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UNIVERSIDADE ESTADUAL PAULISTA
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WILLIAN RICARDO BISPO MURBAK NUNES

A New Dynamic Model Applied to Electrically Stimulated Lower Limbs and Switched Control Design Subject to Actuator Saturation and Non-Ideal Conditions

Ilha Solteira
2019

WILLIAN RICARDO BISPO MURBAK NUNES

A New Dynamic Model Applied to Electrically Stimulated Lower Limbs and Switched Control Design Subject to Actuator Saturation and Non-Ideal Conditions

Thesis submitted to the Faculdade de Engenharia de Ilha Solteira - UNESP in conformity with the requirements for the degree of PhD in Electrical Engineering.
Field of Expertise: Automation.

Prof. Dr. Aparecido Augusto de Carvalho
Advisor

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Raiane da Silva Santos
Raiane da Silva Santos
Supervisora Técnica de Seção
Seção Técnica de Referência, Atendimento ao usuário e Documentação
Diretoria Técnica de Biblioteca e Documentação
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Câmpus de Ilha Solteira

CERTIFICADO DE APROVAÇÃO

TÍTULO DA TESE: A New Dynamic Model Applied to Electrically Stimulated Lower Limbs and Switched Control Design Subject to Actuator Saturation and Non-Ideal Conditions

AUTOR: WILLIAN RICARDO BISPO MURBAK NUNES
ORIENTADOR: APARECIDO AUGUSTO DE CARVALHO

Aprovado como parte das exigências para obtenção do Título de Doutor em ENGENHARIA ELÉTRICA, área: Automação pela Comissão Examinadora:

Prof. Dr. APARECIDO AUGUSTO DE CARVALHO
Departamento de Engenharia Elétrica / Faculdade de Engenharia de Ilha Solteira

Prof. Dr. MARCELO CARVALHO MINHOTO TEIXEIRA
Departamento de Engenharia Elétrica / Faculdade de Engenharia de Ilha Solteira

Prof. Dr. MARCELO AUGUSTO ASSUNÇÃO SANCHES
Departamento de Engenharia Elétrica / Faculdade de Engenharia de Ilha Solteira

Prof. Dr. ALBERTO CLIQUET JUNIOR
Departamento de Ortopedia e Traumatologia / Universidade Estadual de Campinas - UNICAMP

Diogo Ramalho de Oliveira
Prof. Dr. DIOGO RAMALHO DE OLIVEIRA
IFMS - Câmpus de Três Lagoas / Instituto Federal de Educação, Ciência e Tecnologia de Mato Grosso do Sul

Ilha Solteira, 04 de julho de 2019

À minha família, em especial aos meus pais Wilson, Gisele e Maria (in memoriam),
ao meu irmão Wallisson, por todo amor, apoio,
confiança e incentivo nos momentos difíceis.

I dedicate to my family.
Grateful for all support, confidence and encouragement in difficult moments.

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First, I must say that I am grateful to the God that I believe. He is invisible to human eyes, but I can hear and feel this presence all the time. To the God who gave me life, health, and security. I may not deserve it, but He is merciful to me. Even though I fail, He forgives me and loves me. What love is that? It's the true love that God has for everyone, including you dear reader. I am grateful to God for all the blessings and opportunities he gave me, including this important study. Are there times when I think of giving up? Yeah, but He gave me strength and courage to overcome the challenges during this journey. I am not worthy of anything, all honor and glory belongs to Him. Difficult moments are inevitable, but God grants us victory to persevere and to continue in the daily toil and life challenges. Praise, adoration, and thanksgiving to the one true God.

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“Um pouco de ciência nos afasta de Deus. Muito, nos aproxima.”

“Little science takes you away from God but more of it takes you to Him.”

