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Time-scaling based sliding mode control for Neuromuscular Electrical Stimulation under uncertain relative degrees

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ABSTRACT

This paper addresses the application of the sliding mode approach to control the arm movements by artificial recruitment of muscles using Neuromuscular Electrical Stimulation (NMES). Such a technique allows the activation of motor nerves using surface electrodes. The goal of the proposed control system is to move the upper limbs of subjects through electrical stimulation to achieve a desired elbow angular displacement. Since the human neuro-motor system has individual characteristics, being time-varying, nonlinear and subject to uncertainties, the use of advanced robust control schemes may represent a better solution than classical Proportional-Integral (PI) controllers and model-based approaches, being simpler than more sophisticated strategies using fuzzy logic or neural networks usually applied in this control problem. The objective is the introduction of a new time-scaling base sliding mode control (SMC) strategy for NMES and its experimental evaluation. The main qualitative advantages of the proposed controller via time-scaling procedure are its independence of the knowledge of the plant relative degree and the design/tuning simplicity. The developed sliding mode strategy allows for chattering alleviation due to the impact of the integrator in smoothing the control signal. In addition, no differentiator is applied to construct the sliding surface. The stability analysis of the closed-loop system is also carried out by using singular perturbation methods. Experimental results are conducted with healthy volunteers as well as stroke patients. Quantitative results show a reduction of 45% in terms of root mean square (RMS) error (from 5.9° to 3.3°) in comparison with PI control scheme, which is similar to that obtained in the literature.

1. Introduction

Electrotherapy has been used for the treatment of paralysis, contractions and other nervous diseases [1]. With the advances in electronics and informatics, medical equipments for such purposes became specialized and portable, opening a new range of options to this type of treatment, as Neuromuscular Electrical Stimulation (NMES) [2].

The NMES technique is based on electrically generating muscle contractions through activation of intramuscular nerve branches [3]. Although the use of NMES has effects on motor recovery of stroke patients mostly evident on upper limbs, it is also very commonly used for lower extremities, such as the treatment of drop foot [4]. In addition, it helps the recovery of muscle strength in upper and lower limbs ([5,6]). NMES has also been explored to enable spinal cord injured individuals to make grasping, standing and another functional movements, being a useful tool in the rehabilitation process of paralysis and stroke patients ([7–17]).

In order to improve the movements produced or aided by NMES, there is a need for control algorithms that can handle patients variability, external disturbances and uncertainties ([9,18]). For precise closed-loop feedback control of NMES, a mathematical description of electrically stimulated muscle is vital. However, identification of such a model is widely seen as impractical in a clinical setting due to time constraints and rapidly changing dynamics (due to fatigue, spasticity, and shifting physiological and environmental factors such as skin impedance, temperature, and electrode placement). Thus, there are many mathematical models of the human neuro-motor system which are in general time-varying, nonlinear and different for each individual ([12,19–26]).

In this context, models with uncertain relative degrees are often common and represent a challenging task [27]. Motivated by

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this issue, the concept of practical relative degree was introduced in another biomedical control application [28] to facilitate the design of a differentiator based quasi-continuous higher-order sliding mode control for blood glucose regulation. However, the use of differentiators increases the sensitivity of the closed-loop system with respect to measurement noise, sampling discretization and time delays [29]. As a rule of thumb: the higher relative degree, the higher sensitivity ([30,31]).

A known weak point of most control approaches for NMES is the need for a well defined, constant, and known system relative degree ([10,13–15,25,32–36]). On the other hand, any small perturbation or model inaccuracy can lead to the increase/decrease of the relative degree, or even to its disappearance [27]. Thus, the use of advanced control techniques robust to model order variations and parametric uncertainties is welcome and may be more appropriate to stabilize biological or biomedical processes [18].

In the output-feedback control design described by Levant [29] using differentiators, the relative degree of the dynamic system must be known. Since the relative degree of the controlled system is considered unknown for the user in our approach, it would impose an additional difficulty in the observers/differentiators implementation due to the lack of knowledge regarding the exact order of the neuromuscular model. This makes our strategy innovative, since less information of the model is required when compared to the existing literature.

This paper proposes a robust sliding mode control (SMC) scheme free of differentiators and implements it to a custom NMES device. The designed approach aims to move the upper limbs through electrical stimulation to achieve predetermined angle trajectory reference. Despite that, the control and movement of other joints could be envisaged following the same idea. It is expected to show experimentally the efficacy of the proposed controller in terms of root mean square (RMS) error, when compared to classical approaches such as a Proportional-Integral (PI) compensator. We have considered tests with healthy volunteers and stroke patients in order to support the final objective of our control application for motor rehabilitation of stroke patients.

