Adaptive Fuzzy Neuro Sliding Mode Control of the Hindlimb Movement Generated by Epidural Spinal Cord Stimulation in Cat

M. Khazaei and A. Erfanian

***Abstract*— A robust control strategy for closed-loop control of hindlimb movement induced by epidural electrical stimulation (EES) of the spinal cord is developed here. The method is based on adaptive fuzzy neuro-sliding mode control (AFNSMC). An AFNSMC is designed for multi-joint extension movement as well as flexion movement. The multi-joint flexion and extension movements are generated by stimulating the rostral (L5) and caudal spinal (L7) segments of the spinal cord, respectively. The experiments were conducted on cats. The results indicate that the decentralized robust control provides excellent tracking control. The average tracking errors over different trials of experiment on three cats are 8.65%, 8.80%, and 7.70% for ankle, knee, and hip joint, respectively.**

I. Introduction

Epidural electrical stimulation (EES) of the spinal cord has been suggested as a technique for possible restoration of the motor functions in the absence of any supraspinal input [1]. It was demonstrated that EES can activate the motoneuronal pools that, in turn, can generate locomotor-like activity.

In [2], initiation of locomotor activity in spinal cats was tested by EES of the spinal cord. It was demonstrated that stimulation of segments L4-L5 induced rhythmic, in most cases alternating, limb movements in air. In [3], formation of locomotor patterns in decebrated cats was devalued by EES of the spinal cord. They reported that by applying the electrical stimulation to segments L4-L5, the stepping movement can be generated in the hindlimbs only when the cat's limb was on the moving treadmill band. Gerasimenko *et al.* demonstrated that stepping-like pattern in complete spinal rats can be induced using EES plus quipazine administration [4]. Stepping was elicited only when the hindlimbs were placed on a moving treadmill. The stepping induced by EES and quipazine administration in trained rats was highly coordinated with clear plantar foot placement and partial weight bearing while in non-trained rats the stepping was non-weight bearing.

Tai *et al.* have investigated the hindlimbs generated by EES at different spinal segments in cats [5]. They demonstrated that the stimulation of a dorsal or ventral root on one side only induced ipsilateral hindlimb movements. The ipsilateral movements changed from flexion to extension as the stimulation of individual dorsal or ventral root was moved from a rostral spinal segment (L5) to a caudal spinal segment (S1). A stepping-like movement was generated with an amplitude-modulated stimulation of the rostral (L5) and the caudal (L6/L7) spinal segments.

The role of afferent information in generating stepping was investigated during recovery of rhythmic activity of the hindlimbs in spinal rats using EES [6]. They have shown that by using EES and training on the moving treadmill, spinal rats were able to generate stepping-like patterns on the moving treadmill on the non-deafferented, but not deafferented side. They suggested that the facilitation of stepping through EES was mediated by ipsilateral afferents that project to the locomotor networks. Dougherty *et al.* have investigated the effects of stimulus amplitude and stimulus duration on the resulting isometric force generated at the hindpaw of the rat by EES [7].

All these works demonstrated that EES can activate the spinal neural networks that generate oscillating movements of the lower limbs in a step-like fashion or activate a functional units in the spinal cord (i.e. primitive) that produce a specific motor output by generating a specific pattern of muscle activations [8]-[11].

One important issue in restoring motor functions using EES of the spinal cord is the design of dynamic multisite stimulation patterns [12] and control of EES-induced movement. A major problem to determine the stimulation patterns and control of EES-induced movement is the highly nonlinear and time-varying properties of the neuromuscular systems. One of the effective and powerful nonlinear and robust control strategies to deal with system uncertainty and external disturbances is sliding mode control (SMC) [13]. We have already developed an adaptive fuzzy neuro-sliding mode control (AFNSMC) for control of multi-joint movement through intraspinal microstimulation while for each motor muscle-joint complex an independent AFNSMC was designed [14]. In the current study, the application of AFNSMC is presented for control of multi-joint movement through EES of the spinal cord.