Louis Pasteur (1822-1895)

RESUMO

A estimulação elétrica é uma técnica promissora para reabilitação motora em casos de lesão medular. A saturação do estimulador também é um requisito importante no projeto de sistemas de controle aplicados à estimulação elétrica. A negligência da saturação do atuador pode conduzir a resultados de controle indesejados, que evidencia os efeitos de fadiga muscular. Pela primeira vez é proposto um controlador chaveado sujeito à saturação para membro inferior estimulado eletricamente. O modelo dinâmico de extensão do membro inferior é não linear e incerto. O sistema descrito por modelos fuzzy Takagi-Sugeno e operando dentro de uma região de operação no espaço de estados é considerado neste trabalho. Além disto, falha do atuador, incerteza de ativação muscular, e não idealidades musculares, tais como fadiga, espasmos e tremor foram considerados em três níveis de severidade. O controle chaveado é comparado com a compensação distribuída paralela. Simulações denotam melhores resultados do controlador chaveado lidando com incertezas paramétricas da planta. Por outro lado, um desafio dos sistemas de controle para estimulação elétrica funcional é monitorar a dinâmica do torque em contrações musculares. Em aplicações de contração isotônica, medir o torque é algo difícil. A novidade neste estudo é a proposta de um novo modelo não linear, cujas variáveis de estado são posição angular, velocidade angular e aceleração angular. Neste novo modelo a variável torque é substituída adequadamente pela aceleração angular. Ensaios experimentais listam os parâmetros correspondentes a 24 indivíduos (20 saudáveis e 4 paraplégicos) para o modelo linearizado usando abordagem de identificação caixa cinza.
Palavras-chave: Estimulação elétrica. Paraplégicos. Modelos fuzzy Takagi-Sugeno. Desigualdades matriciais lineares. Controle chaveado.

ABSTRACT

Electrical stimulation is a promising technique for motor rehabilitation in cases of spinal cord injury. Stimulator saturation is important in the control system designs applied to electrical stimulation. The negligence of the actuator saturation in the electrical stimulation can lead to unwanted control results, which evidences the muscular fatigue effects. For the first time a switched controller subject to actuator saturation for electrically stimulated lower limb is proposed. The dynamic limb extension model is nonlinear and uncertain. The uncertain nonlinear system described by Takagi-Sugeno fuzzy models operating within an operating region in the state space is considered in this study. In addition, fault in the actuator, muscle activation uncertainty, and muscular non-idealities, such as fatigue, spasms, and tremor were considered at three three severity levels. The switched controller is compared to parallel distributed compensation technique. Simulations denote better results of the switched controller by dealing with parametric uncertainties. On the other hand, a challenge for FES control systems is to monitor torque in muscle contractions. In isotonic contraction applications, measuring torque is difficult. The novelty in this study is the proposal of a new nonlinear model, whose state variables are angular position, angular velocity and angular acceleration. In this new model the torque variable is replaced by the angular acceleration. Experimental tests list the parameters corresponding to 24 individuals (20 healthy and 4 paraplegic) for the linearized model using gray box identification approach.

Key words: Electrical stimulation. Paraplegics. Takagi-Sugeno fuzzy models. Linear matrix inequalities. Switched control.

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LIST OF ABBREVIATIONS & ACRONYMS

BMC	BioMedCentral
CFT	Constant-Frequency Trains
DM	Direct Model
DFT	Doublet-Frequency Trains
I	Electrical Current
FC	Fatigue Compensator
FEL	Feedback Error Learning
FN	Feedforward Neural
FM	Frequency Modulation
FES	Functional Electrical Stimulation
GS	Gain Scheduling
GA	Genetic Algorithm
HOSM	High Order Sliding Mode
IOFL	Input Output Feedback Linearization
IEEE	Institute of Electrical and Electronics Engineers
IOP	Institute of Physics
IM	Inverse Model
ILC	Iterative Learning Control
LMIs	Linear Matrix Inequalities
LMPC	Lyapunov-based Model Predictive Control
LQG	Linear Quadratic Gaussian
MPC	Model Predictive Control
MRAC	Model Reference Adaptive Controller
MLP	Multilayer Perceptron
MFTDNN	Multilayered Feedforward Time Delay Neural Network
NN	Neural Network
NMES	Neuromuscular Electrical Stimulation
NMPC	Nonlinear Model Predictive Control
NI	Not Informed
OL	Open-loop
PDC	Parallel Distributed Compensation
PG	Pattern Generator
PS	Pattern Shaper
PD	Proportional Derivative

