Electronic platform for control algorithms evaluation of a four-parallel actuator upper limb prosthesis

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Abstract—**This paper presents the development of an electronic platform that helps in the design and implementation of control algorithms for a robotic arm developed by CINVESTAV, Mexico and aimed for amputees above the elbow. The system includes four BLDC (Brushless Direct Current) motor driver boards, four motion control system boards, one general control system board, one dual switched power source, one Lithium ion (Li-Ion) battery charger, one four-cell Li-Ion battery pack, and a linear power source for battery charger. An open loop algorithm was applied using I^2C (Inter-Integrated Circuit) communication protocol between digital subsystems, which allowed the execution of flexion and extension movements in the prosthetic arm.**

Keywords-algorithm; control; evaluation system; parallel actuator; parallel control; upper limb prosthesis.

I. INTRODUCTION

The last decade represents an outstanding increase in upper limb prosthetics research [1] which seeks to obtain the natural performance of the human limb. One of the most used techniques in prosthetic control is proportional myoelectric control [2]. There are several works focused on finding techniques to obtain electromyographic signals from targeted muscle reinnervation [3] or via implanted electrodes [4]-[6]. Such techniques increase the need of advanced prosthetic control systems.

Technological advances have led researchers in this area apply various theories and processing methods on EMG signals having as main objective the improvement of control strategies for artificial limbs.

The Bioelectronics division in CINVESTAV began a project to develop upper limb prosthesis for patients with amputation above the elbow. On 2002, Escudero [7] designed a first version of this prosthetic arm with four active degrees of freedom (DOF) for replacement above the elbow.

Different works on the CINVESTAV's prosthesis have been done [8]-[12] and have represented several improvements mainly related to the prosthesis control [11], [12]. These control strategies have been implemented on electronic systems designed by each author. Even though the hardware designs were dependent of the available technologies at the time, they have set an important precedent for future versions.

The present prosthetic arm has four parallel axial actuators built with BLDC servomotors which allow it to lift up to 7 kg at a 54% maximum efficiency [8], [9]. In spite of the parallel configuration, the designed control hardware has been implemented with sequential digital systems such as microcontrollers (μCs). The advantages of applying simultaneous control on each actuator have been exposed in [13], [14] which posed sharper movements and DOFs control, as well as an increase in available lifting capacity. Although the results have been promising, the methods have not been applied on commercial prostheses [1].

This paper presents the design of an electronic platform for evaluation of control algorithms over the four active DOFs prosthesis developed by CINVESTAV.

The proposed system offers the possibility to control independently each actuator that constitutes the artificial limb via the serial communication protocol I^2C.

II. DEVELOPMENT

A. Applied solution

Each prosthetic development involves multidisciplinary research topics which can be unified by creating a scheme that groups the objectives based on their methodology.

Losier [15] proposed in 2009 an eight-layer functional model (Fig. 1) about the prosthesis control. Each layer represents the main functions of the control system as a whole. These layers are framed in three functional categories: 1) preprocessing, 2) intent interpretation, and 3) output. These categories are defined by [1] as follows:

Preprocessing (Layers 1-3) is the collection of information from the human user. Its implementation includes sensors and signal processing.

Intent interpretation (Layers 4-5) is the interpretation of user intent from the available information captured in the previous layer.

Output (Layers 6-8) is the implementation over the actuators of the decisions made in the previous layer.

Based on this model, the shadowed area in Fig. 1 shows the proposed location of the presented platform. This system fits in the *output* category because it allows applying movement control algorithms on the prosthesis's actuators. It is implied that the myoelectric signals for the prosthesis control have been previously processed. The codification of the myoelectric signal into digital words can be used to determine the function of each of the actuators by calling a dedicated routine for the task.

While the feedback referred by Losier's model could involve a sensory return to the human user, the feedback used for this platform is applied to the control system.

