Advanced Motoric Controller

E. Provatos, A. Efthymiadis and Th. Laopoulos
Electronics Lab. Physics Dept., Aristotle University of Thessaloniki,
Thessaloniki, 54124, Greece,
Emails: eprovato@physics.auth.gr, anevthym@physics.auth.gr, laopoulos@physics.auth.gr

Abstract—The A.M.C Project is an effort to create a working exoskeleton arm. It involves both mechanical and electronic design. In this paper the reader can find details about the electronic design which incorporates both high power electronics and high accuracy measuring systems.

Keywords: ***Analog circuits, Battery management systems, Current measurement, Exoskeletons, Force sensors, Microcontrollers, Motor drives, Switched-mode power supply***

I. Introduction

Despite the rapid advances in both technology and lifestyle in today´s society, manual labor is often required to complete various assignments. These assignments could frequently involve physically demanding, or even dangerous, tasks. It would not be inappropriate to suggest, that the person assigned to these tasks might be, neither physically capable, nor willing to undertake the dangers involved. To further reinforce the above statement, the population ageing, especially in developed countries, should be taken into consideration, as people remain in the workforce, even at an older age. Without a device to assist these people, they could be potentially made targets of employment discrimination. This could further lead to social and economic problems. The A.M.C. Project, which stands for Advanced Motor(ic) Controller, aims to resolve those issues. More specifically the primary goal of the design team at this stage of development is to create an exoskeleton for the left arm of its user, supporting and reinforcing the elbow joint. Thus the design needs are separated in the development of the mechanical structure, capable to attach to the user's arm and following the arm's movement, without restricting it in any fashion. Finally the reader should be informed that the research has not been concluded and that this paper is rather a report of the progress done, until the day this paper was written.

II. Challenges of the Design

A. Mechanical Design Challenges

Although the main purpose of the design team's efforts was to create the basic electronics needed to drive such an exoskeleton, a mechanical design was needed, as it would be the main driving force behind the engineering decisions. The exoskeleton needed to be lightweight but also sturdy enough for practical use. Also it was deemed very important to find a clever way of transferring the power from the main motor to the mechanical elbow without making the device cumbersome and the weight of it not well distributed. Finally, a seamless interface to the user technic had to be developed, one that would not fatigue the user but also be very responsive to his/her movements.

B. Electronics Design Challenges

The electronics design was the main purpose of the design team. The design team was faced with many problems and dilemmas. Firstly such a device is meant to be portable, therefore battery power. The proper battery and battery chemistry had to be selected, to fulfill this need, plus all the corresponding systems for monitoring and protecting it from extreme working conditions, which could potentially lead to hazardous situations. Furthermore the system incorporated high power electronics along with sensitive high accuracy circuits, all of them powered from the same battery system, thus noise isolation was really important. To further clarify, the high power electronics were needed to power the main motor and the high accuracy measuring platform would read the user's arm relative position to the moving part of the exoskeleton. All these systems had to work together from the same power source, thus the latter had to be as much immune to noise as possible. Finally, as mentioned above such a system is meant to be portable so a small form factor has to be achieved along with good thermal performance for system stability and longevity.

III. Current Design And Implementation

As of the day, this paper is written, only the electronics design is materialized. The difficulty and cost of the mechanical design unfortunately prohibits the early prototyping, plus as it will be mentioned later in this paper there are reconsiderations being made about its final form.

The electronics design consists of the following parts: the motor controller board, the sensor Analog/Digital Converter (ADC) board, the battery voltage and current monitoring system, the power distribution system and in the heart of all the TM4C123GH6PM Cortex – M4 Arm microcontroller [1] to control all these peripherals.

A. The Current Mechanical Design

The overall design of the mechanical system is presented in **Figure 1**. The mechanical design of the exoskeleton can be further divided in two main parts: The motorized arm joint and the sensor platform.

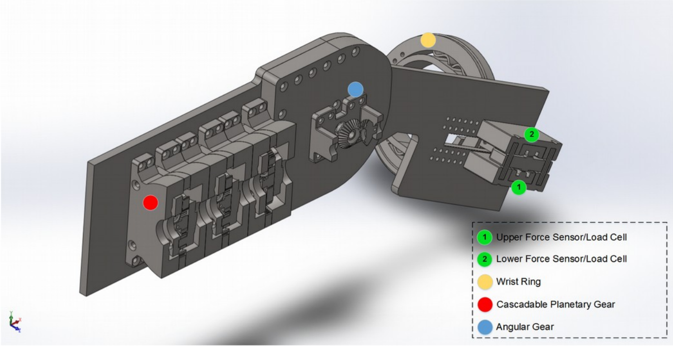

Figure 1: A section view of the mechanized arm.
The mechanical drawing was done using Solidworks

The motorized arm features a set of cascadable planetary gearboxes, each offering a gear reduction of 5:1. Since such a planetary system is integrated in the elbow joint and a second one provides support for the motor, thus the minimum reduction ratio has to be 25:1. The user could fit more gearboxes to get a greater gear reduction ratio. A gear ratio of 125:1 is usually preferred but one could either opt for speed or torque.

