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Adaptive Terminal Sliding Mode Control of Ankle Movement Using Functional Electrical Stimulation of Agonist-Antagonist Muscles

Vahab Nekoukar and Abbas Erfanian, *Member, IEEE*

Abstract—**This paper presents a robust control strategy which is based on synergistic combination of an adaptive controller with terminal sliding mode control (TSMC) for online control of ankle movement using functional electrical stimulation (FES) of dorsiflexor and plantar flexor muscles in paraplegic subjects. The major advantage of TSMC derives from the property of robustness to system uncertainties and external disturbances with fast convergence without imposing strong control force. To implement TSMC, a model of *neuromusculoskeletal* system should be presented in standard canonical form. In this work, we design an adaptive updating law to estimate the parameters of the model during online control without requiring offline learning phase. The experimental results on two paraplegic subjects show that the TSMC provides excellent tracking control for different reference trajectories and could generate control signals to compensate the effects of muscle fatigue and external disturbance.**

I. INTRODUCTION

A MAJOR impediment to stimulate the paralyzed neuromuscular systems is the highly non-linear, time-varying properties of electrically stimulated muscle, muscle fatigue, spasticity, and day-to-day variations which limit the utility of pre-specified stimulation patterns and open-loop control systems of functional neuromuscular stimulation (FNS). To deal with these problems, researchers have developed many control strategies including fixed-parameter and adaptive controller [1]-[5]. All the past works demonstrate that the tracking quality was improved using the adaptive control law compared to the non-adaptive one but adaptive control generally suffers from the disadvantage of being able to achieve only *asymptotical* convergence of the tracking error to zero.

A useful and powerful control scheme to deal with the uncertainties, nonlinearities, and bounded external disturbances is the sliding mode control (SMC) [6].

In previous work [7], we designed a control methodology which is based on synergistic combination of two artificial neural networks with SMC for control of knee joint angle with quadriceps muscle stimulation. In [8], we presented a robust control strategy resulting in a simpler design for control of the ankle joint angle with stimulation of ankle dorsiflexor and plantarflexor muscles. However, both controllers are based on linear sliding mode and require offline identification of the muscle-joint dynamics. A linear sliding mode technique can only guarantee the asymptotic error convergence; therefore, error dynamics cannot converge to zero in finite time. Terminal sliding mode control [9]-[12] was developed to provide faster convergence than linear hyperplane-based sliding control.

In all the above mentioned TSM controllers, it is assumed that an accurate model of the plant is available, and the unknown parameters are assumed to appear linearly with respect to known nonlinear functions. However, this assumption is not sufficient for many practical situations, because it is difficult to describe a nonlinear plant (e.g., *neuromusculoskeletal* system) by known nonlinear functions precisely.

To overcome this problem, Tao *et al.* [9] proposed a discontinuous terminal sliding mode controller for linear systems with mismatched time varying uncertainties while the uncertain linear system was approximated by the fuzzy logic system and its parameters were adapted on-line. Fuzzy wavelet network [10] and pure neural network [11] were also incorporated into the discontinuous TSM for control of robot manipulators.

The above mentioned adaptive TSM controllers need the discontinuous control to guarantee the finite-time reachability to TSM. The chattering caused by the discontinuous control action is undesirable in many applications such as functional neuromuscular stimulation applications.

In this work, we present a new adaptive continuous TSM control while the dynamics of the plant is identified online requiring no prior knowledge about the dynamics of the plant and no offline learning phase. Fuzzy logic systems are employed to approximate the plant's unknown nonlinear functions and an adaptive law is derived based on Lyapunov stability analysis for online updating the parameters of the model. The controller is employed for control of the ankle movement by using functional electrical stimulation of dorsiflexor and plantar flexor muscles in paraplegic subjects.

II. CONTROL STRATEGY

A. Design of AFTSMC

Consider the following single input – single output (SISO) time-varying nonlinear system

$$\ddot{\theta}(t) = f(\theta, \dot{\theta}, t) + b(\theta, \dot{\theta}, t) \cdot u(t) + d(t) \tag{1}$$

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V. Nekoukar and A. Erfanian are with the Department of Biomedical Engineering, Iran University of Science and Technology (IUST), Iran Neural Technology Centre, Tehran, Iran (e-mail: nekoukar@iust.ac.ir, phone: 98-21-77240465; fax: 98-21-77240490; email: erfanian@iust.ac.ir).