II. Methods

A. Animal Preparation

The experiments were conducted on three cats (2 males and 1 female, 2.5 kg to 3.5 kg). All protocols involving the use of animals were approved by the local ethics committee. The cats were initially anesthetized with intravenous injection of ketamine. The animals were then intubated and maintained at a surgical level of anesthesia through the inhalation of isoflurane (1%-5% in O_2). A partial dorsal laminectomy was performed at the L4–L6 level, and the dura mater over these laminas was opened longitudinally.

After the surgery, the cats were fixed in a modified stereotaxic frame (SN-1N, Narishige Group Product) such that hindlimbs can move freely. The spinal vertebrae (L3 and L7) were clamped rigidly to the frame (Fig. 1).

B. Data Acquisition and Stimulation Protocol

To measure the joint angles, colored markers were attached to each joint. A webcam was positioned orthogonally to the sagittal plane and used to record the hindlimb movements elicited by EES. Using custom-made software written in the NI Vision development module in LabVIEW, the joints angles were estimated.

* This work was supported by Iran Neural Technology Research Centre under Grant 48.M.111194.

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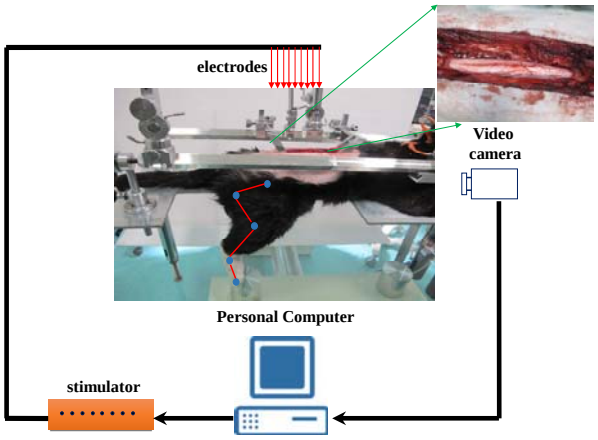


Figure 1. Schematic of the experimental setup.

A custom-made computer-based 16-channel stimulator was used to stimulate the spinal cord. The stimulator can generate charge balanced, biphasic current pulses. The amplitude, pulse width, and frequency of the stimulation signal can be varied online, using software package written in LabVIEW. Stimulus pulses were delivered to the spinal cord through a custom-made 50-electrode array implanted at the dorsal surface of the spinal cord.

C. Control Strategy

The control strategy used here is based an adaptive fuzzy SMC (AFSMC) proposed in [14]. The proposed method is a well-defined SMC while the plant's unknown nonlinear functions are estimated using fuzzy logic systems. The conventional SMC suffers from the problem which is known as chattering. Chattering is undesirable because it can excite unmodeled high-frequency plant dynamics. To reduce the chattering and to preserve the main advantages of the original SMC, we combined the AFSMC with a single-neuron controller [14], called Adaptive Fuzzy Neuro-SMC (AFNSMC). The configuration of the proposed strategy used for control of EES is shown in Fig. 2, where u_1 is the output of the AFSMC and u_2 is the output of the single-neuron controller. The details about the adaptive Neuro-SMC can be found in [14].

For each rostral (L5) and the caudal (L7) spinal segment, an independent AFNSMC controller was designed. The error signals used for each controller were defined as follows:

$$\begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} +1 \\ -1 \end{bmatrix} \left[e_a + e_k + e_h \right]$$
$$e_a = k_a(\theta_a^m - \theta_a^d) \quad (1)$$
$$e_k = k_k(\theta_k^m - \theta_k^d)$$
$$e_h = k_h(\theta_h^m - \theta_h^d)$$

where e_a, e_k, and e_h are the error signals of the ankle, knee, hip joints, respectively, e_1 and e_2 are the error signals for the flexor and extensor controllers, respectively. θ^m is the measured joint angle and θ^d is the desired trajectory.

