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Development of a Software for the Control of a Hybrid FES–Robotic Orthosis for Upper Limb Rehabilitation

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Abstract— **Stroke can lead to upper limb impairments. However, due to the brain's neuroplasticity, the upper limb's motor skills may be recovered through hybrid robotic rehabilitation systems. This study presents a software architecture to control a hybrid FES-robotic orthosis, whose function is to rehabilitate the upper limbs of individuals with post-stroke hemiplegia. A software was developed to integrate the equipment different drive system in order to control two modules: the elbow module controlled by the motor and the hand module controlled by FES. The software was divided into three layers with different functionalities. The open loop control is based, for each functional task, on a predefined sequence of actions to be executed in a given time. The result is a modular software, which is flexible enough to accept future expansions focused on specific patient needs.**

Keywords— **Software architecture, upper limb rehabilitation, Hybrid FES-Robotic Orthosis, stroke, hand control.**

I. Introduction

According to the World Health Organization [1], stroke occurs when there is obstruction or rupture of the cerebral blood vessels and affects 13 million people per year worldwide [2]. Stroke can lead to several neurological impairments, one of which is motor impairment [3], with the upper limbs usually being the most severely affected [4]. Robotic therapy is a new form of rehabilitation in which a robot [5] increases the intensity and regularity of treatment [6]. Several articles, including current systematic reviews [7]-[13] evaluate the effects of robotic therapy on functional performance in individuals with motor deficits caused by stroke. The most recent systematic review of this subject, by Mehrholz et al. [14], states the potential for improvement in activities of daily living, arm function, and muscle strength of individuals affected by a stroke with electromechanical training.

Another technological resource for rehabilitation is Functional Electrical Stimulation (FES), which artificially activates muscles through a series of electrical stimuli with a specific duration (pulse width), frequency, and current intensity. The improvement in movement control through muscle activation directly [15] also contributes to the activation of compromised neural connections, then the motor function of the limb affected by the stroke can be recuperated [16][17]. Hybrid FES-Robotic Rehabilitation Systems (HRRS) combine these two technology (robotic therapy and FES) in a single system, thereby increasing the probability of rehabilitating stroke patients. The addition of FES to robotic assistance contributes to reducing the equipment weight and greater control of the movements through an appropriate sequence of direct activation of the paretic muscles [18]-[20].

In the last few years, there has been a significant increase in the number of HRRS. However, most of the devices are only in the early stages of development and there is no commercially available equipment [4]. Moreover, the developed equipments often employ unfavorable materials and aesthetics for rehabilitation (most are bulky and heavy), making portability difficult or impossible, significantly interfering with the ability to perform activities of daily living[21]-[25]. Thus, developing new equipment with low weight, volume, aesthetically pleasing, portable, and with high technological performance is necessary.

A portable robotic orthosis was developed for upper limb rehabilitation of individuals affected by stroke: Pinotti Portable Robotic Exoskeleton (PPRE), described in previous articles [26]-[28]. In this paper, we present an improvement on that orthosis, transforming it into a hybrid device, simplifying the mechanical structure, decreasing the volume and weight and increasing the number of movements provided. We developed a software to integrate the different orthosis

drive systems (motor and FES). This work aims to develop the software, in a modular way, flexible to be expanded in the future.

II. Methodology

The HRRS in Fig. 1a comprises two modules (elbow and hand module). The elbow module performs elbow flexion and extension powered by a DC motor (Maxon Motors™, Switzerland). The hand module performs flexion and extension from 2nd to 5th finger, thumb extension, thumb adduction, abduction with thumb opposition, enabling palmar grip and lateral pinch triggered by FES using a commercial electrical stimulator Hasomed (RehaStim™, Germany) with 8 channels. The objective of the HRRS is to rehabilitate the upper limbs of individuals affected by stroke, through the repetition of several movements involving the elbow and hand. Due to the neuroplasticity property of the brain, the tendency is to recover the movement of the upper limb.

A software was developed using Python 3.9 to control the different drive systems of the hybrid orthosis, called the HRRS Controller Program. It receives the information from a Graphical User Interface (GUI), decode the commands, and control the actuators (elbow and hand module). Two serial communications channels were used so that one of them transmit the command to the elbow module and the other transmit the command to the hand module, as shown in Fig. 1b.

In the elbow module, the parameters related to the elbow flexion angle and drive speed are received through a serial communication, between the HRRS Controller Program and an Arduino. The Arduino transmit the parameters to an Bluetooth module HC-05, which is paired with an another Bluetooth module the HC-06. The last module transmit the parameters to a Microcontroller responsible to control the mechanical actuator, that performs the flexion and extension of the elbow.

