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CONTROL SIMULATION IN FUNCTIONAL ELECTRICAL STIMULATION APPLICATION

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Abstract. *Through the use of Musculoskeletal Modelling Software (MSMS) together with Matlab - Simulink, a tool called Model Control and Musculoskeletal Simulation (MCSM) has been developed, which allows the simulation of an electrical stimulation generator in conjunction with a PID controller, acting on the musculoskeletal model simulated by computer. Thus, it is possible to simulate the muscle response to an electrical stimulus, helping to reduce the use of human beings in the preliminary stages of the development of Functional Electrical Stimulation (FES) orthoses. As an example of application, an FES orthosis is simulated which acts on the muscles of the biceps and triceps to achieve the angular position of the arm relative to the forearm of a person.*

Important concepts about FES applications are explored, allowing us to understand details of the development of MCSM, where the simulated arm is positioned at different angle.

To achieve this result, the gains of the PID controller were obtained through the experimental methods proposed by Ziegler-Nichols making use of two criteria of calculations, to determine the best approach for the tuning of PID gains resulting in a more realistic behavior.

From the tests performed to preset positioning angle, trend curves were generated for PID gains, where it is assumed that the variation in gains between known points can be represented by a straight line, which allows to calculate the value of gains at intermediate angular positions. These dealings contribute to the development of a controller for automatic tuning of the PID gains starting from predefined angle.

It was found a PID gains to allow a more coherent movement with the concept of functionality expected for an FES orthosis, generating a significant contribution for developing biomechanical devices, which allow greater motor independence to patients.

Keywords: *Computer Simulation, Functional Electrical Stimulation FES, Control Biomechanics, Skeletal Muscle.*

1. INTRODUCTION

The aim of present work is to contribute for the decreasing number of patients participating in preliminary stages in FES research studies. This goal was reach through the integration of a simulated controller in Matlab with a human arm model; created by Musculoskeletal Modeling Software- MSMS (Davoodi, *et al.*, 2004) developed and distributed free of charge by the Alfred Mann Institute and Biomedical Engineering Department, University of Southern California.

This research presents a closer approach to the concept of Functional Electrical Stimulation (FES) (Aguiar, *et al.*, 2005); (Davoodi, *et al.*, 2003), where the electric stimulus is used to recreate movement and increase independence to patients who lost their natural control of muscular movement. Following this direction, the Model Control and Musculoskeletal Simulation (MCSM) was developed in the scope of the Laboratory of Robotics and Rehabilitation (LABORE) Federal Institute of Education, Science and Technology of São Paulo (IFSP), allowing simulation of angular moment response of the human arm. The arm model was developed using the MSMS software in an application where arm position angle was reach using a PID controller with PWM output (Pulse Width Modulation) generating in Matlab a signal control similar to electrical stimulation in FES applications (Aguiar, *et al.*, 2005).

For the first test PID controller was tuned by the Ziegler - Nichols (ZN) approach, this method would require subjecting the patient to the critical conditions of musculature activation, and the tests must be repeated until it is possible to determine the PID parameters where the system finds its point of convergence.

Using the MCSM the tests under critical conditions are simulated by computer, saving the patient from unpleasant procedures

2. MCSM DEVELOPMENT

The first step that allows the development of the MCSM is the configuration of the musculoskeletal model (Garcia, 2014) through the MSMS software. This configuration results in a software that is used within the Matlab Simulink environment, represented by a block named as MM (Fig.1) where the inputs allow the biceps and triceps to be triggered by the signals produced through the pulse width modulation generator (PWM generator). The PWM generator allows dosing the amount of energy applied to the muscle, implying in a movement intensity.

To achieve an angular position, the PWM generator receives from proportional integral derivative controller (PID) signal that is converted to values compatible with the range of values accepted by the PWM generator.

The system receives an angular value positioning in degrees, the musculoskeletal model MM informs the instantaneous positioning of the arm, making possible to calculate a positioning error that tends to be minimized by the PID controller action.

The angular positioning of the arm as a function of time is recorded in a graph where it is possible to verify the behavior of the system for several configurations of the PID controller, allowing to find the effects caused by the application of the different sets of PID gains.

3. EXPERIMENTAL PROCEDURE

The tests performed by using MCSM (Fig.1) to obtain the PID gains though calculating critical parameters for predefined angle, were used to determine the PID gains for intermediate angle by interpolating values obtained by the trend curve of the PID gains.