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Where $\theta(t)$ is the state to be controlled so that it follows a desired trajectory $\theta_d(t)$, $d(t)$ is the lumped disturbance, which include the system uncertainties and external disturbances; and assume it is bounded by $|d(t)| \le D$, and $u(t)$ is the control input. The nonlinear dynamics $f(\theta,\dot{\theta},t)$ and $b(\theta,\dot{\theta},t)$ are not known exactly, but are estimated as the known nominal dynamics $\hat{f}(\theta,\dot{\theta})$ and $\hat{b}(\theta,\dot{\theta})$, respectively, with the bounded estimation errors. The objective of the controller is to design a control law to force the system state vector to track a desired state vector in the presence of model uncertainties and external disturbances. For this purpose, a continuous TSM is chosen as follows [12]

$$s(t) = e(t) + \beta\,|\dot{e}(t)|^{\gamma}\, sign(\dot{e}(t)) = 0 \tag{2}$$

where $e(t) = \theta_d(t) - \theta(t)$ is the tracking error, $\beta > 0$ and $1 < \gamma < 2$. To implement the continuous TSM controller, a fast TSM type reaching law is defined as

$$\dot{s}(t) = -k_1 s(t) - k_2 sig(s)^p \tag{3}$$

$k_1 > 0,\ k_2 > 0,\ 0 < p < 1$ and $sig(s)^p = |s|^p\, sign\,(s)$. By differentiating (3) with respect to time, we have

$$s = \dot{e} + \beta\gamma|\dot{e}|^{\gamma-1}\ddot{e} \tag{4}$$

By comparing of (1), (3) and (4), the equivalent control law can be written as:

$$\begin{aligned} u_{eq} &= b^{-1}(\theta,\dot{\theta},t)\big(-f(\theta,\dot{\theta},t) - d(t) + \ddot{\theta}_d(t) \\ &\quad + \beta^{-1}\gamma^{-1} sig(\dot{e})^{2-\gamma} + k_1 s + k_2 sig(s)^p\big) \end{aligned} \tag{5}$$

In practical applications, system functions $f(\theta,\dot{\theta},t)$ and $b(\theta,\dot{\theta},t)$ are not known and it is difficult to obtain the control law (5). In this paper, fuzzy logic system is used to approximate the nonlinear unknown functions as follows

$$\hat{f}(\theta,\dot{\theta},v_{\mathrm{f}}) = v_{\mathrm{f}}^T \psi_f(\theta,\dot{\theta}) \tag{6}$$

$$\hat{b}(\theta,\dot{\theta},v_{\mathrm{b}}) = v_b^T \psi_b(\theta,\dot{\theta}) \tag{7}$$

where v^T is adjustable parameter vector and ψ is a fuzzy basis vector [8]. To approximate the uncertain nonlinear functions $f(\theta,\dot{\theta},t)$ and $b(\theta,\dot{\theta},t)$ in (1), adaptive update laws to adjust the parameter vectors in (6) and (7) need to be developed. The update laws are chosen as

$$\dot{v}_f = -\eta_f \beta\gamma|\dot{e}|^{\gamma-1}\psi_f(\theta,\dot{\theta})s \tag{8}$$

$$\dot{v}_b = -\eta_b \beta\gamma|\dot{e}|^{\gamma-1}\psi_b(\theta,\dot{\theta})su_{eq} \tag{9}$$

where $\eta_f > 0$, $\eta_b > 0$. Also, a corrective controller is defined to guarantee the stability of the closed-loop control system and compensate the approximation errors. A control input is chosen as

$$u = u_{eq} + u_c \tag{10}$$

where u_{eq} is given by (5) and u_c is defined as

$$u_c = \bar{\varepsilon}_f + \bar{\varepsilon}_b|u_{eq}| + |u_0| \tag{11}$$

$$\begin{aligned} u_0 &= \hat{b}^{-1}(\theta,\dot{\theta},v_{\mathrm{b}})\big(-\hat{f}(\theta,\dot{\theta},v_{\mathrm{f}}) + \ddot{\theta}_d(t) \\ &\quad + \beta^{-1}\gamma^{-1} sig(\dot{e})^{2-\gamma} + k_1 s + k_2 sig(s)^p\big) \end{aligned} \tag{12}$$

and $\bar{\varepsilon}$ is the upper bound of the estimation error.