PID	Proportional Integral Derivative
PAM	Pulse Amplitude Modulation
PW	Pulse Width
PWM	Pulse Width Modulation
RBF	Radial Basis Function
RISE	Robust Integral of the Sign of the Error
RMS	Root Mean Square
RMSE	Root Mean Square Error
SSRMSE	Root Mean Square Error in the steady-state time
SMC	Sliding Mode Controller
SOF	Static Output Feedback
TS	Takagi-Sugeno
TRMSE	Root Mean Square Error in the transient time
TTRMSE	Root Mean Square Error in the total time
VFT	Variable-Frequency Trains
V	Voltage
WHO	World Healthy Organization

LIST OF SYMBOLS

$\otimes$ — Kronecker product. For example, consider $\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$, and $\mathbf{B} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}$. Then, the Kronecker product $\mathbf{A} \otimes \mathbf{B}$ is equal to

$$\mathbf{A} \otimes \mathbf{B} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \otimes \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = \begin{bmatrix} a_{11} \cdot \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} & a_{12} \cdot \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \\ & \\ a_{21} \cdot \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} & a_{22} \cdot \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \end{bmatrix},$$

$$= \begin{bmatrix} a_{11} \cdot b_{11} & a_{11} \cdot b_{12} & a_{12} \cdot b_{11} & a_{12} \cdot b_{12} \\ a_{11} \cdot b_{21} & a_{11} \cdot b_{22} & a_{12} \cdot b_{21} & a_{12} \cdot b_{22} \\ a_{21} \cdot b_{11} & a_{21} \cdot b_{12} & a_{22} \cdot b_{11} & a_{22} \cdot b_{12} \\ a_{21} \cdot b_{21} & a_{21} \cdot b_{22} & a_{22} \cdot b_{21} & a_{22} \cdot b_{22} \end{bmatrix}.$$

$\star$	For a symmetric matrix, it denotes the symmetric blocks in relation to the main diagonal
$\mathbb{R}$	Set of real numbers
$\mathbb{R}_+$	Set of positive real numbers
$\mathbb{Z}_+$	Set of positive integers numbers
$\mathbb{Z}_+^*$	Set of non-zero positive integers numbers
$\mathbb{N}$	Set of natural numbers
$\mathbb{R}^{n_x}$	Set of vectors $n_x \times 1$ with real elements
$\mathbb{R}^{n_x \times n_u}$	Set of matrices $n_x \times n_u$ with real elements
$\overset{\rightleftharpoons}{p}$	It corresponds to $p2^{p-1}$
$\mathbf{I}_{n_u}$	Identity matrix, $n_u \times n_u$
$\mathbf{P}^T$	Transposed matrix, $\mathbf{P} \in \mathbb{R}$
$\mathbf{P} > (\geqslant) 0$	It is a symmetric matrix and defined (semidefinited) positive
$\mathbf{P} < (\leqslant) 0$	It is a symmetric matrix and defined (semidefinited) negative
$\mathbf{sl}_{p,j}$	$\mathbf{sl}_{p,j} \in \mathbb{R}^{1 \times p}$ denotes a row vector whose j-th element is 1 and the others elements are zero
$\text{co}\left\{v_1, \cdots, v_p\right\}$	It denotes $\alpha_1 v_1 + \cdots + \alpha_p v_p$, $\alpha_1, \cdots, \alpha_p \geqslant 0$ and $\alpha_1 + \cdots + \alpha_p = 1$
$\mathbb{I}_k$	Set of first non-zero positive integers $\mathbb{I}_k = \{1, 2, \cdots, k\}$, $k \in \mathbb{Z}_+^*$
$\prod$	Product operator between elements
$\arg^* \min\limits_{i \in \mathbb{I}_{nr}} \{x_i\}$	Lower index $j \in \mathbb{I}_{n_r}$ such that, for the set $\{x_1, \cdots, x_{n_r}\}$, $x_j = \min\limits_{i \in \mathbb{I}_{nr}} \{x_i\}$