The sensor platform mainly consists of a freely moving plate between two load cells (FX1901 from Measurement Specialties [2]), the housing is made in such a manner that, the user could adjust the preloading of the cells to bring them to their lineal region. A ring within a ring contraption then attaches to the moving plate. The inner ring, which embraces the users arm, is free to turn, thus the mechanism is able to transfer the user's motion to the sensors without impairing the user's arm pivoting capabilities. Here it should be noted that the system is designed so that, it could be adjusted to the user's arm length.

B. Motor and H-bridge/Motor Driver

For this stage of the implementation a direct current (DC) brushed motor was chosen. These types of motors are relatively simple to control and even bigger motors are cheaply available as they are often used in commercial power tools such as drills, etc. Although the simplicity DC motors offer, extra steps were taken to ensure that the motor controller will not fail catastrophically in case wrong signals arrive at the inputs, plus some extra hardware protection. Before further analyzing the protection systems used, it should be noted that the MOSFET drivers and corresponding protection circuits are galvanically isolated from the rest of the circuit. This is done to avoid unwanted current ground loops and increase the overall system noise performance. It should be taken into account, that for both high side and low side of the H-bridge, two N-channel MOSFETs were used. The double MOSFET arrangement offers a degree of redundancy and lowers the power loses.

The hardware fail safe system consists mainly of two subsystems. A resistor programmable temperature switch (TMP709 [3]) and a high speed comparator (TLV3501 [4]) which monitors the low side MOSFET gate voltage. Both ICs are manufactured by Texas Instruments. The thermostat IC switches off the PWM signal to the driver with the incorporation of an AND gate, when the temperature of the MOSFETs surpasses the fixed programmed value of approximately 110°C. The comparator IC is used to detect when the voltage of the MOSFET's gate exceeds the nominal voltage threshold for the MOSFET to start conduction. In such an event the circuit signals the high side of the H-bridge to forbid the MOSFET driver from making the high side MOSFETs conduct. The latter is by no means equivalent to PWM deadband but a protective measure to a prolonged rail shoot through. The working diagram of the H-bridge module can be seen below in **Figure 2**.

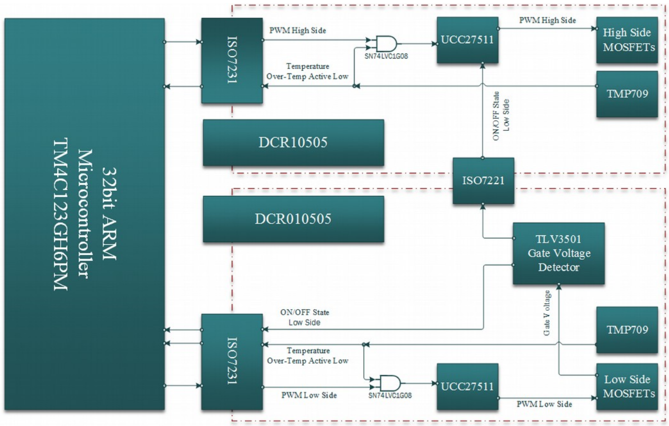

Figure 2: H – Bridge working diagram
(Only half bridge presented above)

C. The ADC Module

The ADC module is by far the most important element of the design. Earlier in this report it was mentioned that care was taken to reduce as much as possible the fatigue of the user. By having a high resolution ADC, detecting even small changes to the outputs of the load cell, would be possible. For this task the ADS1274 [5] from Texas Instruments was chosen as the converter of choice. Although it was not required, the fact that ADS1274 [5] is a simultaneous sampling ADC ensured the lag-free operation of the software position controller. Due to the differential output swing of the load cells not exceeding 100mV at full load and the relative high output impedance, some pre amplification was necessary. For the preamplification, buffering and filtering, the LMP2022 [6] operational amplifier was selected as the main building component. LMP2022 [6] offers excellent low drift characteristics, electromagnetic interference (EMI) hardened inputs, which were required for high reliability and seamless functionality under noisy environments and most importantly high output current capability, so it would be possible to interface them directly to the ADC input pins. With this setup, the noise floor achieved was 18uV, measured through the digital output of the ADC.

Furthermore, it was a necessity to provide the module with some extra functionality and versatility, to make it future-proof to changes in the design, a Digital/Analog Converter (DAC) was added to manipulate the voltage reference of the ADC and the voltage offset of the output buffers. It should be mentioned here that, the design achieved to make the ADC module work as a standalone unit. Both ADC and DAC could be addressed from a single SPI bus through the use a single input selection pin. The working diagram of the ADC module can be seen below in **Figure 3**.

