Profectus: Non-conventional Control and Implementation of an Electric Wheelchair Designed to Climb Up Stairs, Controlled via Electromyography and Supported by Computer Vision and Artificial Neural Network Processing

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ABSTRACT

Non-Conventional controls offer highly relevant support for disabled people in terms of independency and life quality. Profectus is a Latin word that means improvement, progress or growth. Profectus project's main objective is to design and implement an electric wheelchair capable of climbing up and down stairs operated thru silent speech non-conventional control using electromyographic (EMG) signals and a computer vision algorithm for wheelchair navigation. EMG signals are fed to a multiple artificial neural network (ANN) system for pattern recognition so that commands can be generated for wheelchair operation. Two approaches to movement control were implemented; one refers to movement via forward, backwards, left and right commands, while the second approach is based on destination selection on a computer screen so that the computer navigation system is responsible for automatic generation of movement commands with obstacle avoidance. Both approaches apply silent speech commands produced by user's gestural movements from a seleted group of phonetically different spanish words to interact with a Graphic User Interface (GUI) for wheelchair navigation. Mechanical, electronic and algorithmic designs are presented on this paper. The system was tested on five users, achieving an overall recognition accuracy of 95% for four gestural commands with 0.6s maximum response time.

Keywords: Silent Speech, Electromyography, Artificial Neural Network (ANN), Computer Vision, Tri-Star System, Pattern Recognition, Electric Wheelchair

1. INTRODUCTION

The National Spinal Cord Injury Statistical Center –NSCISC- estimaded in February 2012 that there are aproximately 270,000 people suffering some sort of spinal cord injury in the United States of America. It can be estimated that lifetime health care and living expenses for a severe spinal cord-injured individual can be up to US$4.5 Million (NSCISC, 2012). In addition to high costs, reduction of life quality and life expectancy should be taken into consideration. Life expectancy of 78 is estimated in the United States of America (NCHS, 2010) but data shows that this life expectancy is largely reduced for spinal cord-injured people (NSCISC, 2012). Psychological impact and dependency upon others are just some factors that surely diminish life quality for these individuals. Supportive technology for spinal cord-injured people has a lot of potential; reducing costs of living and mainly improving life quality for these people.

The human body has many bioelectric signal sources due to its electrical nature. The most studied bioelectric signals are analyzed using Electroencephalography (EEG), Electrocardiography (ECG) and Electromyography (EMG). This has allowed the development of many interfaces between machines and human's electrical nature in order to control applications in a non-conventional way. One of the main ideas behind these non-conventional controls is to allow disabled people to overcome their physical limitations and develop additional capacities.

Some research has been done in the field of speech recognition based on EMG signals at NASA Ames Research Center, where researches worked on a sub auditory speech recognition system using larynx and sublingual areas below the jaw in order to classify six sub-vocally pronounced words with up to 92% accuracy using one pair of surface electrodes (Jorgensen et al., 2003). Additional research has been carried out at Zaragoza University, where researchers designed a system for automatic speech recognition using eight facial muscles and capable of classifying 30 syllables from spanish language obtaining 71% overall accuracy (López Larraz et al., 2010). Related work was also developed at Karlsruhe Institute of Technology, where they report their research on speech recognition by surface electromyography (Wand and Schultz, 2011).

The idea of silent speech recognition systems is to avoid the need to produce acoustic signals to recognize what a patient is trying to say. Simple movement from patient's facial muscles produces a voltage that can be detected by surface electrodes producing a EMG signal, which can be used to replace acoustic signals. EMG signals can be very weak and complex.

Nowadays there are multiple ways to extract patterns from complex and rich data (like an EMG signal), one of them uses artificial neural network-based recognition systems. An artificial neural network is a mathematical or computational model inspired by various aspects of biological neural networks in order to emulate the behavior of the human brain (Gestal Pose). The adaptive learning, tolerance fault and flexibility are the main advantages behind the idea of using artificial neural networks to perform pattern recognition. On this work multiple feedforward multilayer artificial neural networks were used. Probabilistic inference was used in order to add robustness to the application.

At present there are several alternatives to facilitate the mobility for disabled people, from ramps and/or elevators up to some functional wheelchairs capable of moving freely on any surface, being "iBOT" one of the best known. Given that there is little known development of these functional wheelchairs in Latin America, a group of engineering students thru the Department of Electronics Engineering at Del Valle de Guatemala University (Castillo et al., 2011) set out to create an autonomous prototype wheelchair that could get around in areas with obstacles or steps controlled via brain waves. Based on the results of this project and research in the area of non-conventional methods via the ANIMA project (Valdeavellano et al., 2009) development continued and new design alternatives were proposed, both in mechanical and electronic aspects. New mechanisms were implemented in order to expand and improve wheelchair functionality. A new type of control via electromyography was implemented, which detects electrical signals produced by the gestures of a patient.