CONTENTS

1 INTRODUCTION

This chapter describes the problem treated and briefly introduces the proposal, motivation, objectives and thesis outline.

1.1 Context of the problem

Spinal cord injury has a significant incidence in the world population. The lesion may result in a partial or total obstruction of the sensory and motor connections below the level of the lesion. With this, the central nervous system ceases to receive the sensory-motor signals referring to the parts of the body below the level of the lesion. Paraplegic individuals begin to live under different limitations of locomotion and changes in their daily activities. Simple activities for healthy individuals become complex and painful for paraplegics. In this sense, the use of functional electrical stimulation has the potential to restore the movement of paralyzed limbs, offering both therapeutic and functional benefits.

Results in the area of motor rehabilitation with electrical stimulation show a promising future of this technique. Different approaches by researchers have concentrated efforts in intramuscular and surface stimulation, neuro technological implants, and hybrid mechanisms aided by robotic systems to enable that paraplegic individuals walk again.

One strand of this field is the study of controllers using surface electrical stimulation. Recent works in this area of closed-loop control highlights the challenges related to muscle delay; to high frequency switching in the control signal, also called chattering; to modulation parameters; to the parametric uncertainties of the plant; strategies to compensate muscular fatigue, among others.

However, the effect of the actuator saturation is also an important requirement in the system control design applied to electrical stimulation. The negligence of the actuator saturation in electrical stimulation can lead to unwanted control results, causing a overstimulation that evidences the effects of muscular fatigue.

By the author's knowledge, for the first time, a switched controller for the lower limb is proposed considering the saturation and fault of the electric stimulation actuator and analysis under non-ideal muscular conditions (fatigue, spasm and tremor). The dynamic model of the lower limb extension is nonlinear and uncertain. An exact description by the Takagi-Sugeno fuzzy model of the plant, operating within a region of operation is considered in the control design. A comparative analysis between the switched and parallel distributed compensation controllers is presented. Due to the uncertainties of the plant, the parallel distributed compensation (PDC) performance is compromised, because it is dependent on the knowledge of membership functions. Results obtained by simulation emphasize the best performance of the switched control law in non-ideal conditions, treated as parametric uncertainties.

In this study, the idea is to design several feedback gains, being only one gain used at a time, chosen based on a switching law that depends on the state vector of the controlled system. A schema that represents the use of the switched control is shown in the Figure 1.

A challenging problem is to measure muscle torque dynamics. In general, the variable of muscle torque state is estimated through strategies from the control signal or from state observers. Therefore, measuring torque becomes a complex task, especially for isotonic contractions.

The novelty in this study refers to a new nonlinear dynamic model. The proposed model presents the state variables: angular position, velocity, and acceleration. Therefore, the torque state variable is replaced by angular acceleration, which can be measured easily by accelerometers, for example. In addition, the nonlinear plant is described by fuzzy TS models and the LMIs-based control design is presented. LMIs are convex constraints to solve optimization problems with convex objective functions. The LMI constraints can easily be solved efficiently using specific softwares. In recent years, this method has been widely used among control engineers because a wide variety of control problems can be formulated as LMIs.