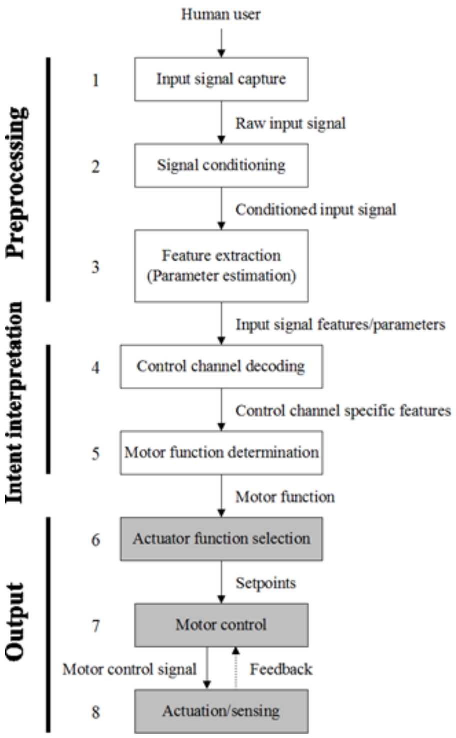

Figure 1. Augmented version of the model proposed by Losier [15]. The evaluation platform is located in shadowed area. This figure is licensed under a Creative Commons BY-NC-SA license.

B. *System overview*

Fig. 2 shows the block diagram of the proposed solution to control the prosthesis developed in CINVESTAV.

The platform is constituted by the following subsystems:

Four *BLDC (*Brushless Direct Current*) motor driver* boards, aimed to generate three switched voltages for BLDC motor coils.

Four *motion control system* boards that receive each motor function in a code using the I^{2}C protocol in master/slave mode. This system is in charge of decoding, generating and sending the appropriate control signals to each *brushless motor driver* board. It has an expansion analog input port that allows the board to receive the feedback signal from a position sensor. Due to the tasks performed by both previous and current blocks, it is possible to locate them in the 7th layer of Losier's model.

One *general control system* board aimed to encode and send the functions to be performed through I^{2}C bus. It has analog and digital expansion ports that allow inserting preprocessed signals from a myoelectric acquisition system.

One PIC *microcontroller programmer* that is essential for loading the hexadecimal file into each microcontroller.

One *dual step-down buck converter power source* based on one integrated circuit (IC) capable of generating two voltages within the maximum electrical values allowed by the evaluation platform.

One *Li-Ion battery charger* based on an IC and capable of recharging a battery with up to four Li-Ion cells.

One *Li-Ion battery pack* with four cells that serves as the main energetic resource for the evaluation platform.

One *linear power source for the battery charger* used for generating the recharging voltage and current needed by the lithium ion battery charger.

Losier's model 8th layer is composed by the prosthesis's motors and sensors that detect the position of each one of them.

C. *Subsystem description*

In order to allow individual system performance, the evaluation platform has been constructed in a modular way (Fig. 3).

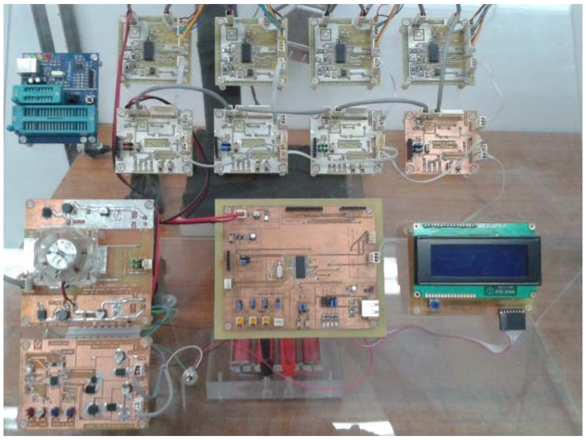

Figure 3. Evaluation system mounted on acrylic platform. The prosthesis's actuators are connected to the BLDC motor driver boards.

Each subsystem of the electronic platform is showed in Fig. 4 and described as follows.

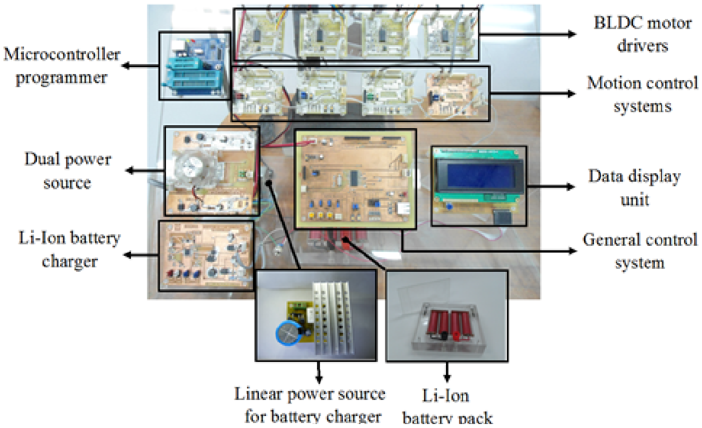

Figure 4. Location of blocks on the evaluation platform.