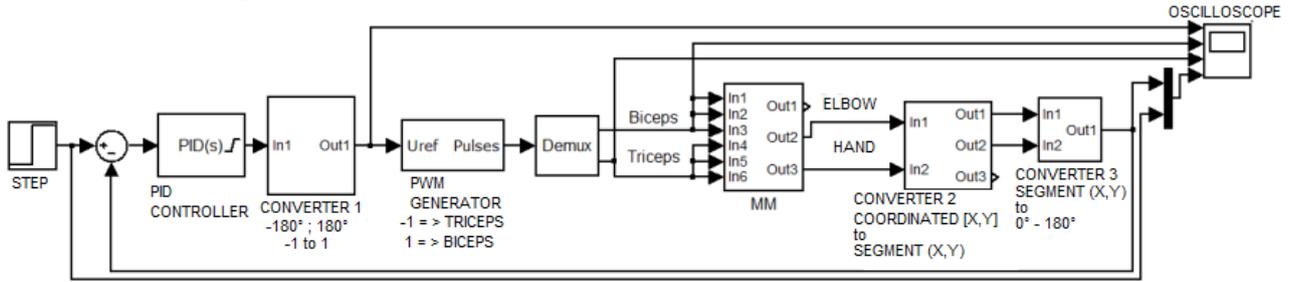


Figure 1: Musculoskeletal Simulation and Control Model (MCSM)

Through this procedure it is possible to demonstrate the functionality of the MCSM, and establish which method best meets the functional movement expectation. At the same time is possible to verify the possibility to find the PID gain through interpolation of a trend curve produced by PID predefined angle gains. This test suggests next steps for the future development a controller for automatic tuning PID gains using point interpolation to determine PID gain for intermediate angle positions between predefined tested points.

The PID parameters were calculated through the original ZN1 approach Eq.(1) and through an alternative approach ZN2 Eq.(2) that applies a correction in cases where the overshoot is approximately 60% higher than desired (Ogata, 1998).

$$P_{ZN1} = 0,6 \times K_{CR} \quad ; \quad I_{ZN1} = \frac{1}{0,5 \times P_{CR}} \quad ; \quad D_{ZN1} = 0,125 \times P_{CR} \quad (1)$$

$$P_{ZN2} = 1,2 \times K_{CR} \quad ; \quad I_{ZN2} = \frac{1}{P_{CR}} \quad ; \quad D_{ZN2} = 0,25 \times P_{CR} \quad (2)$$

The predefined angle 20°, 40°, 60°, 80°, 100°, 120°, 140° are used as reference for both ZN1 and ZN2. The PID gain for each angle was calculated after reaching the critical gain K_{CR} and the critical period P_{CR} that lead the system to a self-sustained oscillation. The trend curves for predefined angle were the start point in order to obtain PID gains for intermediate angle 30°, 50°, 70°, 90°, 110°, 130° through interpolation gains of predefined angle, for both ZN1 and ZN2 methods, this procedure allows to find PID gains without knowing the critical parameters for intermediate positioning angle, however it was necessary to simulate the system behavior of the PID gains attributed to the intermediate angles to identify which method results in a functional movement, and also to verify the possibility of obtaining PID gains for intermediate angle without investigate critical parameters K_{CR} and P_{CR} .

4. RESULTS AND DISCUSSION

The PID controller working with the tuning method proposed by Ziegler - Nichols, is an example of MCSM applicability. Without this tool would be necessary to perform many simulations to determine that ZN1 approach does not represent a solution capable to generate the PID gain values (Fig.2A) compatible with functional movement (Fig. 3) and (Fig. 4), each simulation that does not reach a satisfactory result is potentially a procedure from which the patient will be spared.