2. EXPERIMENTAL SETUP

This work uses silent speech gestural movements in order to produce electromyographic signals related to a word that is part of a specific set of phonetically different words. The electromyographyc signals are electronically processed (Figure 1) before being sent to a computer for artificial neural network (ANN) processing for pattern recognition where movement commands are generated in combination of a computer vision navigation system for obstacle avoidance so that final movement commands are sent to electronic circuitry for driving wheelchair motors.

2.1 ELECTROMYOGRAPHYC MODULE

Figure 1 shows all the necessary stages for electromyographic signal capturing, conditioning and transmission to a pattern recognition module based on ANN systems.

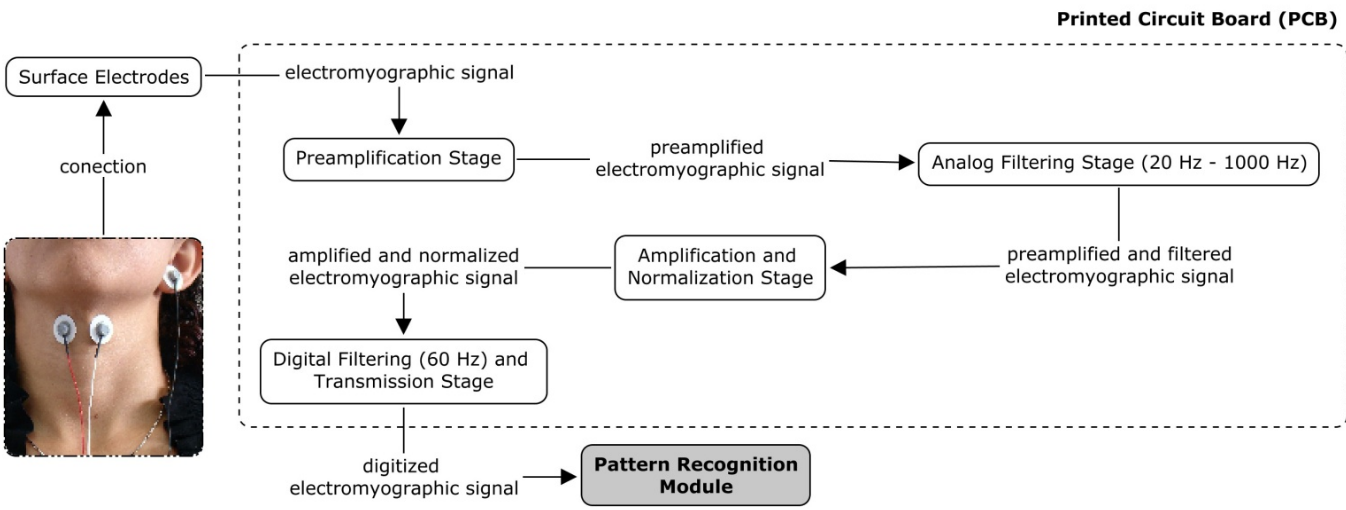

Figure 1: Electromyographic Signal Module

Three Ag/AgCl F-E9M-40 surface electrodes (from Grass Technologies) were used to capture electromyographic signals from the neck muscle area. These surface electrodes were connected to the implemented printed circuit board implemented on this work using safety female connectors which meet the corresponding DIN standard for these applications. Surface electromyography was chosen over invasive methods for simplicity and safety. Conductive gel is used to achieve low electrode-skin impedance and washers are used to attach the surface electrodes to the user's skin. Two electrodes were placed in bipolar configuration on the anterior triangle of the neck muscle area and a reference electrode was placed on the left ear lobule (Figure 1).

2.1.1 PREAMPLIFICATION STAGE

An AD620 instrumental amplifier was used. This IC offers up to 1000X adjustable differential gain which can be set using a single external resistor. AD620's high-input impedance and high CMR (Common-Mode Rejection) are some useful features. The gain at this stage is adjusted using a precision potentiometer on the implemented PCB.

2.1.2 ANALOG FILTERING STAGE (20HZ – 1000HZ)

Filtering consists of an eight-pole anti-aliasing (low-pass) Butterworth filter with 1KHz cut-off frequency and a fourth-pole high-pass Butterworth filter with 20Hz cutoff frequency so that the DC component is eliminated.

