A Flexible Finite State Controller for Upper Limb Functional Electrical Stimulation

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***Abstract*— This paper reports on a flexible finite stage machine (FSM) controller for the real-time control of functional electrical stimulation (FES) during upper limb rehabilitation, and an associated setup Graphical User Interface (GUI) guides clinical users through the process of setting up new FSM controllers for practicing user-defined functional tasks across a range of patients. The FSM control has been demonstrated using the "drink from a cup" example task. The test results illustrate the functionality of the controller and also demonstrate the success of implementation.**

I. Introduction

There is good evidence supporting intensive, task-focused, voluntary-initiated FES-supported practice as a mechanism driving recovery of upper limb function following stroke [1, 2]. However, the ability to deliver this type of therapy in clinical practice is limited by available tools [3-5]. The number of commercially available FES systems for the upper limb is small and most systems provide only a limited number of stimulation channels, with some systems restricted by design to stimulation of particular body anatomy [6-8]. For example, the H200^{TM} stimulation system (Bioness Inc., Santa Clarita, Calif) is limited by design to deliver stimulation to the fingers and wrist and cannot be used to assist movement at more proximal joints. Relatively little attention has been paid to the development of flexible systems which allow the user to set up an FES-controller to suit a particular patient to practice a particular functional task [9, 10].

In this paper, a flexible controller model is presented, which allows the user to generate Finite State Machines to support particular patients, each with their own pattern of impairment, to practice user-defined tasks. The controller delivers the following functionalities:

- It offers the user the ability to specify the number of states and state transition rules governing exit from each phase.
- It can use, as inputs to state transition rules, either time, or data from a range of sensors (button press; angles from sensors located on the upper limb).
- Patient-tailored stimulation channels and stimulation parameters on each of them

An associated graphical user interface has been designed which allows the therapist with little or no programming skills

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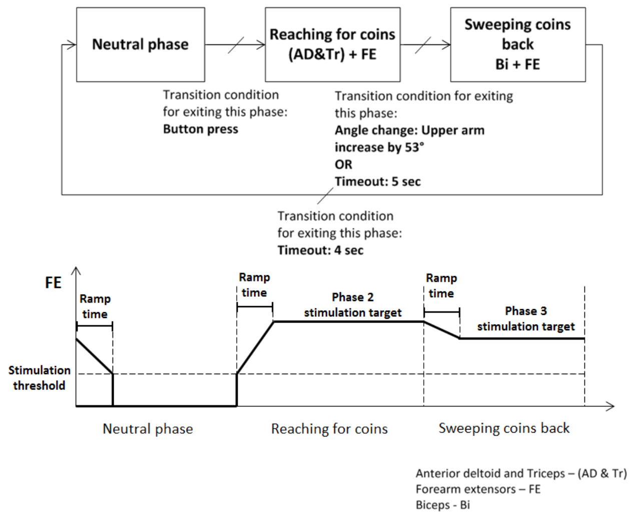

Figure 1. Example FSM: sweeping coins into contralateral hand & stimulation profile for Forearm extensors muscle

to setup FSM controllers bespoke to both the patient's pattern of impairment and task requirements.

II. Methods

A FSM controller is usually composed of a set of states, input signals, output functions, and state transition conditions [11]. In this particular case, each *"state"* corresponds to one movement phase and the state's *"output functions"* implement the ramping of muscle stimulation(s) towards their respective targets (note the target may be zero) and then holding them at those targets. The set of possible *"input signals"* for the FSM controller are button status, clock time and different body segment (e.g. upper arm, forearm) angles from vertical via accelerometer units attached to them [12]. The *"state transition conditions"* implement the conditions for exiting each movement phase. Each of the parameters listed above are defined by the user, depending on the chosen task and the patient's pattern of impairment.

The first phase in the FSM is termed the *"neutral"* phase, which is always associated with no muscle stimulation. The FSM returns to the *"neutral"* phase every time on exiting the last phase. Thus, a functional task will always begin and end in the *"neutral"* phase. The exceptional transitions (i.e. emergency stop) have a higher priority than the normal transitions between successive movement phases.

