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Muscle Rehabilitation Using a Fuzzy Controlled Stimulator

Radu Ciorap[*], Robert Lupu[*], Florin Topoliceanu[**], Ana Stratone[**], Iulian Răducanu[*]

[*] Gr.T.Popa University of Medicine and Pharmacy, Medical Bioengineering Faculty Str. Universitatii 16, IASI 6600, ROMANIA
[**] Gr.T.Popa University of Medicine and Pharmacy, Medicine Faculty Str. Universitatii 16, IASI 6600, ROMANIA

Abstract: In many medical fields, such as rehabilitation, occupational medicine and dental applications, the recovery of muscular activity or its improvement up to the level of the optimal parameters is required. Apart from the classical solution for rehabilitation (physical exercises) the use of electrical stimulation has become quite frequent of late. The paper presents an interface that detects the electromyographic (EMG) activity, assesses it, and generates appropriate electrical stimuli, by means of a specific type of fuzzy control system, in order to control the dynamics of the EMG.

1. Introduction

Often after accidents, patients must spend a long period of time immobilized in bed. Because of the lack of exercise many muscle group lose their normal proprieties. Under these conditions, for a correct interpretation of EMG traces, it is necessary to know very well the normal aspects of the neuromuscular activities. This means that it is necessary to know the interpretation of the duration, the amplitude and the frequency for motor unit action potential (MUAP) from EMG traces as well as the modifications which appear in these traces representing muscular activities ranging from the smallest contraction to the maximal contraction.

The classic way to generate the stimulation is independent of the neuromuscular activity of the patient. The advantage of this method consists in the fact that the electrical stimuli, by their very nature, are very close to the natural biological stimuli, and can be applied repeatedly and precisely in the chosen areas at various voltage or current levels, during a selected period of time and in different waveforms. The electrical stimuli act upon the target area directly and immediately. The neuromuscular excitation consists in impulse trains. Recently, the use of neuromotor feedback to stimulate the patients with neuromuscular disorders was suggested. Such a system could be seen as a specific prosthetic device. The number of impulses per train, their amplitude, frequency and duration are controlled in accordance with the input signal.

The control is partly predetermined, during the training phase. The training has to be performed for each subject. The decision criterion is the maximization of EMG amplitude in time. The characteristics of tremor are firstly extracted to be used as input to the fuzzy control system. Initially these characteristics were: the duration of motor unit action potential (MUAP), the amplitude of MUAP and the frequency of MUAP.

2. Fuzzy Controller

The control is partly predetermined, during the training phase. The training has to be performed for each subject. The decision criterion is the maximization of EMG amplitude in time. The characteristics of signal are firstly extracted to be used as input to the fuzzy control system. Initially these characteristics were: the duration of motor unit action potential (MUAP), the amplitude of MUAP and the frequency of MUAP.

The proposed fuzzy control acts upon one parameter of the output signal, the pulse amplitude; the pulse duration and pulse pause, (equivalently, one of the former parameters can be replaced by the number of pulses per second, i.e., frequency) will be maintained constant. For the fuzzification of the excitation signal parameters we use triangular membership functions with 5 linguistic attributes (very small, small, medium, big, very big).

We try to simulate a second strategy in order to reduce the computation load, and to eliminate other drawbacks, taking into account the fact that each disease and each patient have their specific features and devising a control strategy for each of them. This strategy is based on the evaluation of EMG signal amplitude at the current moment and of the muscular response to the electrical stimulation at the previous moment. The new fuzzy control systems will have two input variables: voluntary EMG amplitude (A_r) and difference between voluntary EMG amplitude at the current moment and at the previous moment (ΔA_r). For each of these variables we choose linguistic variables with 3 linguistic attribute (small, medium, big). The structure of the control system is shown in the Figure 1.