Remark 1: For the nonlinear system (1) with nonlinear functions $f(\theta,\dot{\theta},t)$ and $b(\theta,\dot{\theta},t)$ which are approximated by (6) and (7), the control input is as (10), and adaptation laws are selected as (8) and (9), then we have

i) Estimation errors converge to zero asymptotically and all signals in the closed-loop system are bounded

ii) Tracking errors and their first derivatives converge to (small) balls centered at the origin in finite time.

B. Adaptive TSM Control of Ankle Movement

To control the ankle movement using agonist-antagonist co-activation, a stand-alone controller is designed for each muscle-joint dynamics (Fig. 1). To implement the ATSM controller, each muscle-joint dynamics are first presented in a standard canonical form as

$$\ddot{\theta}(t) = f_f(\theta,\dot{\theta},t) + b_f(\theta,\dot{\theta},t)\cdot u_f(t) \tag{13}$$

$$\ddot{\theta}(t) = f_e(\theta,\dot{\theta},t) + b_e(\theta,\dot{\theta},t)\cdot u_e(t) \tag{14}$$

where (13) and (14) present muscle-joint dynamics for dorsiflexion and plantarflexion movements, respectively. Parameter θ denotes the ankle angle and u_f and u_e are the input commands to the dorsiflexor and plantarflexor muscles, respectively. The tracking error signals are calculated as follows

$$\begin{bmatrix} e_e(t) \\ e_f(t) \end{bmatrix} = \begin{bmatrix} \theta_d(t) - \theta(t) \\ \theta(t) - \theta_d(t) \end{bmatrix} \tag{15}$$

where $e_e(t)$ and $e_f(t)$ are the tracking error signals for extensor and flexor controllers, respectively.

III. RESULTS

A. Experimental procedure

The experiments were conducted on two thoracic-level complete spinal cord injury subjects with injury at T11 and T7 levels using an eight-channel computer-based closed-loop FNS system [14]. The subject was seated on a bench with his hip flexed at approximately 90° and knee joint positioned at 0°, while the ankle was allowed to plantarflexing and dorsiflexing. The tibialis anterior and calf muscles were stimulated using adhesive surface elliptical electrodes (5×10 cm GymnaUniphy electrodes, COMEPA Industries, Belgium). Pulsewidth modulation (from 0 to 700 μsec) with balanced bipolar stimulation pulses, at a constant frequency (25 Hz) and constant amplitude was used. The controller adjusted the pulsewidths and pulsewidths with negative value were then set to zero. The joint angle was measured by using the motion tracker system MTx (Xsens Technologies, B.V.) which is a small and accurate 3DOF Orientation Tracker.

The computer-based closed-loop FNS system uses Matlab Simulink (THE MATHWORKS, R2007b), Real-Time Workshop, and Real-Time Windows Target under Windows 2000/XP for online data acquisition, processing, and controlling. The proposed control strategy was implemented by S-functions using C^{++}.

B. Trajectory Tracking

Examples of the joint angle trajectories obtained with the adaptive TSM control on two subjects are shown in Fig. 2. Excellent tracking performance (RMS error1.3°) with no chattering was achieved using proposed control strategy. The most interesting observation is the fast convergence speed of the proposed control strategy. The ankle movement trajectory converges to the desired trajectory after about 2 s. It is observed that by passing the time, the control signals are trending upward to compensate the effect of muscle fatigue.