To illustrate the way in which the flexible FSM controller can be set up for a specific FES task, an example ("Sweeping coins into contralateral hand") is discussed below. Referring to Fig. 1, this FSM has three movement phases; *"neutral"*, *"reaching for coins"*, and *"Sweeping coins back"*. Apart from *"neutral"* phase, each movement phase output function contains a set of muscles to be stimulated and their associated stimulation parameters. For example, in phase 2, to open hand and reach for coins, stimulation is applied to the Forearm extensor and Anterior deltoid and Triceps muscles.

Transitions between phases are instantaneous events that occur on satisfaction of the *transition condition*. In the example, the transition between phase 2 (*reaching for coins*) and phase 3 (*Sweeping coins back*) will be triggered either by the angle of the upper arm increasing by 53° (since entering that phase) or the time period in phase 2 exceeding 5 seconds.

A. Functionality

1) Movement phases and stimulation control

In each movement phase the associated set of muscles are stimulated to achieve the required movement. The stimulation profiles for each phase were computed based on user-defined parameters (i.e. stimulation target, threshold, and ramp time).

The stimulation targets are the stimulation levels that produce sufficient muscle force to achieve the expected movement in a phase. As the force required from a particular muscle will vary across the task, stimulation targets for a particular muscle are likely to vary with phase (see Fig. 1 stimulation profile for FE). If muscles are not already at the required stimulation target, they are ramped up or down to reach that target (which can be zero). Like the stimulation targets, the ramp rates may also be changed to achieve different movements in different phases.

The FSM controller also allows for stimulation to jump to a pre-defined threshold before ramping up. Similarly, when stimulation is stopped, stimulation can jump down to zero after ramping down to a threshold (see Fig. 1 stimulation profile for FE). In this implementation, sensory threshold is used (i.e. the lowest pulse width, at predefined pulse amplitude, needed to elicit a sensory response). Stimulation below the threshold will not lead to any movement or sensation. Each muscle will have its own stimulation threshold that does not change with phase.

Ramp time is another user-defined FES parameter describing the time period over which simulation ramps from its previous target to its new target. The ramp rate is determined from ramp time and two consecutive nodes in the stimulation profile (i.e. either threshold and target or two consecutive targets, see Fig. 1 stimulation profile for FE). Obviously, for a given difference in stimulation levels a smaller ramp time means a higher ramp rate.

2) Transitions

Transitions between phases depend on input signals and the transition conditions for leaving the current phase. The FSM controller, as implemented, can take signals from up to four accelerometers for tracking the movements of the upper limb (i.e. hand, lower arm, upper arm and torso). In this case, the accelerometer provides the *x*, *y* and *z* components of the measured vector in the accelerometer reference frame. The acceleration data are streamed into the FSM controller in real time during a functional task. An angle tracking approach, incorporated into the FSM controller, takes as its input the three signals from a given accelerometer and outputs the absolute angle of that accelerometer's x-axis from the vertical, which can be used to measure upper limb segment angle [12]. Apart from segment angle, transition conditions can also use button press and timeout functions. To extend the flexibility of the system, logical operators (N/A, AND or OR) can be used to combine a maximum of two Boolean conditions (condition A and condition B) to create a transition rule. Using N/A as the logical operator means that only one condition needs to be specified (always condition A).

3) Methods to improve the robustness of angle triggering

In additional to above, we have included a number of methods in the angle triggering algorithm to improve robustness and hence the usability of the system, as following [13],

- Using the change in angle since entering a state rather than absolute angle;
- Ignoring readings where the acceleration vector is significant in comparison to the gravity vector (i.e. the magnitude of the measured vector is significantly different from 9.81);
- Requiring a given number of consecutive or non-consecutive valid readings before triggering a transition.

