinear models with the PID controller.

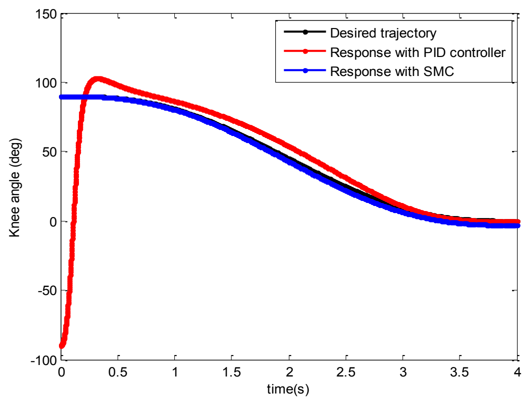

Fig. 4 Response with the PID and SM controllers.

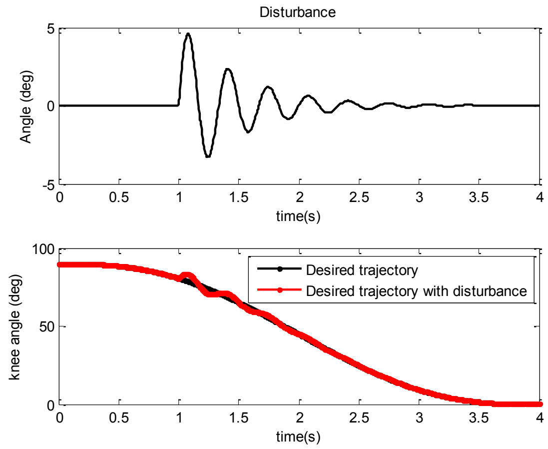

Fig. 5 Disturbance, desired and the combined desired trajectory and disturbance.

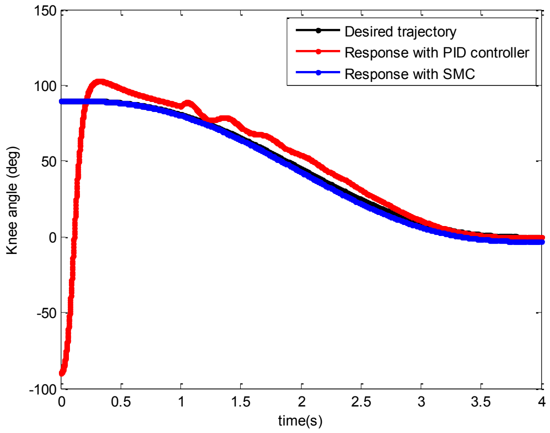

Fig. 6 Response of the system with PID and SM controllers in presence of perturbations.

4. Summary of Study

FES is the utilization of a refined form of electricity to revive movement functions previously hampered due diseases or accidents. Although FES showed remarkable potentials not only for movement restoration but for gait rehabilitation and therapy. Literature shows an annual rise in neurological disorder without corresponding rise FES based support devices and could be due to more refinement to meet up with clinical requirements. Control system has been continuously strengthened to catch up with the challenge.

In this work, the sliding mode controller was proposed for FES induced sit-to-stand movement restoration in paraplegia. Which can also be used for other manoeuvres as well as other forms of FES aided movement applications. The study tried to fine-tune older developed control schemes for STS movement. The control scheme portrays robust performance in rejecting disturbances related to such systems and better tracking performance compared to the PID control scheme. Simplicity is another factor worth mentioning compared to intelligent control methods as well as the availability of mathematical model for further analysis. Another information worth mentioning is the usefulness of the linearized model. It was used to obtain the PID gains which were maintained when the nonlinear model was considered. It also serves as the basis for obtaining the sliding mode controller parameters. And the novelty of the study was that the mentioned contributions were just explored for this application based on literature in this work.

Therefore, the SMC scheme has shown good tracking and robustness performance for FES-assisted STS movement restoration in paraplegia. Hence, it is expected with further investigations it could shift such FES system towards clinical acceptance.

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