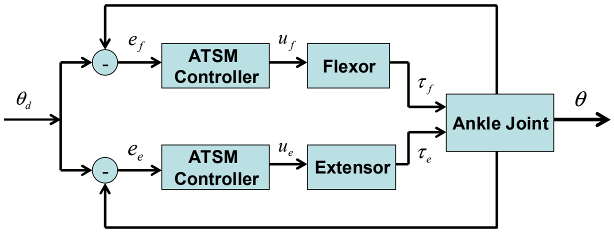
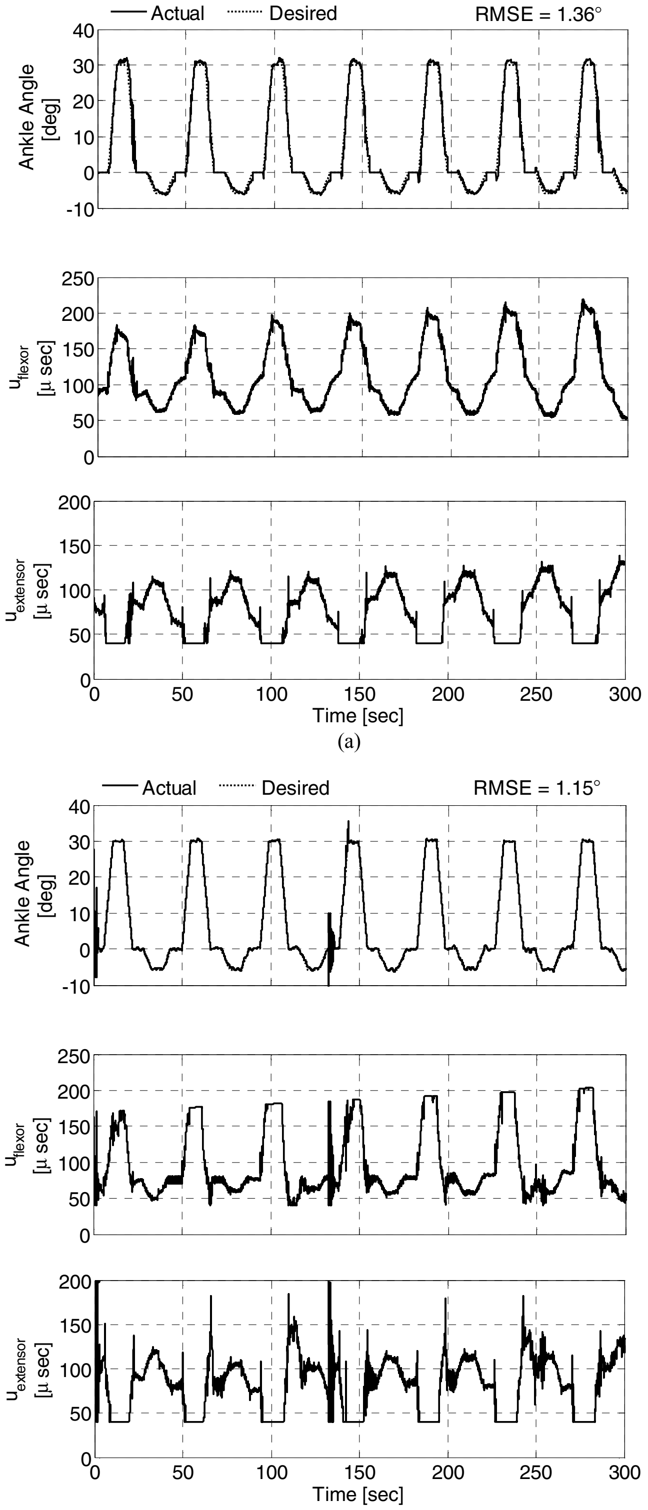


Fig. 1. Control of ankle movement using adaptive TSM control of dorsiflexor and plantar flexor muscles.