2.1.3 AMPLIFICATION AND NORMALIZATION STAGE

Proper amplitude and voltage limits are required before the digitizing process. The output of this circuit is an EMG signal centered in the 0–5 V range so that it is compatible with the digital signal processor's ADC. Both the DC offset voltage and the gain are adjusted using precision potentiometers located on the PCB

2.1.4 DIGITAL FILTERING (60HZ) AND TRANSMISSION STAGE

A dsPIC30F4013 running at 20 MIPS was used. Sampling frequency for digital filtering was set at 2.6 kHz with 12-bit samples. Samples serve as an input to a difference equation that implements a 60-Hz notch second order IIR digital filter. One byte was used as a checksum. The dsPIC microcontroller transfers data to the computer using a UART interface at 115,200 bps.

2.2 PATTERN RECOGNITION MODULE

Once processed EMG signals from patient's gestural movements are received on a computer, a Pattern Recognition algorithm is used to perform silent speech recognition. This work uses silent speech gestural movements from a specific set of phonetically different words in order to generate movement commands for wheelchair navigation. The set is composed of the spanish words "Eco", "Noviembre", "Omega", "Sigma", "Teléfono" and "Uniforme".

Figure 2 shows the stages for silent speech recognition in order to generate commands to be sent to the wheelchair Control Module (module in charge of controlling actuators in the wheelchair).

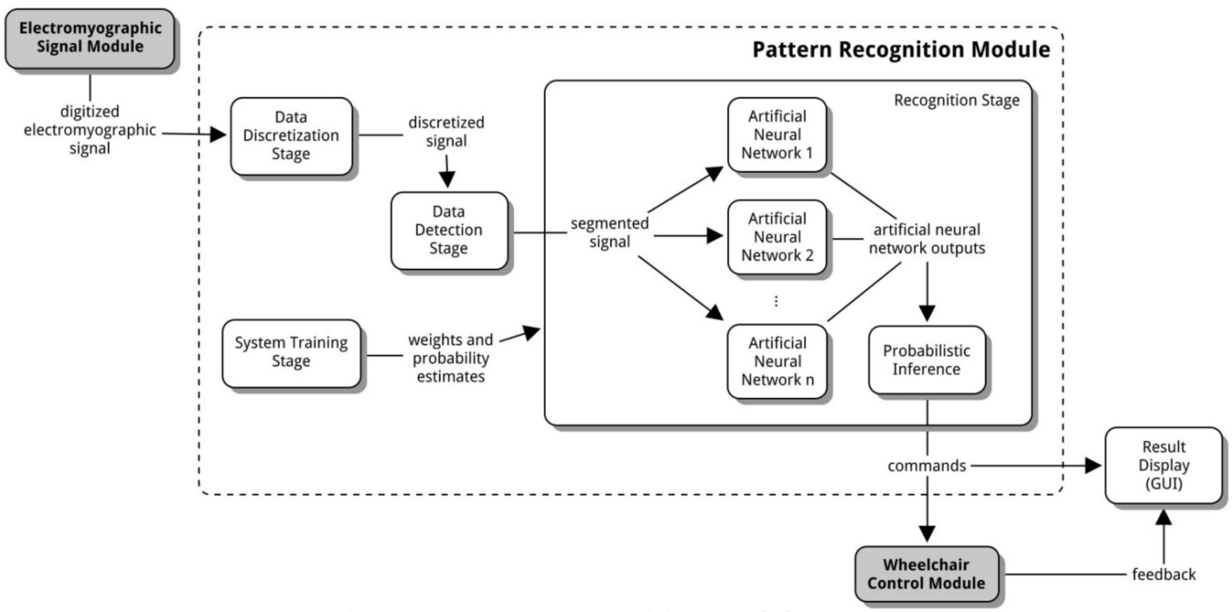

Figure 2: Pattern Recognition Module

2.2.1 DISCRETIZATION STAGE

Discretization seeks to separate the EMG data and divide it into data blocks in order to accelerate the detection process. The block size was defined as 0.05 seconds of data, which was useful for distinguishing consecutive gestural commands from consecutive syllables within a single gestural command.