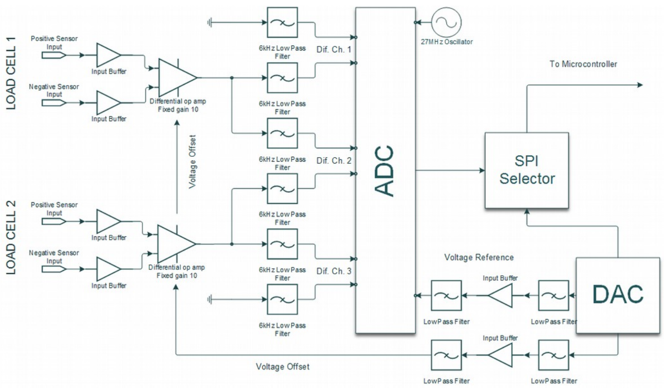

Figure 3: The Functional Diagram of the ADC Module

D. The Battery Monitoring System

The battery selected to power up the complete device was a 4 cell in series Lithium Polymer battery pack with a nominal capacity of 3.3Ah and capable of 30C continuous and 60C burst discharge. The reason behind this choice was the inherit ability of Lithium Polymer batteries to supply big amounts of current plus having a very good weight and volume to capacity ratio. On the other hand with great power comes great responsibility. When draining high currents internal cell mismatched impendences or excessive current drain could potentially pose a fire hazard. Furthermore, discharging these batteries below a certain voltage, could render them inoperable. For the above reasons a monitoring system had to be implemented to measure not only the total battery voltage but the voltage across each individual cell. Also the current of the battery had to be monitor, so that it does not exceed a maximum of 100A. It was also mandatory that the above systems drains the battery as little as possible, does not create current loops and have relatively good stability and have high common mode voltage ratings.

For both, the battery voltage and current monitor, differential operational amplifier topologies were used. Although the battery voltage monitor uses discrete resistor networks along with a single OPA2333 [7] to implement the differential amplifier, the current monitor uses an INA282 [8] dedicated current measuring IC, which amplifies the voltage from a shunt resistor. The current monitor board further uses an OPA2333 [7] to condition the signal for a 3v3 microcontroller integrated ADC. The current monitor board is implemented in a way to be modular. Changing some resistor values, could convert the board from unidirectional measurement to bidirectional, so that the module could be put in series with the motor and measure the current going only to the motor. The schematics for these modules are provided in **Figure 4** and **Figure 5**, for the voltage and the current monitor boards respectively.

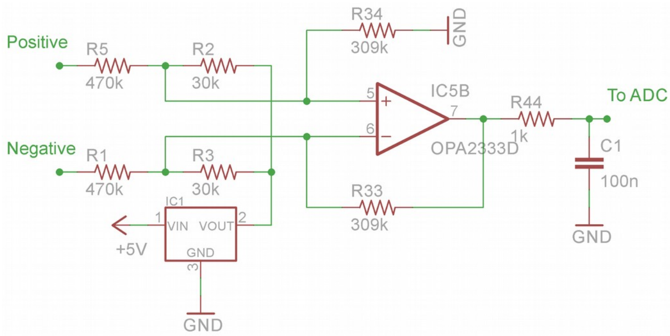

Figure 4: The schematic of battery monitor for only one cell out of four

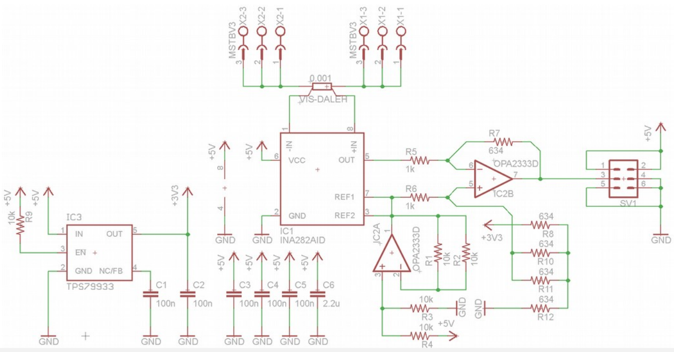

Figure 5: The schematic of the current monitor

E. Power Distribution

At this stage the efforts for doing proper cable management would have been in vein as without the mechanical parts the motor current during the trials did not surpass 10A. Keeping the device modular and keeping simple the process of applying changes is of great importance. Despite this factor, a power supply board was built, featuring a switching step down regulator. The board provides with two individual 6V rails capable of delivering 3.5A but capped at 2A with resettable fuses. Most boards and modules carry individual Low Drop Out (LDO) lineal regulators for noise reduction and isolation purposes, thus explaining the selection of a 6V power rail. With this implementation, both high efficiency and rail stability was achieved.