C. External Disturbance

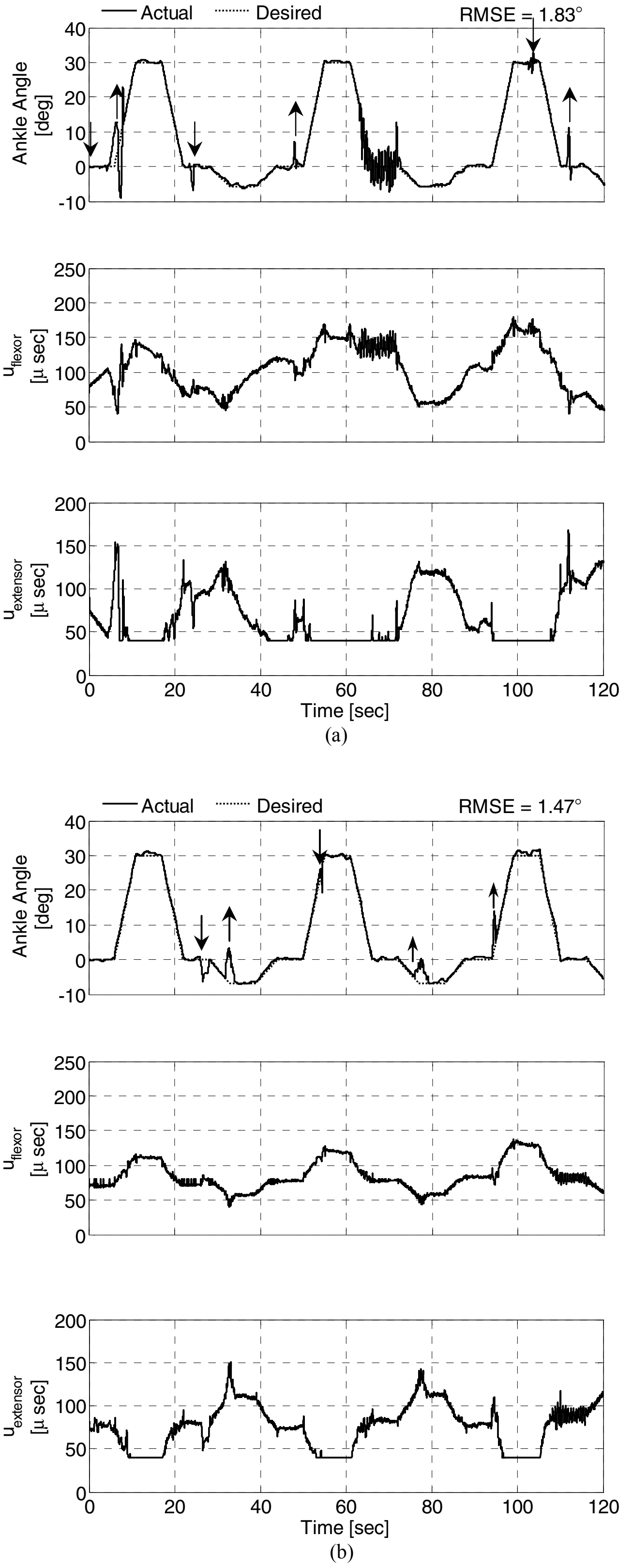
To evaluate the ability of proposed control strategy to external disturbance rejection, a constant load in amount of 0.85 kg was gently applied to the ankle joint of the subjects for short periods of time. Fig. 3 shows a typical result of external disturbance rejection for two subjects. The results indicate that excellent tracking performance and fast convergence speed can be achieved under external disturbances using the proposed control strategy (RMS error 1.65°). The controllers could rapidly adjust the levels of the flexor and extensor muscles at the instant of applying the disturbance to compensate its effect.



(a)

(b)

Fig. 2. Typical results of controlling dorsiflexion and plantarflexion movements using the proposed ATSM control on two paraplegic subjects EA (a) and RR (b).



(a)

(b)

Fig. 3. Results of the external disturbance rejection obtained using the proposed adaptive TSM control scheme in two paraplegic subjects EA (a) and RR (b). For the subject EA, the load was applied between 0 to 5 s, 23.5 to 47.5 s, 102.5 to 111.5 s, and 150 to 162.5 s. For RR, the load was applied between 26 to 32 s and between 54 to 94 s (half of the load was removed at t = 76 s.).

IV. CONCLUSION

In this paper, a robust control strategy based on terminal sliding mode and adaptive control was developed, referred to as adaptive TSM (ATSM) control. The proposed scheme has the advantage of online adaptation ability to handle the plant variations or changing environments. The control scheme does not require offline identification of the controlled process. The results of experiments on two paraplegic subjects indicate that the proposed strategy provides accurate tracking control with fast convergence during different conditions of operation, and could generate control signals to compensate the effects of muscle fatigue and external disturbances.

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