2.2.2 DATA DETECTION STAGE

The aim of this method is to classify all blocks as useful blocks (gestural data present) and not useful blocks (none gestural data present). This data detection method was implemented using confidence intervals based on signal amplitude. Confidence intervals were previously defined by preliminary tests and are calibrated according to the current signal data when the patient is not performing any gesture. This stage provides segments (a group of blocks) of a size corresponding to one second (the approximate time it takes a patient to gesticulate a word). Zero-filling is used to complete segments with less of one second of gestural data.

2.2.3 RECOGNITION STAGE

Block segments are analyzed by multiple feedforward multilayer artificial neural networks (initial tests were performed using a single feedforward multilayer artificial neural network and final tests were performed using 25 different artificial neural networks). A fifth-order Daubechies Discrete Wavelet Transform was repeatedly applied to the data as a coefficient reduction technique. The output of this transform was fed into the multiple artificial neural network system. All artificial neural networks design (number of hidden layers and artificial neurons per layer) was based on heuristic methods.

Artificial neural networks provide outputs which are analyzed by a probabilistic inference method based on probability estimates of success and failure of each neural network for each command. This method seeks the probability for a sample to be or not to be a specific command, so the Bayes Theorem was applied to the specific case of a binary partition. The model used to determine the probability for a sample being a specific command is given by (1).

$$P(C|E_1, E_2, \dots, E_n) = \frac{P(C)\prod_{i=1}^{n} P(E_i|C)}{P(C)\prod_{i=1}^{n} P(E_i|C) + P(\neg C)\prod_{i=1}^{n} P(E_i|\neg C)} \quad (1)$$

Where, $P(C)$ represents the probability that a sample is a command (depends solely on the number of commands) and $P(E_i|C)$ represents the observations obtained by the i-th artificial neural network for the command C. These observations consist of a group of independent events. Once the method has computed the probability of each command, a rule indicating the acceptance is carried out to determine whether the sample corresponds to a valid command or to an unidentified command. The rule of acceptance is based on individual probability magnitude.

2.2.4 SYSTEM TRAINING STAGE

Supervised learning was chosen for ANN training, which required the recording of patient samples. Training is personalized, so it was necessary to record samples from all patients individually. As explained by researchers from Karlsruhe University, the performance of an EMG silent speech recognizer substantially varies across different patients, with the best results for the most experienced patients (Wand et al., 2009). Several samples were recorded for each gestural command, between 250 and 400 samples per command depending on the patient's difficulty to produce gestural movements and experience. A session-independent training method as explained in "Session Independent EMG-Based Speech Recognition" (Wand and Schultz, 2011) was chosen to obtain robust pattern recognition.

2.2.5 GRAPHIC USER INTERFACE

A set of gestural commands is used to interact with a Graphic User Interface (GUI) in order to navigate through a menu of options representing predefined instructions to move the wheelchair. This GUI was implemented using Python language and consists of several screens with either three, four or five options. The option set allows tasks like rotating the wheelchair at a desired angle and moving forward, backwards and sideways. The option set also allows the use of a camera so the patient can select a destination point for the wheelchair to move with obstacle avoidance using computer vision as explained in the following section.

2.3 COMPUTER VISION MODULE

Two cameras and a computer were used for wheelchair vision. One camera was installed at the top of the wheelchair in order to display on the computer screen what is in front of the user. The second camera was installed at the bottom of the wheelchair, facing the floor for texture feedback. Electromyographic commands are used to interact with a GUI so that direct movement commands are chosen (Forward, backwards, left, right, etc.) or a destination is chosen from a point in the computer screen (which shows what is in front of the wheelchair). Image processing, frequency analisis and several algorithms are performed so that final movement commands for actuators are generated in order to navigate with obstacle avoidance. Figure 3 shows the main steps performed by the computer vision module. Output of this module goes to the control module for actuators.