In the hand module, the serial communication transmit the frequency, amplitude, and pulse duration parameters to

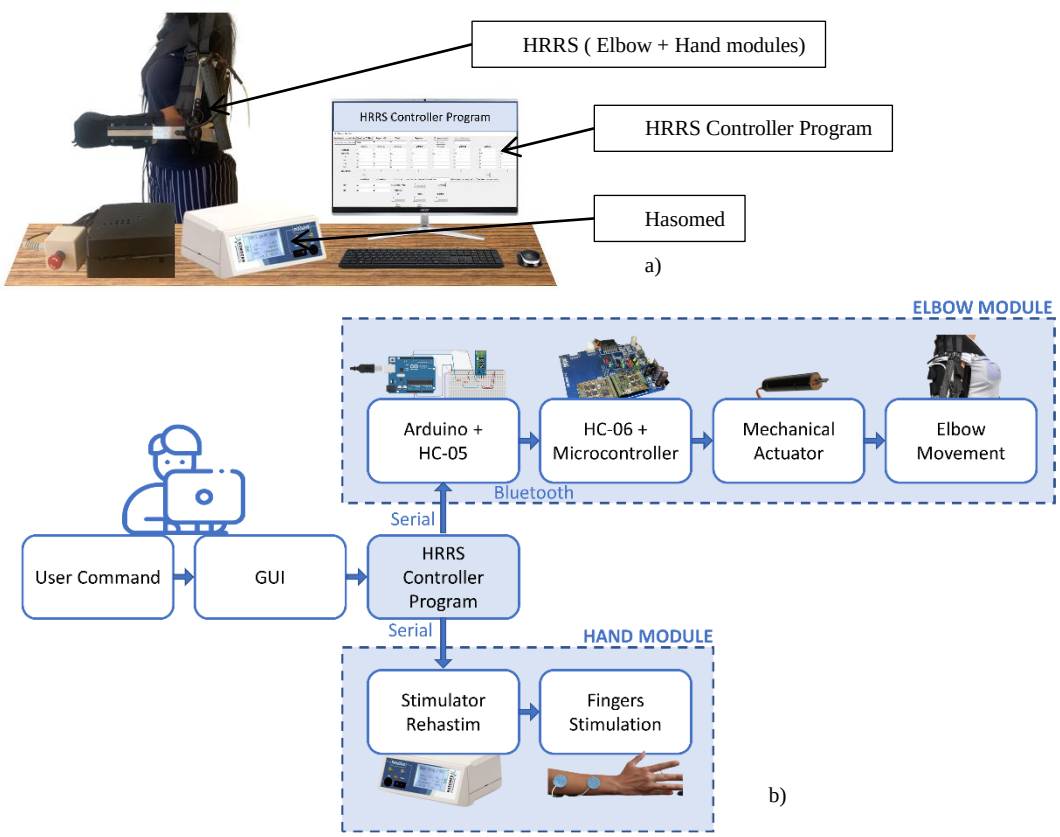

Fig. 1 a) HRRS adapted from [29], composed by Orthosis, HRRS Controller Program and Electrical Stimulator b) System architecture of HRRS adapted from [29], elements of HRRS: GUI, HRRS Controller Program, Hand Module and Elbow Module

the electrical stimulator. Finally, A GUI was used for set-

ting all needed parameters for the orthosis activation. This communication between the GUI and the HRRS Controller Program uses a WebSocket. To develop the program's architecture, three layers were used with different functionalities: Top Layer, Intermediary Layer, and the Bottom Layer. Fig. 2 details the system block diagram, in which the layer division can be seen.

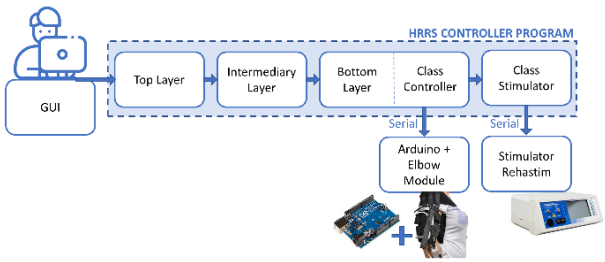

Fig. 2 Diagram Block of the Controller program, based in layers (Top Layer, Intermediary Layer, and Bottom Layer), Elbow Module, and Electrical Estimulator

The Top Layer configures the COM ports for serial communications with the stimulator and the elbow module, First, it starts a WebSocket with an IP address corresponding to localhost and TCP port 4444 to receive a command from the GUI asynchronously. Then it compiles the following information: frequency, pulse width, current amplitude, elbow angle, time open hand(TOH), time closed hand(TCH), and time closed elbow(TCE). The last three parameters are related to the time in which the hand must be in the open or closed position, and the time in which the elbow must be flexed, respectively. After decoding this command, the program switches to an appropriate function of the Intermediary Layer.