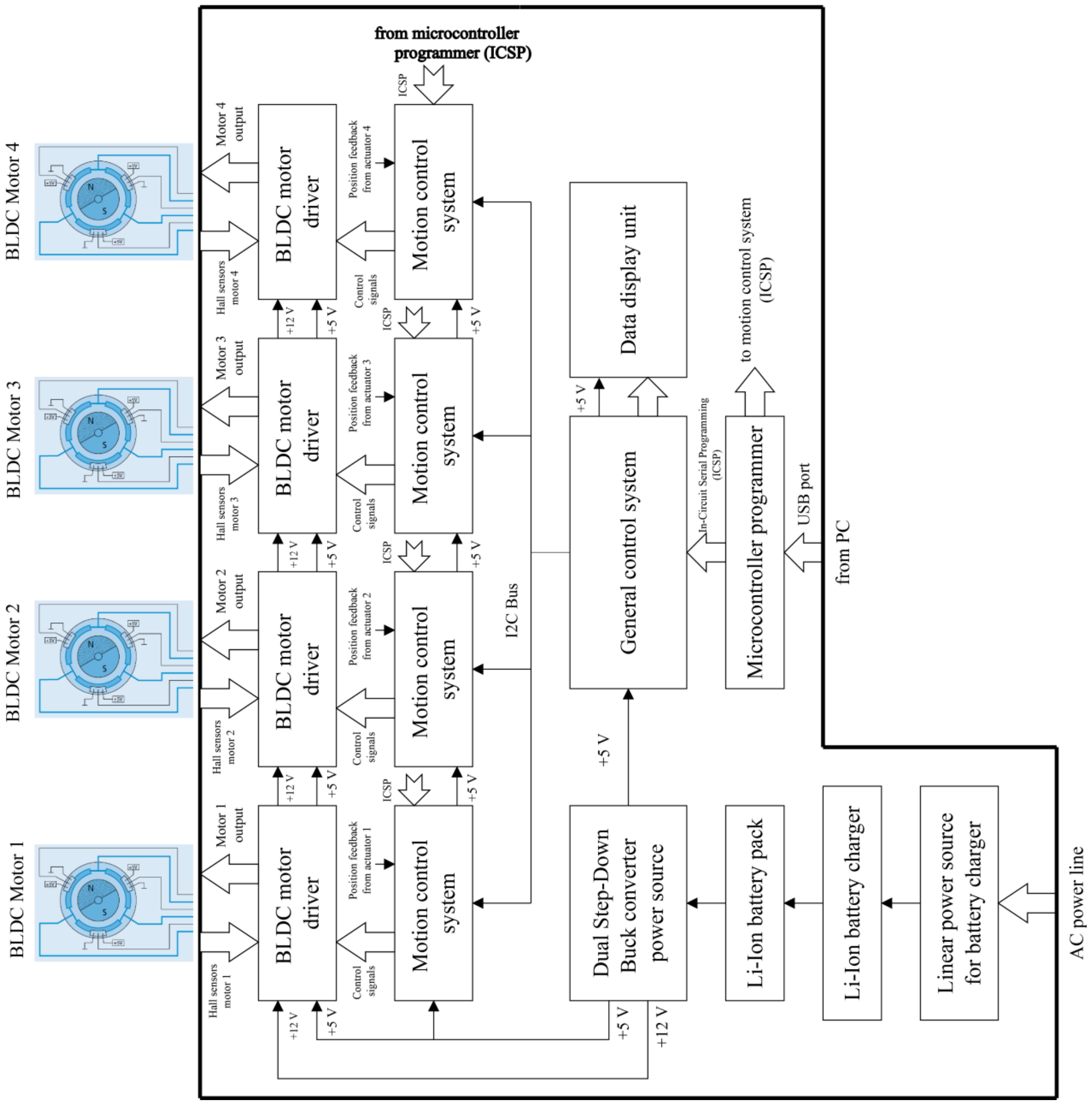

Figure 2. Block diagram for the algorithm evaluation platform. Includes the terminology corresponding to each block and connection lines.