The aim of such methods is to reduce the number of incorrect transition timings caused by signal noise, jerky arm movements and other negative effects, which lead to poor control of FES during reaching tasks. This is most likely to cause the reaching task to fail when early triggering occurs as the change in arm-segment angle may be insufficient to allow the next movement phase to commence successfully.

B. Implementation

Matlab/Simulink was used to implement the real-time FSM controller under the Windows XP Professional platform. Simulink allows on-line data acquisition, data processing and control of stimulation parameters in real-time. Fig. 2 shows an overview of the FES control system. The real-time inputs to the FSM controller in Simulink include three axis accelerations, button pressing signals, and clock time for timeouts. The real-time outputs are stimulation pulse width (μsec), pulse amplitude (mA) and the waveform. Note that the waveform is fixed and pre-set in the Simulink model, and clinicians have no authority to change this. The Simulink system runs at 20Hz and implements angle tracking, robust angle triggering, the FSM controller, and safety checking.

The FSM controller includes: state transition control; and methods to improve the robustness of angle triggering.

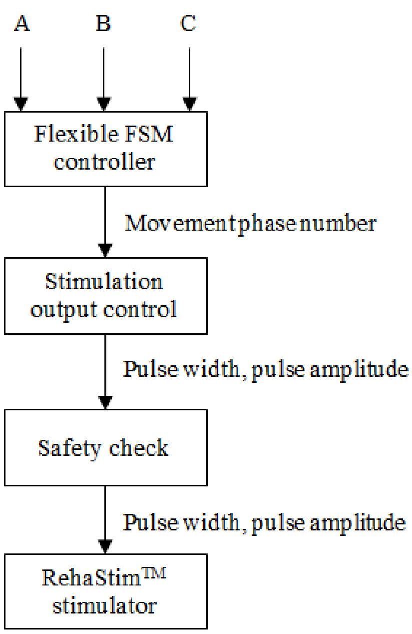

Figure 2. Overview structure of FSM controller (*A = clock time; B = Button status: i. Transion & ii. Emergency stop; C = Signals from accelerometers*)

Stimulation output control simply involves stepping each channel towards its current target at the associated ramp rate (or stepping up to /down from the threshold for that channel). The real-time outputs from the FSM controller (pulse widths and pulse amplitudes) are streamed into the safety check block, which sits between the controller and the Hasomed RehaStim™ stimulator. The purpose of the safety check block is to avoid pain due to inappropriate stimulation levels or rates. The safety block limits pulse width, pulse amplitude, and total charge in a single pulse, as well as maximum step size for ramping. Those limits are pre-set by the programmer in the safety block. There is a separate soft limit for total charge for a channel and user can access and change its value via the setup GUI described below. The soft limit for each channel will be updated and passed to the safety check block each time it is changed. If the demanded step size exceeds the pre-defined maximum step size, then it is limited to the maximum step size. If any other limits are exceeded, then the safety block stops stimulation. Safety checking is applied to every stimulation channel.

A real-time synchronization block has been used to ensure a Simulink execution frequency of ~20 Hz. It achieves this by synchronizing the Simulink FES control system with the computer's real-time clock. A Stimulator interface block, also built in Simulink, is responsible for accessing the RehaStim™ stimulator. Both real-time synchronization and Stimulator interface blocks were created by Hasomed GmbH.

C. setup GUI

A Graphical User Interface (GUI) has been developed in Matlab to guide clinical users through the process of setting up new FSM controllers.

The GUI concept is to break the setup of a FSM for a particular upper limb functional task into the four logical stages:

- Selection and/or modification and/or creation of activities
- Donning of electrodes and sensors and setup of channels
- Setup of stimulation parameters for each movement phase and collection of data from each successful attempt to inform user's choices in stage 4. The user labels each successfully achieved attempt as a *good trial*. For these "*good trials*", data from each of the sensors will be captured (change in angle of each instrumented body segment since entering the phase), as well as time spent in each phase. The captured data from the set of *good trials* are averaged and passed as suggested values to stage 4.
- Setup of automatic transition conditions ("Transitions") for moving between movement phases

D. Experimental setup

The implementation of the FSM controller was demonstrated using a user-defined task, termed "drink from a cup" (see Fig. 3). One healthy subject participated in this study. The subject was required to reach for a cup, grasp it, lift the cup to the mouth, replace the cup and release it (see Fig. 3). Before execution of this task, the subject sat at a table with his right hand comfortably placed on the table at the starting position.