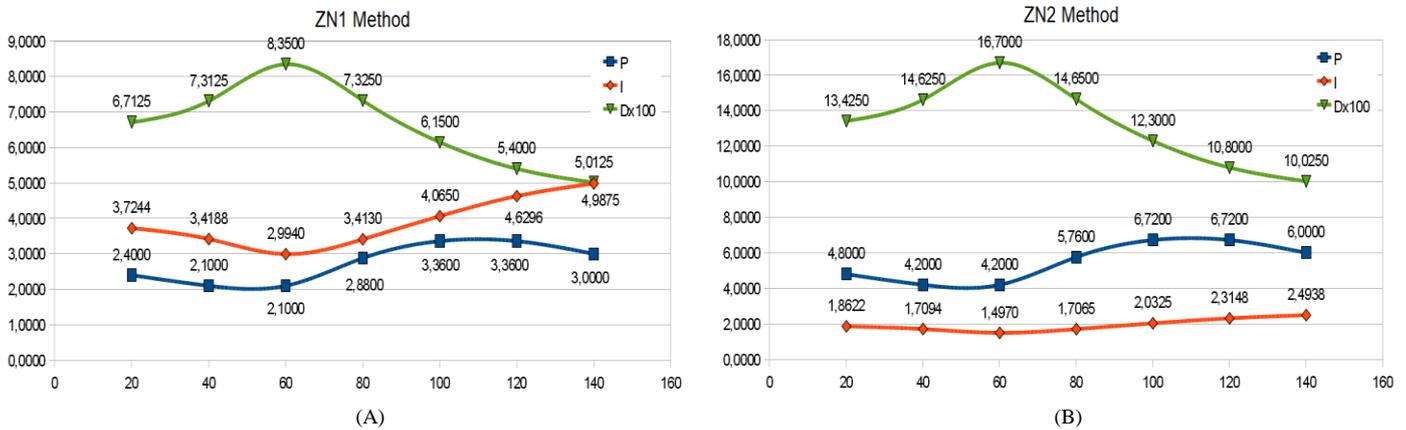


Figure 2: PID Gain Curve for Predefined and Intermediate Angle; (A) Method ZN1; (B) Method ZN2

Through the ZN2 method the PID gains for the predefined angle (Fig. 3) must be determined by the critical parameters K_{cr} and P_{cr} , however it is possible to find the PID gains for intermediate angle (Fig. 4) through the interpolation of the known PID gains (Fig. 2B), resulting in a functional movement.

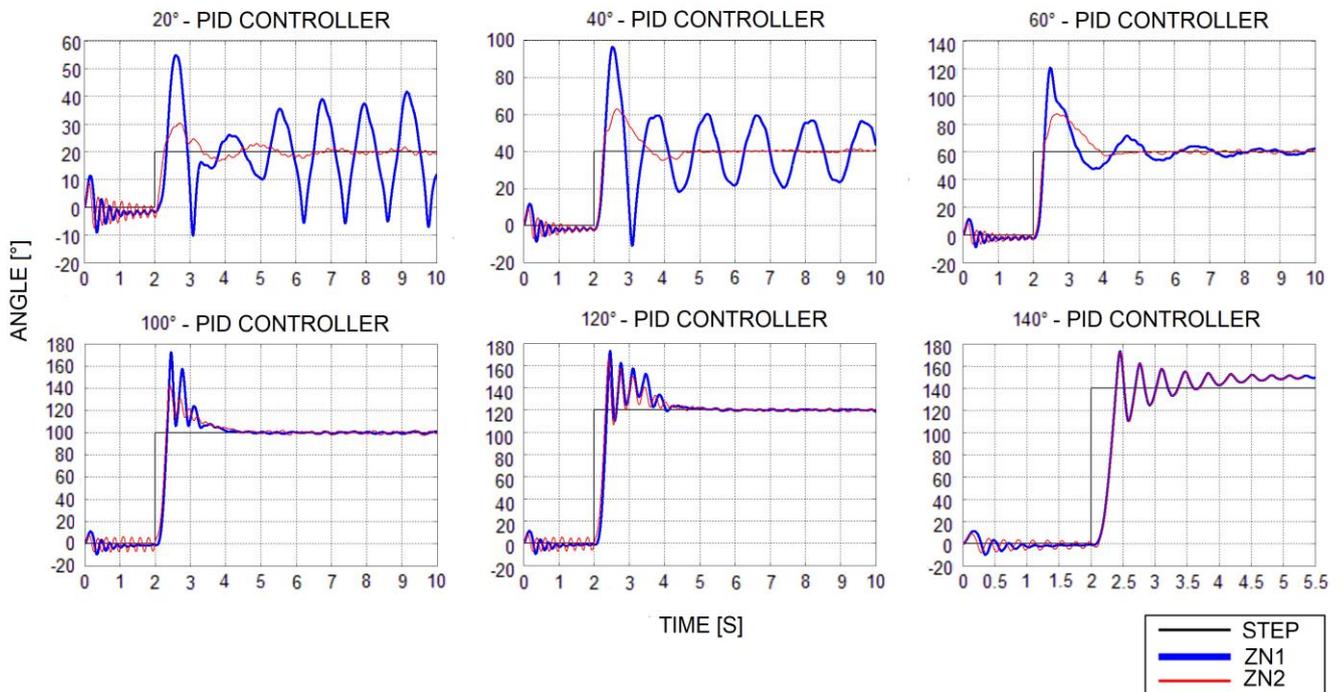


Figure 3: Response to the Unit Step for the Gains Related to Method ZN1 and ZN2 for Predefined Angle

Applying the ZN1 method, for the angle 20° and 40°, the simulated arm cannot achieve a desired angular position without causing undesired oscillation. For the intermediate angle obtained by interpolating the PID parameters only the 30° positioning is reached, there is an undesirable positioning error for all other angles position, making the use of this approach impossible to be applied.