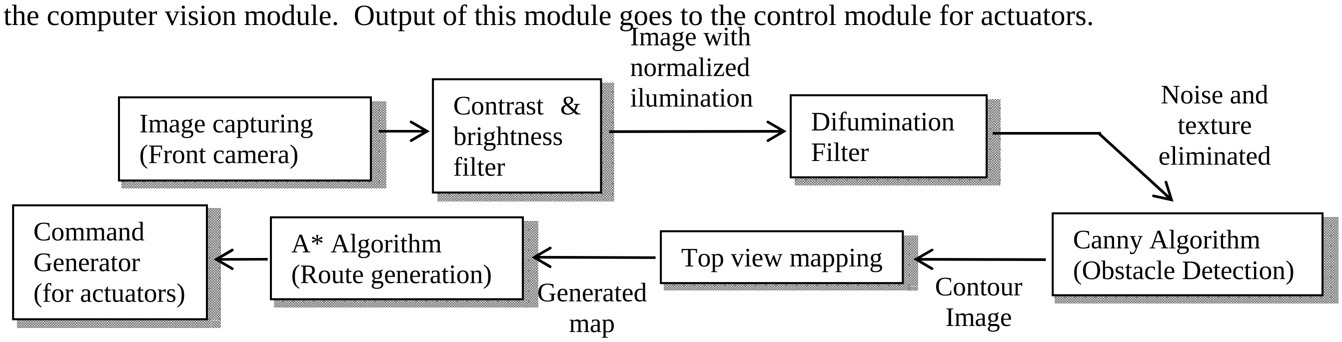

Figure 3: Computer Vision Module

2.4 CONTROL MODULE

This module is based on several sensors and actuators which allow for the efficient wheelchair operation according to the commands received from the user (via electromyography capturing and ANN and computer vision processing). Overall block diagram for the control module is shown in Figure 4.

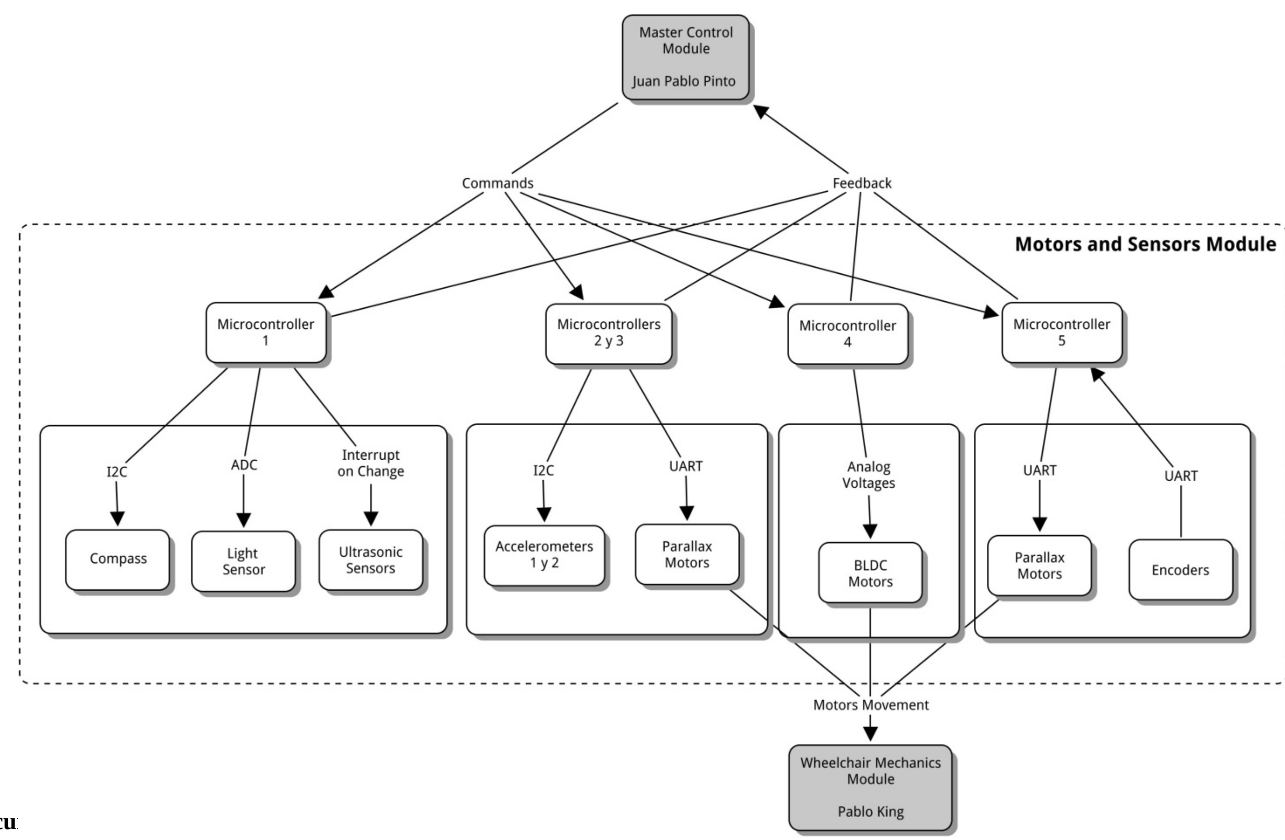

Figure 4: Control Module (Motors and Sensors)

2.4.1 SENSORS

Parallax MMA7455 accelerometers were used for seat position control. The designed wheelchair is capable of climbing up and down stairs so that center of mass is dynamically controlled via accelerometers which determine the best altitude and tilt angle for the seat so that the wheelchair is safe. A PID control loop was used for the center of mass control.