Before running the FSM controller, the Xsens Motion Tracking software was installed (Xsens technologies B.V., Netherlands, version 2.8.1), which provides a solution for directly accessing the Xsens MTx communications hub from Matlab. After installation, Matlab can communicate with the Xsens MTx hub through the serial port and collect real-time acceleration data from the Xsens inertial sensing units that are connected to the MTx hub. The Xsens system was set up to sample the real-time accelerometer signals at a frequency of 100 Hz even though the FSM controller only attempts to upload data at 20 Hz, which is thought to be sufficiently high to prevent users noticing any latency. This was done to avoid the FSM controller missing or double reading any Xsens data.

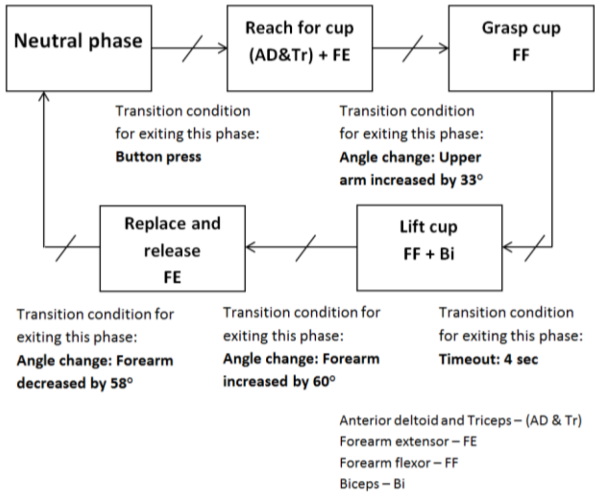

Figure 3. Example FSM controller for "drink from a cup"

TABLE I. STIMULATION TARGETS (μSEC) FOR EACH CHANNEL AND EACH PHASE

Muscle groups	Neutral	Reach for cup	Grasp cup	Lift cup	Replace & release
FE	0	50	0	0	47
AD & Tr	0	58	0	0	0
FF	0	0	40	37	0
Bi	0	0	0	38	0

The parameters which define the example task (see Fig. 3) were set up using the GUI discussed earlier in the paper. The number of phases, the muscles involved in each phase, and the transition conditions are all shown in Fig. 3. The "stimulation targets" are given in Table I. All ramp times for each channel and each phase were set to 1 second. The "stimulation threshold" and "maximum stimulation for comfort" were set to their default values, which are 0 μs and 360 μs respectively. The pulse amplitudes are treated as fixed parameter and the value is set to 30 mA. This is because RehaStim™ stimulator provides better resolution for pulse widths than that of pulse amplitudes. Thus, the pulse width being used to create the varying stimulation profiles (see Fig. 4 c). Surface electrodes were applied on the set of muscles involved in this task.

III. TEST RESULTS FOR THE "DRINK FROM A CUP" TASK

Data was collected from a healthy subject undertaking the "drink from a cup" task. The outputs monitored included:

- Phase number;
- Change in angle from the vertical since entering a state (movement phase);
- Pulse width for each muscle.