BLDC motor driver (Fig. 5) is based on a three-phase BLDC motor driver L6235, from STMicroelectronics, which has internal Hall-effect sensors decoding logic. This makes it able to generate the switched voltages for the three motor phases. It is possible to activate the motor using three control signals:

Enable. A PWM (Pulse Width Modulated) signal with fixed frequency must be entered through this pin in order to control the spin speed of each actuator.

Brake. To hold on the brake a low logic level must be used at this input pin. A high logic level will release the brake.

FWD/REV. A high logic level establishes forward motor spin whilst a low logic level set reverse motor spin.

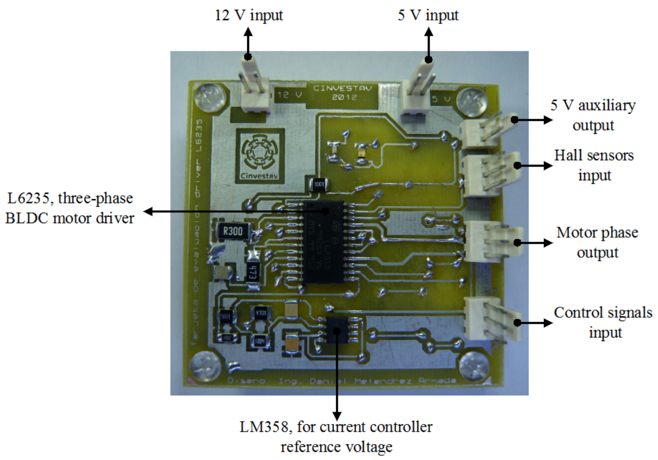

Figure 5. Brushless motor driver board.

The system has three motor connection ports: one for Hall-effect sensors' polarization, another from where sensors' pulses are received, and the last one to connect motor phases.

Motion control system: It is a programmable slave system aimed to send control signals to *brushless motor driver*. Fig. 6 shows a visual description of this board. It executes the control commands through a Microchip's microcontroller PIC18F2550 (located on the back side of the board). The communication with *general control system* is achieved using serial protocol I^2C. A hexadecimal address must be assigned to each slave in order to receive movement commands for its corresponding actuator in the prosthesis.

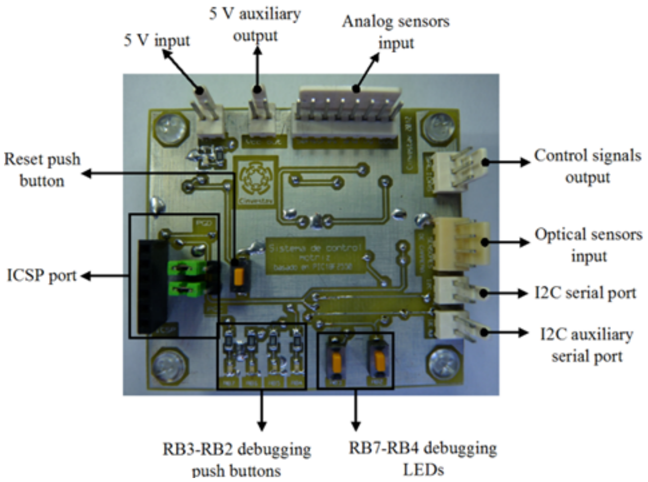

Figure 6. Detailed sections of the motion control system upper view.

General control system: is the programmable system in charge to generate each actuator codes and send them to each *motion control system* through I^2C port. It has a PIC18F2550 µC. Fig. 7 shows with detail the current sections of the design.

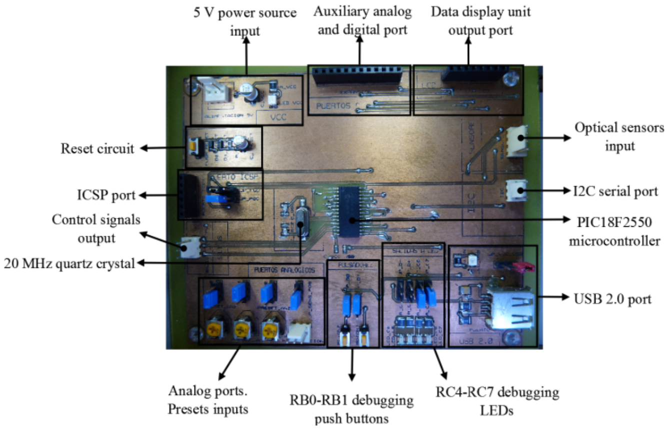

Figure 7. Detailed sections of the general control system.