III. Results

In this section the proposed control is used to control the multi-joint flexion and extension movements by stimulating the rostral (L5) and caudal spinal (L7) segments. Pulse width modulation at constant frequency (50Hz) and constant amplitude (300~1200μA) was used to stimulate the spinal cord. The proposed controller was implemented in LabVIEW. The optimal electrode positions were selected by stimulating different positions between rostral and caudal segments of the spinal cord using the electrode array.

The root-mean-square (RMS) error and normalized RMS (NRMS) are used for measuring the performance of tracking and defined as follows:

$$RMS = \sqrt{\frac{1}{T}\sum_{t=1}^{T}(\theta(t) - \theta_d(t))^2},$$
$$NRMS\ (\%) = \frac{1}{\theta_d^{\max} - \theta_d^{\min}} \sqrt{\frac{1}{T}\sum_{t=1}^{T}(\theta(t) - \theta_d(t))^2} \times 100,$$

where θ and θ_d are the measured and desired joint angle, respectively.

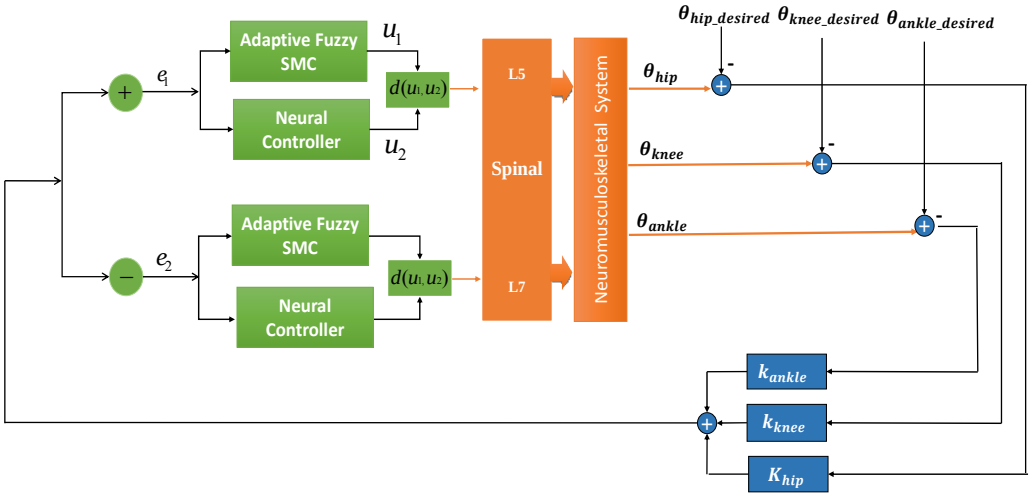


Figure 2. Configuration of the proposed control strategy for control of epidural electrical stimulation of the spinal cord.