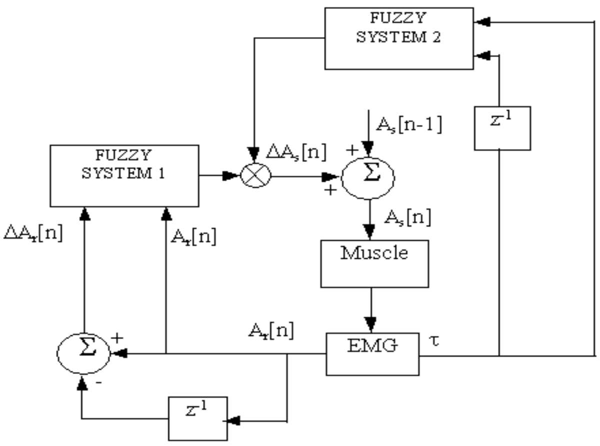

Fig. 1 – The structure of the Control System

The second fuzzy system is for modeling the muscle fatigue. The input variables are τ (the time after the EMG amplitude decrease under a fixed threshold) at the current step and τ at the previous step.

The set of rules was established empirically using the experience of the two medical experts from our team who are active in the function testing domain for more than 30 years. The representation of the fuzzy rule is shown in the Figure 2 and Figure 3. (Mamdani type).

The fuzzy partition can be realized with different types of the membership functions who are distribute respected a user defined rule for the universe of discourse of the input/output variable. We prefer to use the triangular uniform membership function.

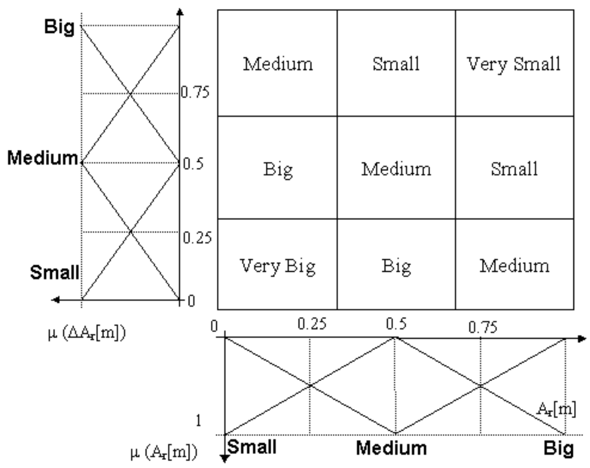

Fig. 2 – The structure of the fuzzy rule

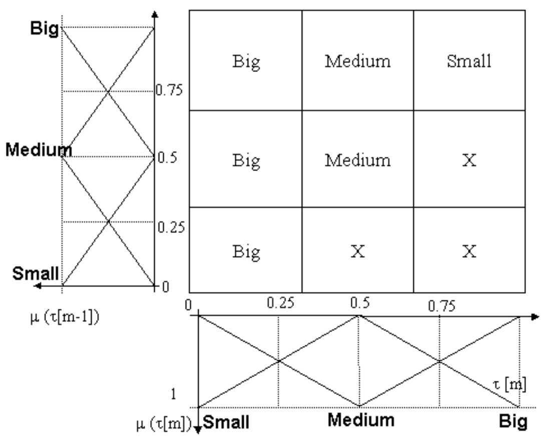

Fig. 3 – The structure of the fuzzy rule

Because the implementation and adaptation of the Mamdani type fuzzy systems is hard we tray to find a fuzzy functional equivalent using an off-line procedure.

3. Off-Line Procedure for Ffs Equivalent Determination

Lets consider one Mamdani Fuzzy Logic Controller, having the canonic form, R(k_1,…,k_n;h):

$$\text{IF } x_1 \text{ is } A^1_{k_1} \ \&\ldots\& \ x_n \text{ is } A^n_{k_n}\text{, THEN } y \text{ is } C_h$$

In control applications the ranges of the inputs x_1, …, x_n are well known so that the above system will provide a hyper-surface, $y=F(x_1, \ldots, x_n)$. Our goal is to obtain an equivalent system having the rules form

$$R(k_1,\ldots,k_n;h):$$

$$\text{IF } x_1 \approx A'^1_{k_1} \ \&\ldots\& \ x_n \approx A'^n_{k_n}\text{, THEN } y \approx \alpha_h$$

with α_h determinist values and which generates above the same surface. The output of this equivalent system is defined as

$$y = \sum_{r=1}^{N} w_r \cdot \alpha_r \tag{1}$$

where w_h signifies the activation degree of the h-th rule, Eq.10; $N=q_1 \cdot q_2 \cdot \ldots \cdot q_n$ and q_i (i=1,2,…,n) is the fuzzy sets number associated to each input x_i.