An electronic compass was used for rotation feedback when moving the wheelchair, so that rotation commands are properly executed even if the wheels slip over the surface. Parallax PING))) ultrasonic sensors where used for stair height and depth detection so that information is available for climbing up and down stairs.

Finally, encoder kits from Parallax were used for wheel positioning and velocity control.

2.4.2 ACTUATORS

A total of 10 electric motors were used for the wheelchair; four brushless DC motors for actuation of a Tri-Star system that enables climbing up and down stairs (presented on the next section), four Parallax DC motors for linear movement of the wheelchair and two windshield DC motors for the seat positioning for center of mass control. All electric motors have gearboxes that offer the required torque.

2.5 MECHANICAL MODULE

Mechanical design for the wheelchair is composed of three main submodules: Tri-star system, stability system and chassis. Each of these submodules involve a lot of design and details that can't be covered on this paper but a description of each is given here. Detailed stress analysis using Autodesk Inventor was performed to all parts of the design before machining them.

2.5.1 TRI-STAR SYSTEM

This system consists of two primary mechanisms; the first is a planetary gear train which transmits torque from the center axis towards each of the three ends where the wheels are located (Figure 5, left image). The second mechanism is a spur gear train, which one of them is attached to the triangular structures allowing rotation of the entire system (Figure 5, right image). An internal detail for this system is shown at the middle of Figure 5.

Figure 5: Tri-Star System for Climbing Up and Down Stairs

2.5.2 STABILITY SYSTEM

During climbing up or down stairs the user would be in a very sloping position (the seat could be at 45° as the structure) causing instability to the point of being able to fall. The mechanism for solving this issue consists of a four-bar translation mechanism and a tilting mechanism for the seat so that center of mass is controlled and falling is avoided. The computerized design for the complete stability system attached to the seat is shown in the middle of Figure 6.

2.5.3 CHASSIS

The chassis and the seat structure are the elements of support that unite and allocate all the sub-systems that as a whole constitute the wheelchair. The dimensions for the seat were based on standards and measures recommended for the design of chairs, on which comfort and health of the user are considered. For the type of application, the structures had to be as light as possible having a high rigidity, for what square aluminum profiles joined by weld were chosen. Figure 6 left shows the computerized design for the chassis and Figure 6, on the right side shows the complete computerized mechanical design for the wheelchair.

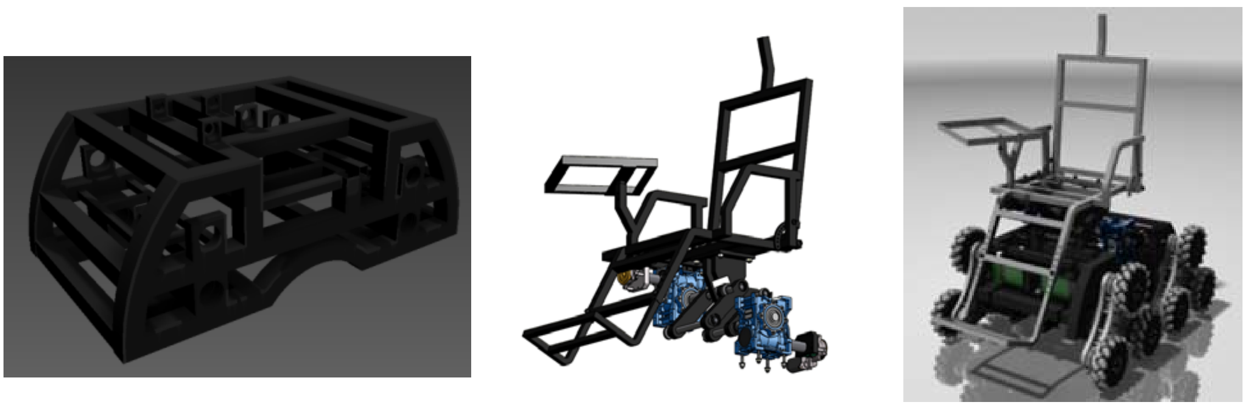

Figure 6: Chassis (left), Seat with Stability System (middle) and Complete Mechanical Model for the Wheelchair (right)

3. RESULTS

The system was tested on five patients. The worst-case response time for the ANN gestural pattern recognition was 0.6 seconds. The ANN system was programmed on Python and tested on a 32-bit architecture 4GB RAM Intel® Core^{TM} 2 Duo 1.5 GHz processor running Ubuntu, Linux.