The system includes debugging elements such as an analog input port useful for microcontroller's 10 bit ADC (Analog to Digital Converter) performance evaluation, push button inputs, and LED (Light-Emitting Diode) outputs. It includes external connections as well such as a USB (Universal Serial Bus) 2.0 intended to give the platform a custom virtual user-PC interface, an auxiliary output port to access directly the six PIC analog ports, and four PIC digital ports. Finally, it contains an output port in order to attach the *data display unit* board.

The I^2C protocol is used to send independently each motor action coded in eight bit words. This feature gives a novel way of controlling the actions performed by the prosthesis in contrast with the sequential activation used previously. Since the serial transmission speed is 100 kHz, actuators response could be considered to be virtually parallel.

It has an ICSP (In Circuit Serial Programming) port in order to load the hexadecimal programming file into the microcontroller.

Data display unit: It is the block that supports an alphanumeric LCD (Liquid Crystal Display) useful to display information defined by the programmer.

Dual step-down buck converter power source: It is designed to generate two fixed voltages: 5 V and 12 V from a 14.8 V battery voltage (Fig. 8). Such voltages are configured using the IC LM2717-ADJ, manufactured by Texas Instruments. This circuit has two step-down buck converters. The 5 V output can deliver up to 2 A, while the12 V output can deliver up to 3 A.

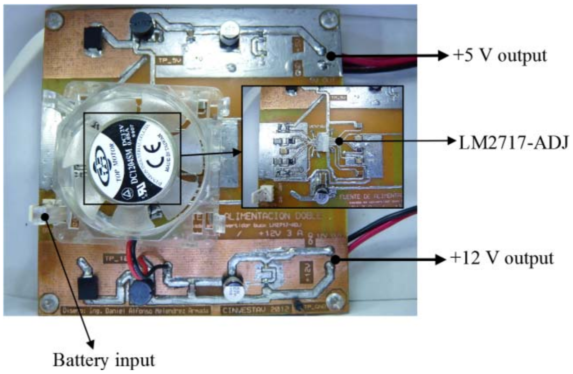

Figure 8. Detailed sections of the dual step-down power source.

Li-Ion battery pack: It is conformed by four Li-Ion cells placed in series, model number 18650. Each cell is capable of providing 3.7 V and delivering up to 2200 mA per hour.

Li-Ion battery charger: It is a system managed by a circuit manufactured by Maxim (MAX745). It consists of a *switch-mode Lithium ion battery charger.* This system was designed to charge up to four cells in series with a maximum current equal to 2 A The charger uses an IRF7303 N-Channel MOSFET as power switch (Fig. 9).

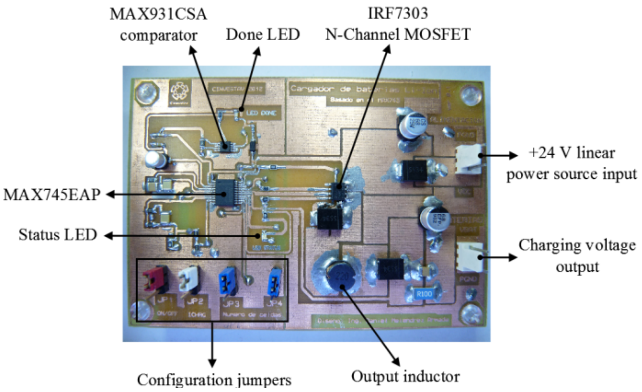

Figure 9. Main sections of the Li-Ion battery charger.

Linear power source for battery charger: It is a regulated power source able to provide a fixed voltage of 24 V and a maximum current of 2 A. It is based on the linear regulator L7824CV manufactured by STMicroelectronics (Fig. 10).

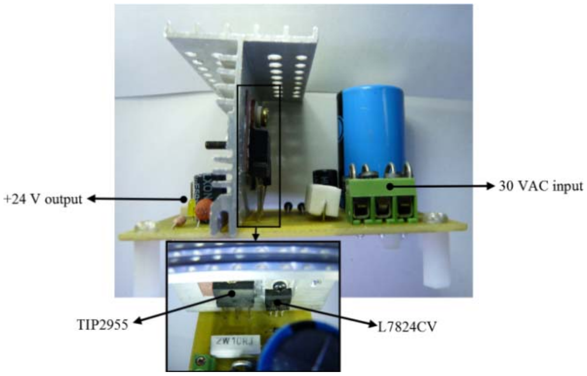

Figure 10. Linear power source for Li-Ion battery charger.