The convergence of the closed-loop system to a small neighborhood close to the desired reference signal is proved by singular perturbations methods ([37–40]). The theoretical contribution is the development of a time-scaling technique which reduces the order of the dynamical system, and therefore, allows the analysis and design of the sliding mode controller without the exact knowledge regarding the relative degree of the plant model. The experimental results illustrate the performance of proposed control algorithm for NMES.

2. Materials and methods

The aim is to develop a control law based on output feedback to drive the angular error defined by

$$e(t) = y(t) - y_m(t) \tag{1}$$

to a small neighborhood of zero, where the output y is the elbow's arm (joint) angle measured by a goniometer and y_m is the desired reference angle. A block diagram of the proposed control system for NMES is illustrated in Fig. 1.

In order to obtain a control strategy robust to modeling uncertainties, but simpler than the current nonlinear controllers used for NMES (e.g., see [14,18]), we will combine principals of both time-scaling and sliding mode control.

The proposed strategy is applicable to a wide class of plants with uncertain and arbitrary relative degree. A limitation of the time-scaling procedure is that it is restricted to open-loop stable systems. However, this is not a problem since the neuromusculoskeletal model considered here satisfies such an assumption (see Appendix A in supplementary material). By using singular perturbation methods [38], it is shown that in a new time scale the considered system can be reduced to a simple integrator perturbed by a rapid sensor dynamics, which in turn ultimately converges to a small residual set.

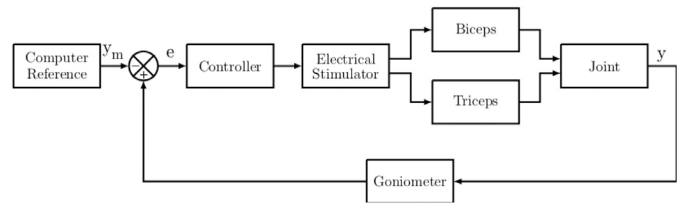

Fig. 1. Block Diagram of the closed-loop system for NMES.

Then, we exploit this particular structure to redesign our sliding mode control to show its robustness with respect to the arbitrary relative degree dynamics at expense of some time dilation, which slows down the system response.

2.1. Approximated model and basic assumptions

Consider the following linear system:

$$\dot{v} = u\,, \tag{2}$$

$$\dot{x} = Ax + Bv\,, \tag{3}$$

$$y = Cx\,, \tag{4}$$

where $x \in \mathbb{R}^n$ is the unmeasured state vector, $u \in \mathbb{R}$ is the control input, $y \in \mathbb{R}$ is output and the relative degree of the subsystem (A, B, C) is denoted by n^*.

Remark 1 (Chattering Alleviation)**.** *Chattering* is a typical but undesirable phenomenon that arises in all sliding mode controllers due to the high-frequency nature of the switching actuator [41]. The source of chattering in sliding mode control schemes are distinct and coexistent: numerical discretization, switching delays, unmodeled dynamics, measurement noise, etc. The integrator in (2) is used to obtain a virtual control signal $v \in \mathbb{R}$, which increases the relative degree of the overall system [30], *i.e.*, $n \geq n^* - 1$ instead of $n \geq n^*$. The increase of the relative degree retains the high-frequency switching to the control signal u, whereas the virtual control v that directly drives the plant is continuous. Thus, it is expected that the effects of chattering in the proposed sliding mode controller can be attenuated.

Remark 2 (Relative Degree Obstacle)**.** The relative degree is a mathematical concept in nonlinear control theory which measures how many times the output of a system must be differentiated so that the control input can be found [37]. For linear systems, the relative degree of a rational transfer function

$$G(s) = N(s)/D(s) = C(SI - A)^{-1}B$$

is $n^* = \deg(D(s)) - \deg(N(s))$, *i.e.*, the difference between the number of poles and zeros of the transfer function. For a proper transfer function, the relative degree is a nonnegative integer. Indirectly, the relative degree indicates the degree of complexity in controlling a given system. In general, for higher relative degrees, the control design will demand higher-order differentiation [29], which is not the focus of our strategy.

Since the neuromusculoskeletal models used in NMES are uncertain in order or not perfectly known, the relative degree is uncertain or unknown as well. It can be easily verified when we (and

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