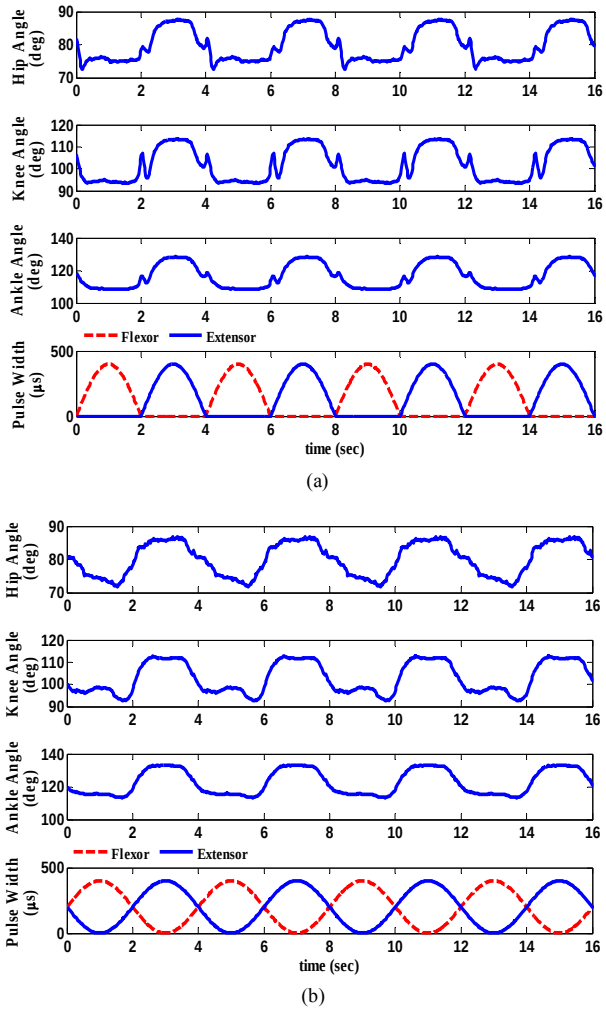


Figure 3. Typical results of joint tracking obtained using predefined half-sine stimulation pattern with no coactivation (a) and coactivation (b).

Fig. 3(a) shows a typical result of generated multi-joint movement induced by combined stimulation of L5 and L7 spinal segments using a predefined half-sine stimulation pattern with no co-activation. It is observed that the hindlimb movements changed from flexion to extension when the stimulation is moved from the rostral (L5) to caudal (L7) segment. At the instance of stimulation switching between rostral and caudal stimulation, an undesirable movement is induced. Fig. 3(b) shows the induced movement when there is a co-activation in L5 and L7 spinal segments. It is observed that a more stable movement is generated with extension-flexion coactivation.

Fig. 4 shows typical results of joint angle tracking using the proposed control strategy for three cats. It is observed that excellent tracking performance was obtained. For the hip joint, the tracking errors are 0.83° (8.35%), 0.82° (8.22%), and 0.78° (7.83%) for cat 1, cat 2, and cat 3, respectively, for the knee joint, the errors are 1.82° (9.12%), 1.79° (8.97%) and 1.83° (9.15%), and for the ankle joint are 1.81° (9.05%), 1.77° (8.85%) and 1.74° (8.74%). It is worthy to note that the antagonist coactivation is determined automatically by the controllers. The level of coactivation is decreased with increasing the agonist activity and decreasing antagonist activity.

TABLE I. ROOT-MEAN-SQUARE TRACKING ERRORS OBTAINED USING AFNSMC DURING TEN TRIALS OF EXPERIMENTS ON CAT2.

Trial	Hip	Knee	Ankle
1	0.58°	1.55°	1.53°
2	0.63°	1.63°	1.59°
3	0.68°	1.59°	1.65°
4	0.80°	1.79°	1.77°
5	0.75°	1.68°	1.72°
6	0.93°	1.67°	1.61°
7	0.83°	1.71°	1.64°
8	0.78°	1.64°	1.73°
9	0.71°	1.62°	1.64°
10	0.96°	1.74°	1.66°
Mean ± STD	0.76°±0.12°	1.66°±0.07°	1.65°±0.07°
NRMS	7.6%	8.3%	8.25%

TABLE II. AVERAGE OF TRACKING ERRORS OBTAINED USING AFNSMC ON THREE CATS.

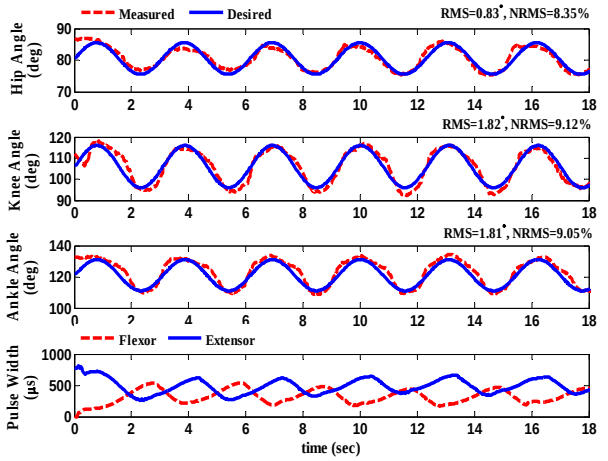
	Cat 1	Cat 2	Cat 3	Mean ± STD
Hip	0.81°±0.04°	0.78°±0.06°	0.73°±0.05°	0.77°±0.05° (7.70%)
Knee	1.78°±0.06°	1.75°±0.08°	1.77°±0.06°	1.76°±0.07° (8.80%)
Ankle	1.76°±0.08°	1.78°±0.09°	1.69°±0.06°	1.73°±0.08° (8.65%)