F. System main controller

All the peripheral modules and boards are controlled by a TM4C123GH6PM ARM Cortex – M4 microcontroller [1] from Texas Instruments. The microcontroller is mounted on a TM4C123GXL LaunchPad Evaluation Kit. The evaluation board is also the point where all control signals are connected. The integrated ADC is used to read the analog signals coming from the battery voltage and battery current monitor boards. The PWM dedicated signals are connected to the H-bridge module and SPI is used to interface with the ADC module. For further control signals some general purpose input output (GPIO) pins were used. Unfortunately, with the completion of the mechanical system still pending, extensive testing and optimization could not be completed. The proposed initial software controller is a position servo implementing a Proportional Integral Derivative (PID) controller, with under-voltage and over-current stop conditions.

IV. Conclusions and Future Plans

The completion of this project although ambitious and expensive, is firmly on track. The above is the result of six months of work. Through the conduction of the research, design and implementation, proposals can be made to bring the project in complete fruition. Some of these proposals along with the future plans are presented below:

A. Proposals and Changes

Here follow the proposals and changes for the mechanical and electrical implementation respectively.

1) Mechanical Design.

a) Although a brushed DC motor is relatively simple to drive, a different approach is probably needed, the gear boxes add weight and lag in the motion and a more direct drive is needed. A brushless direct current (BLDC) motor, needs to be designed specifically for the exoskeleton, to cover the weight and power needs.

b) Making the frame more lightweight and the sensor platform sturdier. Though testing and partial implementation of the sensor platform, with the help of a 3D-printer. Some components need to be widthenned while not encumbering or fatiguing the user.

c) Materilazion and testing. Without the mechanical part, the rest of the components can not be adaquently tested.

2) Electronic Design.

a) H-bridge, find an easy to implement, low loss and compact footprint way to detect if a MOSFET is conducting or not.

b) ADC module, the ADC module was build to initially assert the functionality of the ADS1274 [5] but also an initial implementation of the unit. The proposes include, a wider common mode voltage input, autocalibration functionality, further improve noise performance and user selectable input gain.

c) Migrate from currently using the Lauchpad evaluation kit to implementing a customly designed controller board with all the necessary connections and mounting.

d) Professionally manufacture the printed circuit boards (PCB).

e) Redesign the power distribution board with more failsafes and cutoffs.

B. Future Plans

The idea is that the current work is only part of something bigger, given the chance, the implementation of a whole body power exoskeleton is what the authors really have in mind. Still, there are some ideas, which have not be mentioned in this paper before. For example, implementing an ElectroMyoGraph (EMG) could provide with data that could correlate arm position to given input, or be able to graph and monitor the fatigue of the user. At the current state of development the device, depends on a healthy person, with normally functioning arm, to provide with feedback to operate the exoskeleton. Another proposal is to get the input directly from the human nerves to control the device. This would enable a handicapped person to use the device. Furthermore the device could also provide with connectivity options and join the Internet of Things (IoT). The design can be further and further improved but as soon as the basic platform is formed and working, the possibilities are virtually endless and depend on the users' imagination which features would be implemented.

V. References

[1] Texas Instruments, "Tiva™ TM4C123GH6PM Microcontroller", TM4C123GH6PM datasheet, 2007 [Revised Apr. 2015]

[2] Measurement Specialties, "FX1901 Compression Load Cell", FX19-0-1-0001-0025-L datasheet, May 2014 [Revised May 2014]

[3] Texas Instruments, "Resistor-Programmable Temperature Switch in SOT Package", TMP709 datasheet, Dec. 2011 [Revised Feb. 2012]

[4] Texas Instruments, "4.5-ns Rail-to-Rail, High-Speed Comparator in Microsize Packages", TLV3501AQDBVRQ1 datasheet, Sep. 2010 [Revised Sep. 2010]

[5] Texas Instruments, "Quad/Octal, Simultaneous Sampling, 24-Bit Analog-to-Digital Converters", ADS1274IPAPT datasheet, June 2007 [Revised Feb 2011]

[6] Texas Instruments, "LMP202x Zero-Drift, Low-Noise, EMI-Hardened Amplifiers", LMP2022MA/NOPB datasheet, Sep. 2008 [Revised Dec. 2014]

[7] Texas Instruments, "1.8V, micro POWER CMOS OPERATIONAL AMPLIFIERS Zerø-Drift Series", OPA2333AID datasheet, March 2006 [Revised May 2007]

[8] Texas Instruments, "High-Accuracy, Wide Common-Mode Range, Bi-Directional CURRENT SHUNT MONITOR Zerø-Drift Series", INA282AID datasheet, Nov. 2009 [Revised Sep. 2012]