$$w_h = \mu_1\left(x_1 - a^1_{k_1,h}\right) \wedge \mu_2\left(x_2 - a^2_{k_2,h}\right) \wedge \ldots \wedge \mu_n\left(x_n - a^n_{k_n,h}\right) \tag{2}$$

Note that the fuzzy sets $A'^i_{k_i}$ have its number and distribution fixed by the quantifier structure of the A/D conversion. Consequently, only α_h may be tuning parameters. From Eq.1 yields following LMS algorithm

$$\alpha_h[m+1] = \alpha_h[m] + \beta(m) \cdot e[m] \cdot w_h[m] \tag{3}$$

where the gradient of square error between real and desired output is estimated by the gradient of current square error.

$$e^2(x_1, \ldots, x_n) = F(x_1,\ldots,x_n) - y(x_1,\ldots,x_n) \tag{4}$$

Figure 4 represents the scheme used for α_h generation.

The input $x_1[m]$, …, $x_n[m]$ are provided by a noise generator with uniform distribution in the definition range of the model function $F(x_1,\ldots,x_2)$.

In Eq.3 $\beta(m)$ is an adaptive constant calculated as

$$\beta(m) = {}^{0,5}\!\!\diagup_{E_{in}[m]} \tag{5}$$

$$E_{in}[m] = \gamma \cdot E_{in}[m-1] + (1-\gamma) \cdot \sum_{h=1}^{N} w_h^2[m] \tag{6}$$

with γ a sub-unitary constant (γ=0,15).

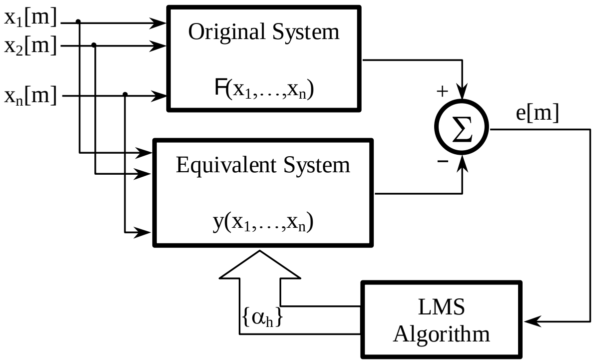

Fig. 4 – The scheme used for α_h generation

The performances of modeling are evaluated with normalized RMS (RMSN),

$$RMSN = \frac{\sqrt{\sum_{m=1}^{M} e^2[m]}}{M \cdot \max\{d[m]\}} \tag{7}$$

where $max\{d[m]\}$ is the maximum of $F(.)$ for all M inputs sets.

Figure 5 and 6 show the two control surfaces.

The response time requested by an implementation on 80C552 support was τ≈150μs. Next table contains the performances of the off-line procedure.