Table I summarizes the results of tracking performance obtained using the proposed control strategy during 10 experimental trials for cat 2. The mean of tracking error for hip, knee, and ankle are 0.76° (7.6%), 1.66° (8.3%), and 1.65° (8.25%), respectively. The standard deviation of the tracking error is very low, indicating the robustness of the control performance over different trials of experiments. Table II summarizes the average of tracking performance for three cats. The mean of tracking error for the hip, knee, and ankle joints are 0.77° (7.7%), 1.76° (8.8%), and 1.73° (8.65%), respectively.

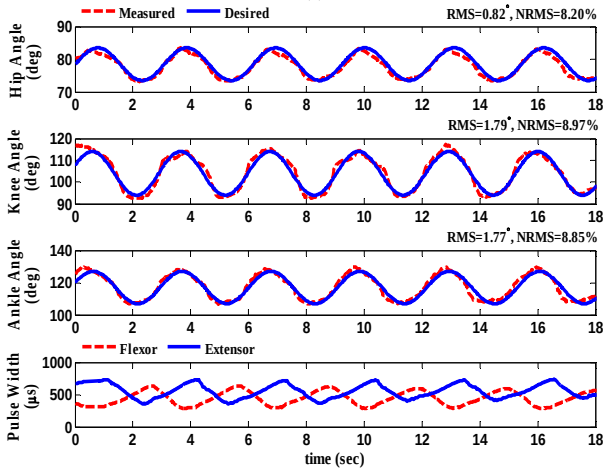
IV. CONCLUSION

In this paper, a robust control strategy was proposed for control of multi-joint movement induced by EES. An independent controller was designed for each multi-joint extension and flexion movement. The flexion and extension movement was induced by the stimulation pattern delivered to the spinal cord through two electrodes placed on the L5 and L7 segments, respectively. Because the stimulation of different spinal sites has different motor effects, future work will focus on exploitation of the proposed control strategy for control of multi-joint movement using multi-electrode array for multi-site stimulation.

In the current study, the desired movement trajectory was a sine wave with period 3 s. The control of EES to generate natural gait trajectories can be considered as a future research direction. The grand challenge of EES control is that the selective control of each joint cannot be achieved. The movement pattern generated by EES depends on the position of electrodes.



(a)



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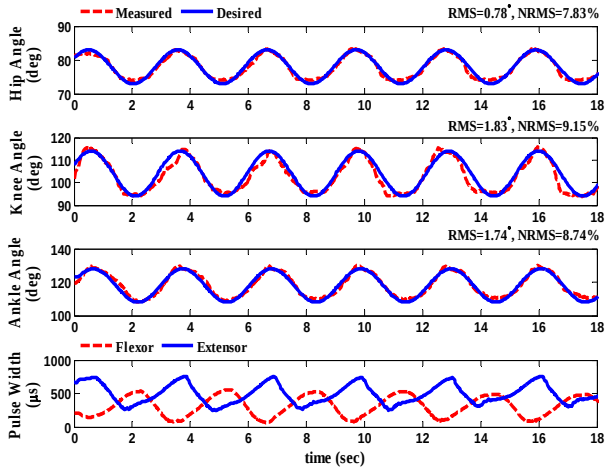

(c)

Figure 4. Typical results of joint tracking obtained using proposed control strategy for three cats (a-c).

ACKNOWLEDGMENT

The authors thank members of Iran Neural Technology Research Centre for their assistance during the animal experiments and preparing the facilities for conducting the experiments and data analysis.

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