1.2 Objectives

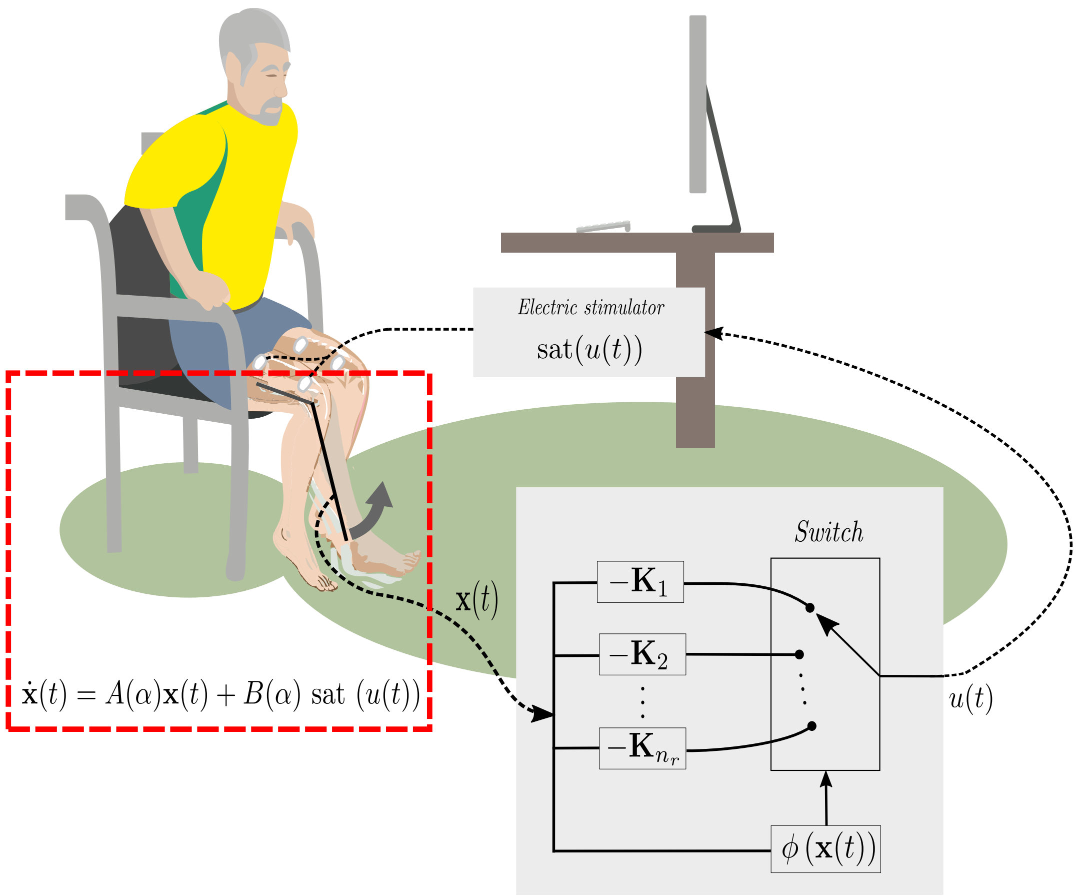
1.2.1 General

This doctoral thesis proposes application of the switched control subject to actuator saturation and a new dynamic model for electrically stimulated lower limbs.

1.2.2 Specific

- Research and investigate the state-of-the-art on closed-loop control techniques in knee joint applications using electrical stimulation.
- Perform the control system design by parallel distributed compensation and switched law via LMI's.

Figure 1 - Electrical stimulation system of the lower limbs using switched controller subject to actuator saturation.



Source: From author.

- Simulate the two control techniques for different operating points of the lower limb under isometric conditions, considering healthy and paraplegic individuals.
- Analyze and compare the controlled system results by inserting saturation and fault in the actuator using torque-based model.
- Develop and test different levels to non-ideal muscle conditions (fatigue, spasms and tremor).
- To highlight the results obtained from switched control law in relation to parametric uncertainties.
- Measure and compare the RMS error between the PDC and switched controllers for the time interval corresponding to the transient and steady-state.
- Propose a new dynamic model applied to electrically stimulated lower limbs.