RMSN	Rules Number	Number of LMS cycles
0,02809	81	10000

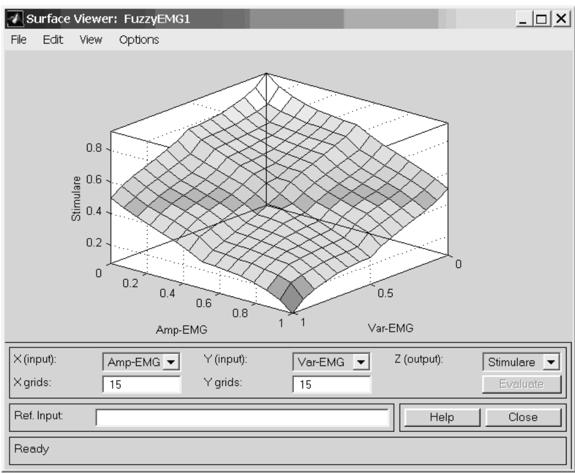

Fig. 5 – Control surface

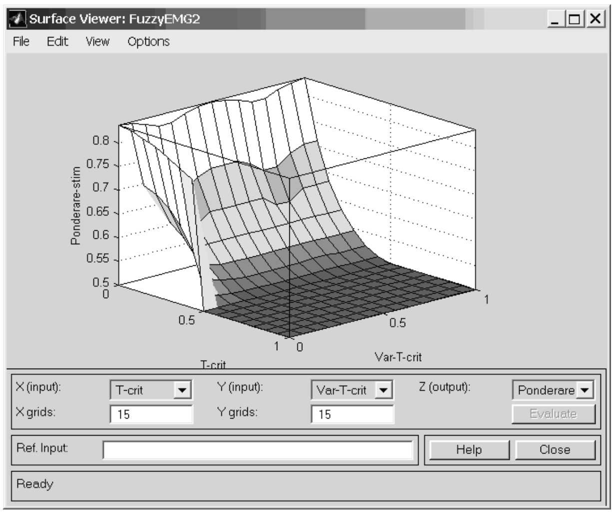

Fig. 6 – Control surface

4. Fuzzy Controlled Stimulator

For monitoring EMG biosignal we used an analog board for acquisition and stimulation and a conversion system (A/D and D/A converter). At the acquisition the sample rate of 500 Hz and the sample are send through serial interface in a computer. We used 12 bit for conversion and at the every 5 ms the sample is written in ADCDATAH and ADCDATAL register of the ADuC812 micro converter.

The software configures the main blocs of the microcontroller depending on the computer request. First are configure UART interface and Timer 1 used for generate the baud rate and after that are configure ADC and DAC blocs. At every conversion cycle the results are sending together with a synchronization octet through serial interface in the computer for processing.

The user interface is very intuitive and easy to use both with mouse and keyboard. This interface is showed in figure 7.

The menu bar contains all the operation necessary for configures the conversion system and the processing the waveforms.

In the main window are presented the EMG signal at the current moment, the EMG signal at the previous moment and the diference beetwen two wave forms. The status bar presents information about transmission rate and the operation executed from computer.

The stimulation menu contains option for configure the stimulus: amplitude, tip and duration.

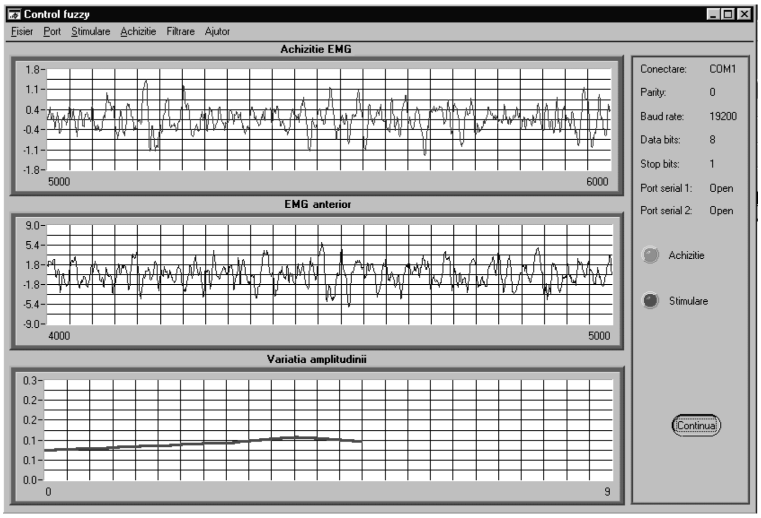

Fig. 7 – User interface

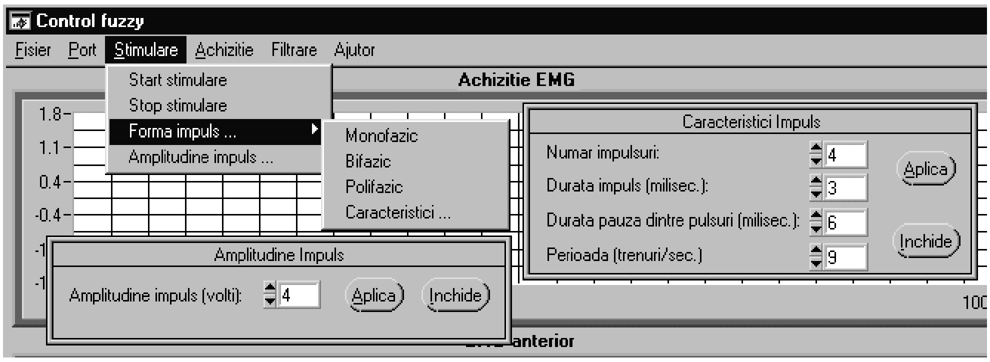

Fig. 8 – User interface

The Fuzzy contrrol application are implemented some digital filter for preliminary processing of EMG signal. This menu are showed in figure 9.

Fig. 9 – Digital filter menu

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