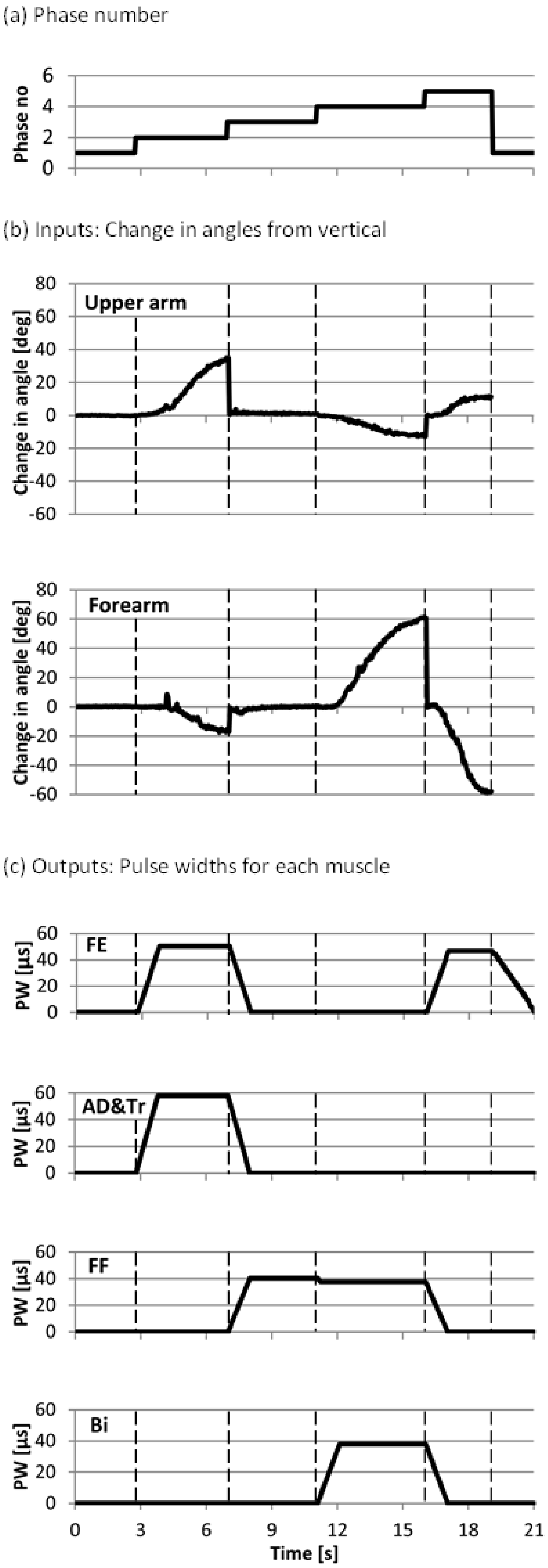

Figure 4. The outputs from FSM controller during the "drink from a cup" task: (a) phase number; (b) "Change in angle since entering the phase" of upper arm and forearm; (c) Stimulation pulse widths for each muscle

The data was captured under real-time conditions and the dashed lines in figure 4 indicate the transitions between the phases. To enable angle-triggering, two Xsens units were located on the upper arm and the forearm respectively and they were approximately aligned with the x-axis oriented along the body segments' long axis. Using the angle tracking approach mentioned earlier in this paper, the acceleration data from the two Xsens units were transformed into "change in angle since entering a phase" of upper arm and forearm respectively (see Fig. 4 b for one repetition of the task). The change in angle returns to zero after each transition between phases.

Fig. 4 a shows the phase number was increasing, from one to five, as the "drink from a cup" task progresses. The phase number was output in real time.

The Fig. 4 c shows the stimulation pulse width outputs to RehaStim^{TM} stimulator for each channel. On entering a new phase, the stimulation pulse widths ramp towards the new targets at rates based on 1 second ramp times. The pulse width on FF ramps towards the target for phase "lift arm" under 0.15 second. This is because there is a lower limit of 1 µs/ step implemented for ramp rate.

IV. Discussion and Conclusions

This paper reports on a flexible FSM controller for upper limb FES applications. The aim was to provide a tool that allows clinicians to set up a variety of different FES assisted tasks for different patients with different levels of impairment by using the setup GUI. The controller has been demonstrated using the "drink from a cup" example task and the test results demonstrated its successful implementation.

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