Left side of Figure 7 shows the designed PCB for electromyograhy capturing and electronic processing while figure's right side shows a 10-second silent speech sampling for the words “uniforme”, “eco”, “teléfono”, “sigma” y “noviembre” used for interaction between the user and the GUI for wheelchair navigation.

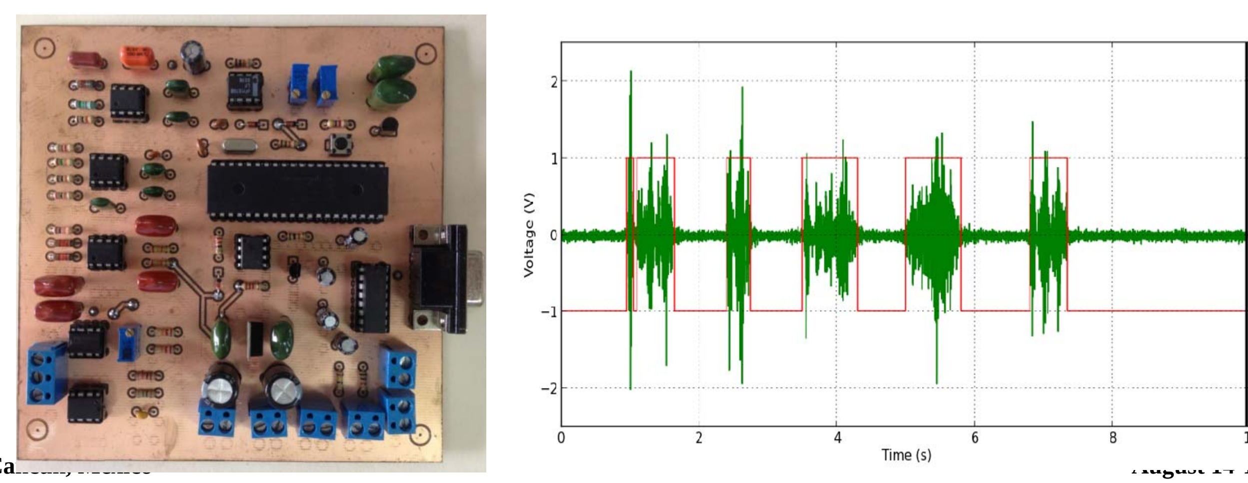

Figure 7: Electromyography PCB (left) and Silent Speech Command Sampling (Right)

Figure 8 shows the GUI implemented on Python so that the usert can interact with the wheelchair by gestural commands. Figure 9 shows the complete built wheelchair (left) and it also shows one of the users while testing it (middle and right images).

Table 1 shows a summary for the testing results in terms of accuracy. All results reported processing time smaller than 0.6 seconds before sending the command and starting the movement.