In the ZN2 approach, the highest accommodation time is around six seconds and one-degree position error, compatible with the concept of functional movement, achieved either by the calculated or estimated PID through interpolation. For 140° angle, there is an error around ten degrees which can influence in the functionality of the movement, however, this discussion must be deepened when a real system can be implemented and real situations can be tested, since the motor independence and the comfort of the movements can be so important as the positioning error.

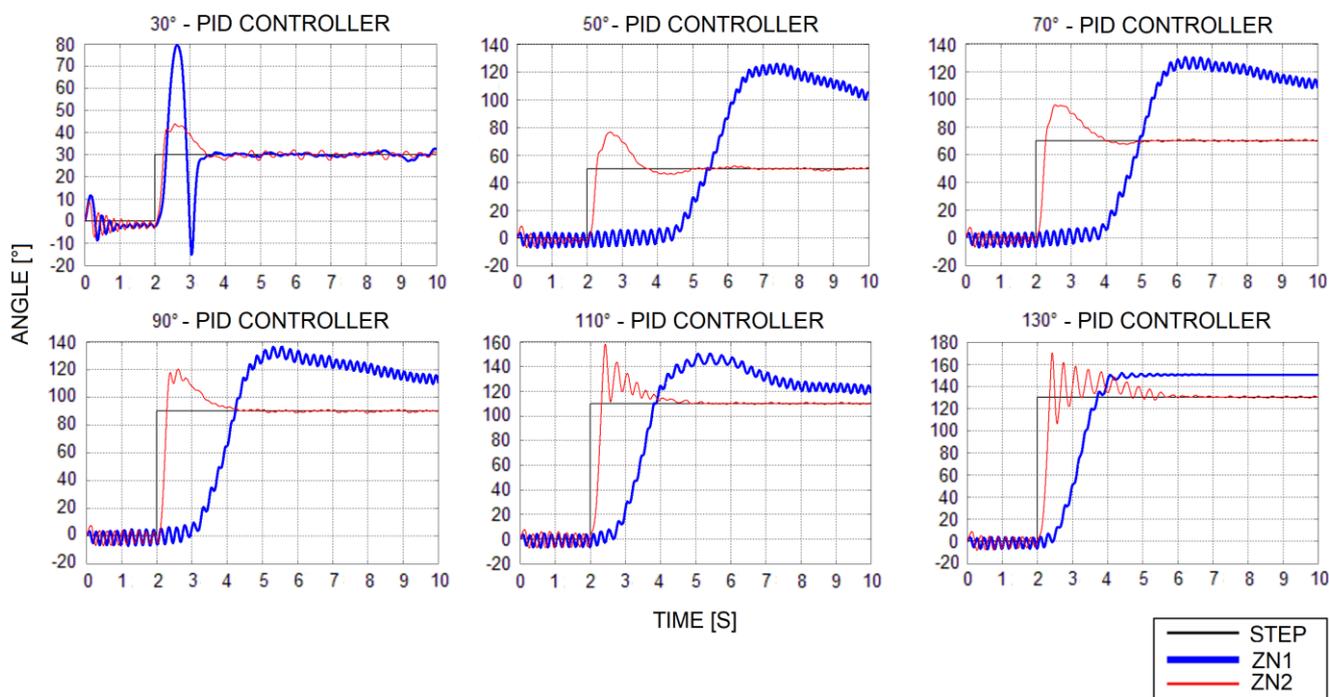


Figure 4: Response to the Unit Step for the Gains Related to Method ZN1 and ZN2 for Intermediate Angle

5. CONCLUSIONS

Preliminary tests of the MCSM operation indicates that is possible to estimate the PID gains for *simulated arm*, using Ziegler - Nichols alternative approach and interpolation of PID gains, resulting in a functional movement, and possibility to implement a control system to achieve intermediate angles, this result allows the development of many other researches accelerating the process of testing and developing solutions. In the future, it may be possible to simulate a real patient by preventing it being subjected to the same tests to determine the PID gains for a real FES controller.

The development of MCSM opens several researches related to its application and improvement, PID gains that achieve a more precise simulated motion can be possible, however these parameters must take into account a functional comfortably movement without prejudice to the patient's physical integrity, it's only possible with a development of a real PID controller, which closely represent the simulated PID controller, and develop a simple methods to obtain individual parameters for musculoskeletal model configuration, it makes possible to feed the MCSM with information that allow simulate and test a real patient's condition and contributing definitively to the development of FES orthoses, improve the quality life of people with special needs.

6. ACKNOWLEDGEMENTS

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