The Intermediary Layer configures the Controller Class, present in the Bottom Layer. This Class performs the control activating the elbow module or the electrical stimulator at the appropriate time. The Controller Class configuration is performed through various functions in the Intermediary Layer, each function represent a specific type of movement that the HRRS can perform, these movements can be of two categories, Familiarization, and Functional Training.

The Controller Class has attributes that store the activation (Ton) and deactivation (Toff) times of the elbow module of each channel used in the electrical stimulator. In this way, control by time occurs by performing the movement of the fingers by electrical stimulation and/or movement of the elbow by motor, according to the set time.

The movement routines allow activation of the elbow and fingers individually and simultaneously and have been programmed in two different categories, as previously described: Familiarization and Functional Training.

The Familiarization category consists of isolated movements. A maximum of 7 can be chosen (flexion or extension of the 2nd to 5th finger, thumb extension, thumb adduction, abduction with thumb opposition, elbow flexion and elbow extension) to be performed in sequence, but not simultaneously. The entire sequence can be repeated.

In the Functional Training category, the exercises performed enable reaching, grasping, holding, releasing, and moving objects to and away from the user's face. Unlike the first category, the hand and elbow module movements can happen simultaneously. Each Functional Training or Familiarization exercise has a specific order in which the channels are activated. The Intermediary Layer then fills in the Controller Class attributes that store the activation and deactivation times of each channel of the hand and elbow modules, forming is the so called movement routine.

III. Results

The software was tested in a simulated environment, with messages showing its status. Fig. 3 shows the GUI used for tests. Ton1 and Toff1 correspond to the first time a

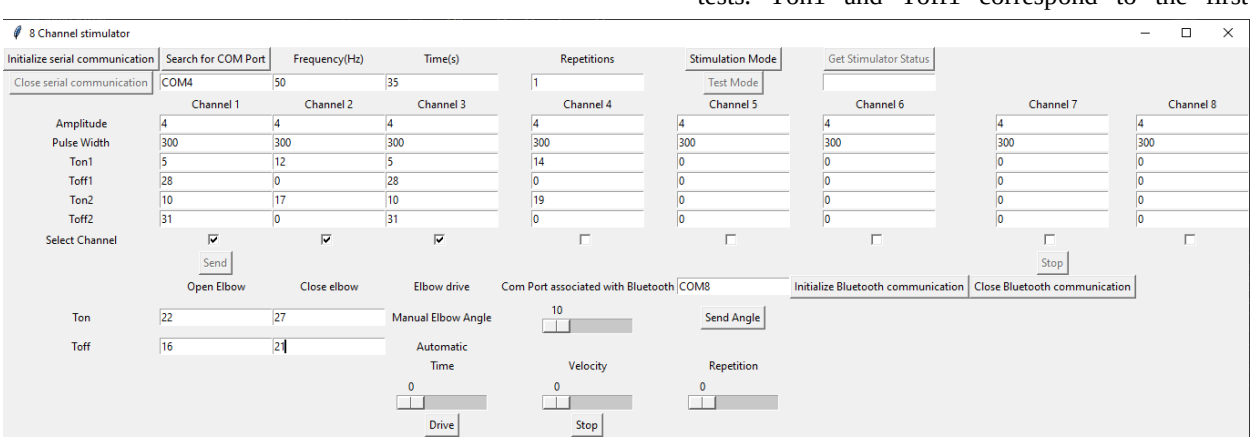

Fig. 3 Python GUI with Tkinter used for tests

```
PROBLEMS    OUTPUT    TERMINAL    JUPYTER    DEBUG CONSOLE

stimulation initiated...
thread initiating stimulator
initializing... 0
Frequency:  50
channel:  5
updating Ton1... width:  [10, 0] amplitude:  [10, 0] Active Channels Ton1:  [5, 5]
updating Ton1... width:  [10, 10] amplitude:  [10, 10] Active Channels Ton1:  [5, 5]
updating Toff1... width:  [0, 10] amplitude:  [0, 10] Active Channels Toff:  [10, 10]
updating Toff1... width:  [0, 0] amplitude:  [0, 0] Active Channels Toff:  [10, 10]
stopping
Finished
end Functional Open Hand
```