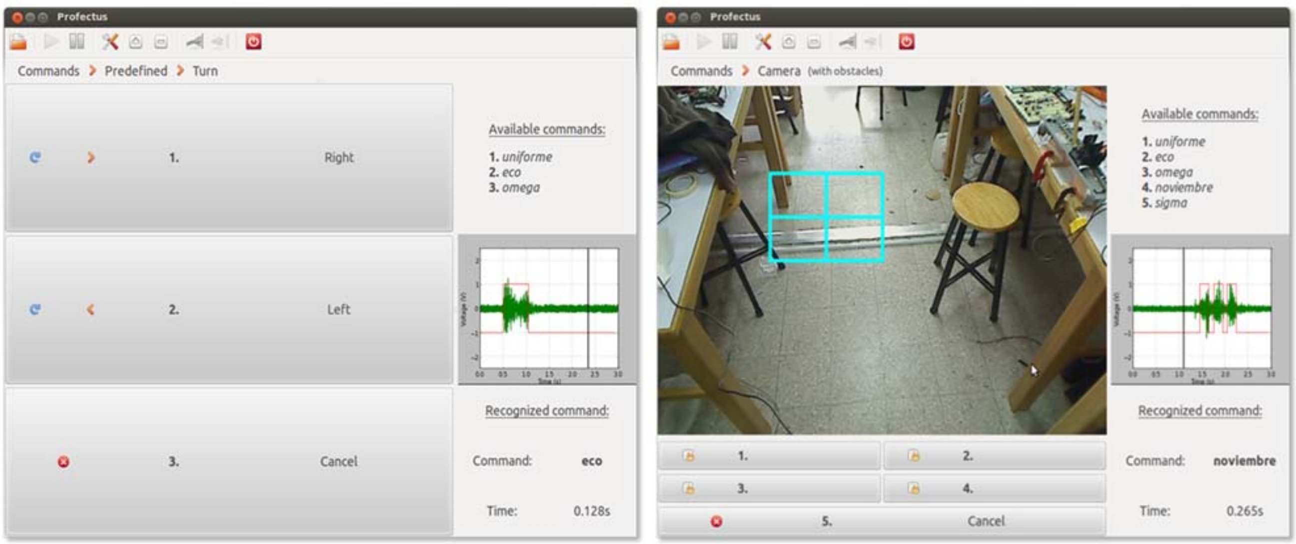

Figure 8: Graphic User Interface for interaction between user's gestural commands and wheelchair

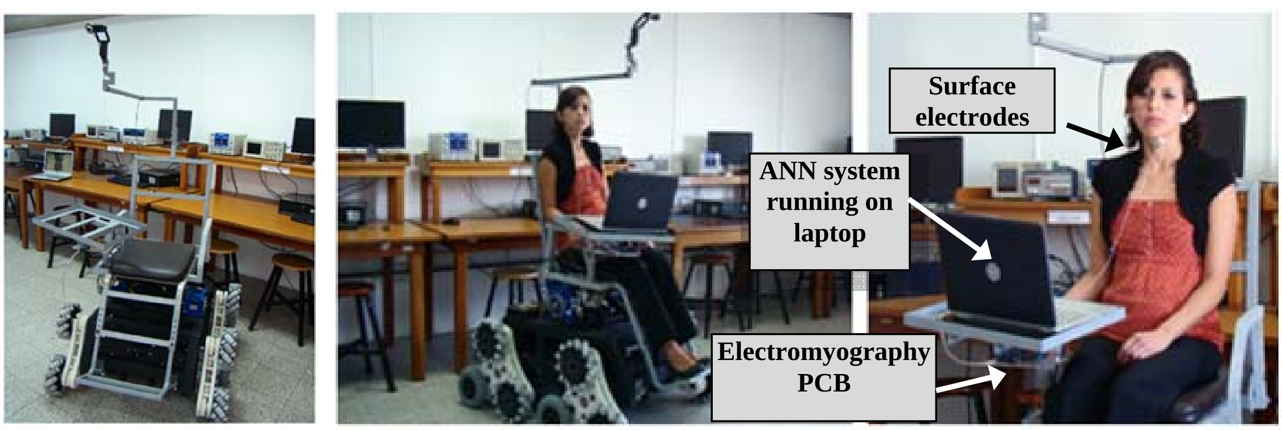

Figure 9: Built Wheelchair (left), User Testing the Non-Conventional Controlled Wheelchair (middle and right)

Table 1: Summary of gestural command recognition for all tested patients (for four silent speech gestural commands)

Patient	Recognized	Misrecognized	Unrecognized	Number of tests
1	94.17%	3.33%	2.50%	120
2	97.50%	1.67%	0.83%	120
3	95.00%	2.50%	2.50%	120
4	93.33%	3.33%	3.33%	120
5	95.00%	0.83%	4.17%	120
Average	**95.00%**	**2.33%**	**2.67%**	

4. CONCLUSIONS

An electronic wheelchair capable of climbing up and down stairs and controlled thru a specific set of silent speech words using electromyography, multiple artificial neural and computer vision was successfully achieved with an accuracy of 95% for four commands with 0.6s maximum response time. The use of a single EMG channel proved to be sufficient for silent speech pattern detection. The Tri-star systems allows the wheelchair to climb up and down stairs with a maximum inclination of 45° and a step height of 7.87 in. The self-locking property of the gearboxes reduced the energy consumption of the motors by not requiring to be energized all the time and avoiding them from overheating.

5. FUTURE WORK

Addition of EMG channels would be useful for more complex signal analysis. Future research has to be done to test the system on handicapped subjects (paraplegic and quadriplegic people). Additional gestural commands can be tested so that the system might be useful for more complex interaction applications. Analyzing the possibility for migrating the ANN system running on the laptop to an FPGA-based system would be of interest in terms of cost, area, weight, response time and portability. Genetic algorithms can be used instead of heuristic methods for ANN design in order to evaluate possible accuracy improvement.

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