- Describe by TS fuzzy models and design PDC and switched control using the new proposed model.
- Perform experiments with healthy and paraplegic individuals and state-space identification of the electrically stimulated lower limb using gray-box approach.

1.3 Justification

The life expectancy of individuals with spinal cord injury is lower than the average of healthy people. In this sense, efforts have been made so that these individuals have facilitated access to physiotherapy activities for muscular strengthening using electrical stimulation with a closed-loop control system. In addition to granting therapeutic and/or functional benefits to individuals with spinal cord injury, the main objective is that these individuals are socially inserted, offering expectation and quality of life.

Arguably, rehabilitation systems using closed-loop control can improve performance and achieve desired movements with safety and reliability. However, some challenges must be overcome to allow a wide reach of this technology, among them we highlight:

- **Nonlinear musculoskeletal system and parametric uncertainties in control system design:** the great challenge of this area corresponds to the system being nonlinear and endowed with uncertain parameters make the control task more complex. More advanced control techniques have been employed in recent years. We propose a contribution to literature using a switched controller for regulation improvement under uncertain and non-ideal conditions of the lower limb.
- **Difficulty in monitoring and designing control systems based on muscular variables:** numerous mathematical models propose state variables that are difficult to measure. One contribution of this thesis is to establish an improved model based on measurable state variables of kinematics and which implicitly contemplating the lower limb muscle dynamics.
- **Model parameter variability in a larger individuals number:** the statistical analysis of parametric variability under electrical stimulation in different situations for a larger number of individuals is a gap in the literature. In this work, we investigate the parameter variability from 24 individuals considering the new model proposed.

1.4 Thesis outline

This work is organized as follows. Chapter 2 establishes the state-of-the-art on the subject of closed-loop control for electrical stimulation of lower limbs, focusing on studies of the knee joint. It presents the basic principles for understanding the area of electrical stimulation. It shows a systematic methodology for the literature review. It discusses and exposes the control techniques already investigated. It then reveals the technical characteristics of the experimental studies regarding the modulation type, stimulator and its output topology, electrode dimension, stimulation parameters, performance indexes of tracking and regulation in isometric contractions. Finally, the levels of spinal cord injury, the benefits and limitations of the FES closed-loop systems are indicated.

Chapter 3 introduces the switched controller and the regulation problem at an operating point subject to the non-ideal muscle condition (fatigue, spasms and tremor), as well as fault and saturation of the actuator. The torque-based model is evaluated for healthy and paraplegic individuals. LMIs conditions are established for the system to operate using switched control law in a region of operation and subject to symmetric saturation. The performance of the switched controller is compared to technique proposed by Gaino et al. (2017). Simulated results attest minor RMS error using switched controller applied to regulation considering non-idealities in the muscular model.

Chapter 4 emphasizes the new dynamic model for electrically stimulated lower limb. The design of the acceleration-based model is presented from a generic system of state space equations, whose states variables relate kinematics of movement and muscle torque dynamics. A description by TS fuzzy models of the nonlinear system is detailed. From this model, fuzzy controllers via PDC are designed to a region of operation considering healthy and paraplegics individuals.

Chapter 5 shows the experimental apparatus for lower limbs electrical stimulation. It then details the protocol of motor-point identification, and technical specifications of the tests. Experimental results are obtained from 24 individuals (20 healthy and 4 paraplegics) and the parameters of the state space model are listed by gray box approach.

Finally, the main conclusion of this work and some future works are in the Chapter 6.

6 GENERAL CONCLUSION

In this thesis, the state-of-the-art on closed-loop control systems applied to knee joint rehabilitation using superficial electrical stimulation were presented.