Fig. 4 Functional Training Open Hand one example result

```
updating Ton1... width:  [10, 0, 0, 0] amplitude:  [5, 0, 0, 0] Active Channels Ton1:  [5, 9, 5, 11]
updating Ton1... width:  [10, 0, 10, 0] amplitude:  [5, 0, 5, 0] Active Channels Ton1:  [5, 9, 5, 11]
updating Toff1... width:  [10, 0, 0, 0] amplitude:  [5, 0, 0, 0] Active Channels Toff:  [8, 12, 8, 14]
updating Toff1... width:  [0, 0, 0, 0] amplitude:  [0, 0, 0, 0] Active Channels Toff:  [8, 12, 8, 14]
updating Ton1... width:  [0, 10, 0, 0] amplitude:  [0, 5, 0, 0] Active Channels Ton1:  [5, 9, 5, 11]
updating Ton1... width:  [0, 10, 0, 10] amplitude:  [0, 5, 0, 5] Active Channels Ton1:  [5, 9, 5, 11]
updating Toff1... width:  [0, 0, 0, 10] amplitude:  [0, 0, 0, 5] Active Channels Toff:  [8, 12, 8, 14]
updating Toff1... width:  [0, 0, 0, 0] amplitude:  [0, 0, 0, 0] Active Channels Toff:  [8, 12, 8, 14]
updating Ton2... width:  [10, 0, 0, 0] amplitude:  [5, 0, 0, 0] Active Channels Ton2:  [15, 0, 15, 0]
updating Ton2... width:  [10, 0, 10, 0] amplitude:  [5, 0, 5, 0] Active Channels Ton2:  [15, 0, 15, 0]
updating Toff2... width:  [0, 0, 10, 0] amplitude:  [0, 0, 5, 0] Active Channels Toff2:  [18, 0, 18, 0]
updating Toff2... width:  [0, 0, 0, 0] amplitude:  [0, 0, 0, 0] Active Channels Toff2:  [18, 0, 18, 0]
stopping
Finished
```

Fig. 5 Functional Training Catch and Release or Catch and Hold one example result

particular channel or elbow module was activated and deactivated, and Ton2 and Toff2 correspond to the second time a particular channel or elbow module was activated or deactivated. All messages were printed correctly, as per the command sent, demonstrating the correct functioning of the system.

Figures 4, 5 and 6 correspond to the software validation. It was performed by monitoring the motor and electrical stimulator channels activation time on a terminal in the IDE Visual Studio Code.

Channel 1 corresponds to the extension of the 2nd to 5th fingers, channel 2 to the flexion of the 2nd to 5th fingers,

```
updating Ton1... width:  [0, 0, 10, 0] amplitude:  [0, 0, 5, 0] Active Channels Ton1:  [5, 12, 5, 14]
updating Ton1... width:  [10, 0, 10, 0] amplitude:  [5, 0, 5, 0] Active Channels Ton1:  [5, 12, 5, 14]
updating Toff1... width:  [0, 0, 10, 0] amplitude:  [0, 0, 5, 0] Active Channels Toff:  [10, 16, 10, 18]
updating Toff1... width:  [0, 0, 0, 0] amplitude:  [0, 0, 0, 0] Active Channels Toff:  [10, 16, 10, 18]
updating Ton1... width:  [0, 10, 0, 0] amplitude:  [0, 5, 0, 0] Active Channels Ton1:  [5, 12, 5, 14]
updating Ton1... width:  [0, 10, 0, 10] amplitude:  [0, 5, 0, 5] Active Channels Ton1:  [5, 12, 5, 14]
updating Toff1... width:  [0, 0, 0, 10] amplitude:  [0, 0, 0, 5] Active Channels Toff:  [10, 16, 10, 18]
turning on elbow command to close Ton close Elbow:  16
updating Toff1... width:  [0, 0, 0, 0] amplitude:  [0, 0, 0, 0] Active Channels Toff:  [10, 16, 10, 18]
turning off elbow command to close Toff Close Elbow:  19
turning on elbow command to open Ton Open Elbow:  20
turning off elbow command to open Toff Open Elbow:  25
updating Ton2... width:  [10, 0, 0, 0] amplitude:  [5, 0, 0, 0] Active Channels Ton2:  [26, 0, 26, 0]
updating Ton2... width:  [10, 0, 10, 0] amplitude:  [5, 0, 5, 0] Active Channels Ton2:  [26, 0, 26, 0]
updating Toff2... width:  [10, 0, 0, 0] amplitude:  [5, 0, 0, 0] Active Channels Toff2:  [29, 0, 29, 0]
updating Toff2... width:  [0, 0, 0, 0] amplitude:  [0, 0, 0, 0] Active Channels Toff2:  [29, 0, 29, 0]
stopping
Finished
end of Functional moviment, bring object to face, palmar grip
```