III. RESULTS

With the purpose of performing flexion and extension movements with the prosthesis, a control algorithm was designed from the conversion of the mechanical travel distance of each actuator to a timing factor represented by a 7-bit variable. One code was designed for the general control system. The motion control systems were programmed through four similar codes in which hexadecimal addresses varied. Fig. 11 shows the *general control system's* code flow chart.

This code is based on functions that form a "slave_byte" from a 7-bit timing variable and one spin direction bit. The system sends corresponding codes through I^2C, and each slave captures it from their hexadecimal address. Fig. 15 shows the designed code flow chart to activate each actuator.

A routine to handle the PIC's serial port interruption was designed in order to capture the byte and extract the timing code assigned to each slave. The I^2C protocol properties are essential for a correct configuration of the registers involved in the establishment of a communication with this module.

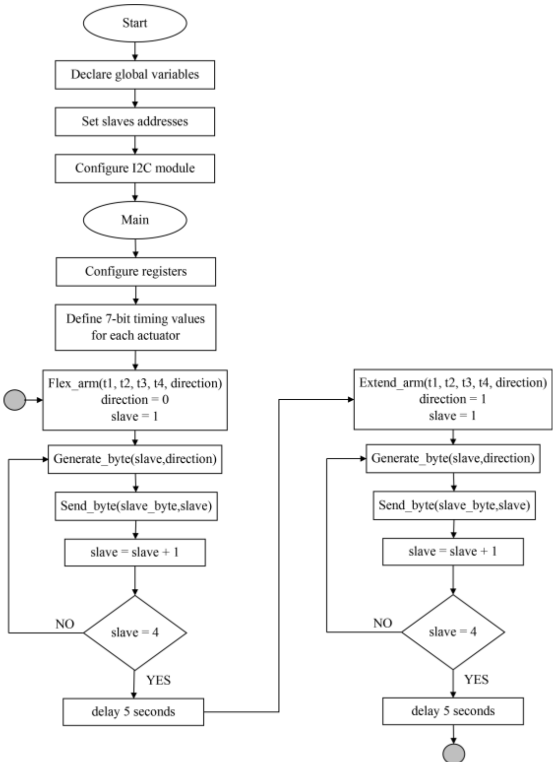

Figure 11. Flow chart of the General control system's code.

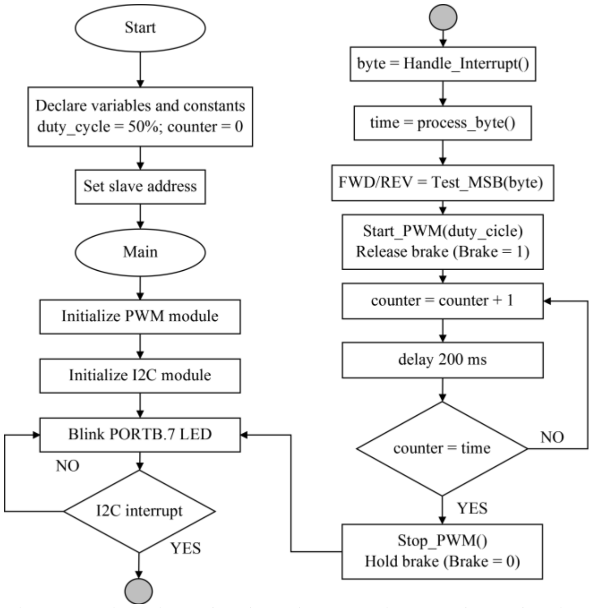

Figure 15. Flow chart of each motion control system for performing flexion and extension movements.

The registers implicated with serial port interruption must be known since the lack of configuration of a single bit could inhibit slave response to a master's request.

IV. CONCLUSIONS AND FUTURE WORK

In order to test the platform performance, the presented algorithms were used to execute antagonistic movements such as flexion and extension in the prosthetic arm. Even though the system was controlled using an open loop algorithm, the response reveals a good approximation to I^2C communication protocol domain.

The behavior of the system when controlled by the present algorithms serves as evidence of the usefulness of this platform for control algorithms evaluation,

The system provides the advantage of evaluating new control algorithms on the prosthesis.

As future work, closed loop algorithms will be evaluated on the prosthetic arm to allow changing the established movements at any time of their evolution.

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