The knee joint control system using electrical stimulation was treated as an uncertain nonlinear system. In the control design, LMIs conditions constrained the TS fuzzy modeling to a state-space operation region was performed. The switched control subject to actuator saturation was compared to Gaino et al. (2017). The performance of these were evaluated under non ideal conditions of the muscle (fatigue, spasms and tremor) and fault in the actuator. Remembering that the fuzzy control law is dependent on the membership functions. When the system has uncertainties, the fuzzy controller is inadequate for this problem. On the other hand, the switched-control law has proved to be an interesting approach because it does not depend on the membership functions. Using the switched control law, we obtained better results than the combination of the control gains by the membership functions, because it chooses a state-feedback controller gain belonging to a given set of gains, that minimizes the time derivative of Lyapunov function, and reduces the control signal. However, an unwanted effect is that the control signal is susceptible to a high frequency switching of the controller gains. This problem can be overcome by using the soft minimum, proposed in (ALVES et al., 2016).

In addition, a new dynamic model of electrically stimulated lower limbs was proposed. The advantage of this model is to obtain the kinematics and muscular dynamics represented in state space through the variables angular position, angular velocity and acceleration. Therefore, in this new representation the torque variable has been replaced by acceleration. A TS fuzzy modeling of this plant was shown, as well as the parallel distributed compensation control design considering an operating region.

Finally, an experimental arrangement was set up to identify parameters of the linearized model. The gray-box identification approach was performed from third-order transfer function. The muscular behavior was investigated in three tests of the system response to the step signal, load disturbance and analysis on different days. A well-defined behavior of parametric variation was observed in the presence of muscle fatigue.

6.1 Future works

The research field is broad and promising, it is possible and interesting to investigate: LMIs conditions for switched control design considering actuator subject to saturation and delay;

LMIs conditions for asymmetric saturation and/or null constraint (e.g. PWM control signal); data-driven TS fuzzy local models; real-time system to monitor muscle fatigue in isotonic and isometric contractions; an electrical stimulator based on amplitude modulation and isolated channels; a electrical stimulator that monitors the current flow into or out of the electrode, and adjusts the voltage output of the power supply to maintain a constant current; and a new hybrid system for lower and upper limb rehabilitation.

6.2 Scientific publications

In this study, the following contributions are proposed to journals:

1) NUNES, W. R. B. M.; ALVES, U. N. L. T.; SANCHES, M. A. A.; MACHADO, E. R. M. D.; CARDIM, R.; TEIXEIRA, M. C. M.; CARVALHO, A. A. *A New Acceleration-Based Model Applied to Electrically Stimulated Lower Limbs*. Submission to Journal of Biomechanics.

2) NUNES, W. R. B. M.; ALVES, U. N. L. T.; SANCHES, M. A. A.; TEIXEIRA, M. C. M.; CARVALHO, A. A. *Isometric Contraction Improvement of Electrically Stimulated Lower Limb under Non-Ideal Conditions Using Switched Controller Subject to Saturation*. Submission to IET Control Theory.

3) NUNES, W. R. B. M.; SANCHES, M. A. A.; TEIXEIRA, M. C. M.; CARVALHO, A. A. *Closed-Loop Control Techniques Applied to Motor Rehabilitation of the Knee Joint Using Electrical Stimulation: A Survey of the State-of-the-Art And Future Perspectives*. Submission to Medical Engineering & Physics.

4) TEODORO, R. G.; NUNES, W. R. B. M.; ARAUJO, R. A.; SANCHES, M. A. A.; TEIXEIRA, M. C. M.; CARVALHO, A. A. *Robust and Switched Control Design for Electrically Stimulated Lower Limbs: a Linear Model Analysis in Healthy and Spinal Cord Injured Subjects*. Submission to Control Engineering Practice.

5) NUNES, W. R. B. M.; KRUEGER, E.; BRONIERA JR, P.; SANCHES, M. A. A.; TEIXEIRA, M. C. M.; CARVALHO, A. A. *EEG-Based Brain-Controlled Functional Electrical Stimulation for Lower Limbs Rehabilitation: Advances and Perspectives*. Submission to Annals of Biomedical Engineering.

And the following contributions were accepted in conferences:

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