Fig. 6 Functional Training Bring Object to Face one example result

channel 3 to thumb extension, channel 4 to the abduction with thumb opposition, and channel 5 corresponds to the thumb adduction.

For a better understanding of how the time control was performed, a flowchart was created and shown in Fig. 7. Regardless of which task must be performed, it can be repeated as many times as the user has chosen and corresponds to the outermost loop of the flowchart. The innermost loop checks when an actuator should be activated through conditional statements that compare the current time with the times Ton and Toff of each actuator. This check occurs until the task's total time is reached. The actuators are up to 8 channels of the electrical stimulator or the mechanical actuator of the elbow module. The algorithm is the same regardless of the actuator type, and they were named "Ak" in the flowchart. The task of each channel of the electrical stimulator is executed in orthosis to perform fingers flexion and extension.

The experiment was not performed with humans or animals, all test were performed on the bench and the results were obtained through the terminal, in this way, the research followed in an ethical way.

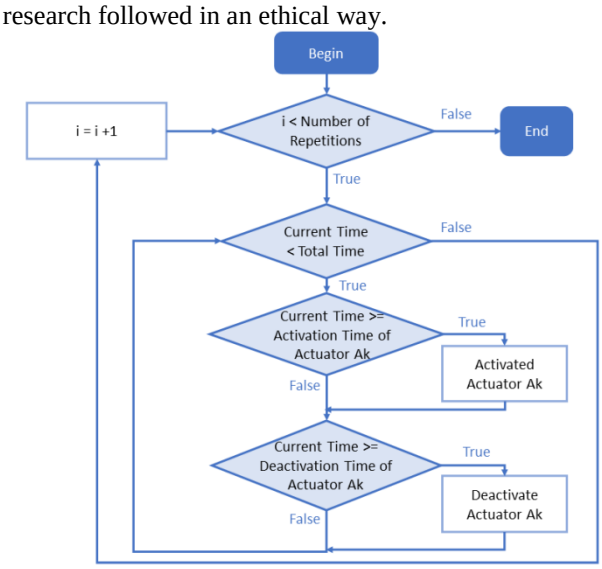

Fig. 7 Flowchart for the description of the time control algorithm, the variable "i" is the repetition counter, "Ak" is the kth actuator

IV. Discussion

The results showed that it was possible to control the elbow module with the mechanical actuator and the hand module by electrical stimulation in the simulated environment. In addition, the movements were activated at the correct time as configured by the Ton and Toff parameters.

The division of the program into several layers made it modular enough so that the implemented system has the advantage of easy addition of new resources. For example,

one can create a new function that configures the Controller Class to correctly perform the desired functional task, including a new movement routine, adding few lines of code.

The advantage of the software regarding the creation of new functional tasks, including personalized exercises, according to the user's level of motor impairment was achieved. Furthermore, complexity was managed through hierarchy (a division of the system into modules) and modularity (modules have well-defined functions and interfaces) [30].

A disadvantage is that the control is based on comparing the current time with the predefined times inside a loop, delays caused by desynchronization can happen, and because of this a strategy based on interruptions might be more adequate. Another limitation of the predefined time control is related to the possible interference in the grip of objects. If the finger extension period is too short, for example, there may not be enough time to position the hand around the object. On the other hand, if it is too long, the user will have to wait a long time to flex the fingers and grasp the instrument [29]. Thus, to avoid this, the time-based control should ideally be replaced or complemented with a user intent recognition system such as in [31], where inertial sensors were used to capture residual body motions and command devices by individuals with tetraplegia.

V. Conclusions

A software was developed to control an HRRS, developed to rehabilitate individuals with post-stroke hemiplegia. It has the advantage of allowing the creation of additional exercises due to the use of the hierarchy, and modularity of the program. It could also be easily adapted to other assistive devices.

Future experiments and more studies can be carried out to implement interruptions to control the time more precisely and add a system that detects the user's intention.

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Conflict of interest

The authors declare that they have no conflict of interest.

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