Prototype of a wheelchair controlled by cervical movements

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***Abstract*— This work presents the development of a motorized wheelchair controlled by cervical movements, where two accelerometers are used as sensors in the definition of movement commands of the wheelchair. One accelerometer is positioned in a helmet on the user's head and the second is positioned on chair base. The use of two sensors has the objective of collecting the signals in differential form providing to system the capability to recognise horizontal plane and slant. The microcontroller STM32F100RB is responsible for processing the signals provided by sensors and for generating the control signals of the wheelchair. Throughout the text are shown the response of accelerometers as a function of the angles of the frontal and transverse tilt of the head, the curves of electric current, the RPM and the efficiency of the transmission system on each wheel as a function of torque, the speed of the wheels as a function of encoder signal frequency and the parameters of the control system adopted. Tests of the wheelchair performance in horizontal and inclined planes were executed and discussed.**

I. INTRODUCTION

Tetraplegy is a physical condition that causes restriction/loss of movement of the upper and lower limbs. This condition can be caused by degenerative illness or cervical spine trauma.

Among the non-traumatic disorders that can cause cervical spine injuries, some can be cited: infection, spinal tumor, vascular dysfunction, vertebral subluxation secondary to rheumatoid arthritis or arthritis degenerative. It is estimated that non-traumatic spinal cord injuries correspond to 30% [1]. Traumatic injuries are the most frequent and affect mostly people in the most productive age group.

According to [2] more than 937463 people has permanent tetraplegy, paraplegy or hemiplegy in Brazil. Regarding the factors that lead to this type of disease, a study done by [3] found that traffic accidents are the incidents that cause most cervical spine traumas, and among these 74.4% involving motor vehicles (23.5% pedestrians, 35.3% of collisions and cars/motorcycle accidents 15.6%), 15.6% involving falls from height and 10% from other factors.

In order to provide a better quality of life for people with disabilities some devices and equipments are developed to generate a greater degree of independence, and with it, a better quality of life. These technologies are called assistive technology.

Some significant results are presented in [4], where accelerometers, gyroscopes and magnetometers were used in upper limb motion tracking. Another related work is [5] where are shown consistent results associated to upper limb motion classification using myoelectric signals and a support vector machine (SVM) as the core of classification in myoelectric control.

Several researches, based on wheelchairs, were presented in [6] such as a wheelchair developed by Madarasz (1986) equipped with ultrasonic sensors which allows the user to navigate in corridors. The project OMNI (Office wheelchair with high Maneuverability and Navigational Intelligence) of University of Hagen (1999) had the functionality of omnidirectional steering and ultrasonic and infrared detectors enabling real-time obstacle avoidance and back tracing. The studies developed in the University of Hong Kong (2002) applied neural networks to map sensor readings to control actions to play back taught routes.

In this same article [6] is presented a project which allows the user controls the movements of the wheelchair in different manners, as follows: eye blinks, eye movements, head movements, sip-and-puff, EEG and face movements.

This work is structured as follows. Section II introduces the wheelchair controlled by cervical movements developed by Universidade de Caxias do Sul. Section III presents the development of the modules which compound the referential system, traction, control and velocity estimation. In Section

978-1-4799-7502-0/14 $31.00 © 2014 IEEE
DOI 10.1109/BIBE.2014.25

IV the results are presented and Section V highlights the discussions and conclusions of this work.

II. WheelChair

A wheelchair controlled by cervical movements can have its operation represented by the block diagram defined in Figure 1.

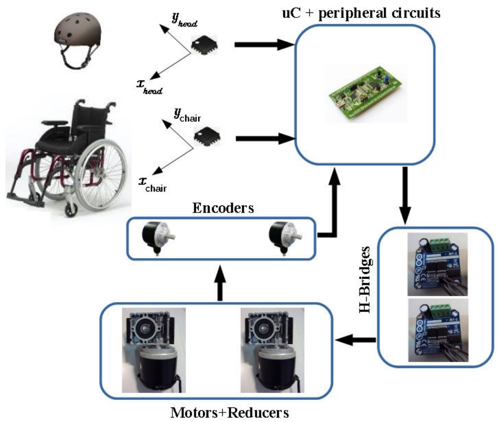

Fig. 1. Wheelchair controlled by cervical movements - Block Diagram

The wheelchair's functionality is based on cervical movements of the user who can, by head's inclination to front, lateral or combining both, make the wheelchair executes forward movements, turn around its own axis and smooth curves respectively.

The use of 2 accelerometers was established in such way that the signals used as reference to control the movements of the chair were generated in its differential form, thus enabling the use of the chair in inclined ground. The functional blocks shown in Figure 1 will be detailed technically in section III.

III. Development

According to Figure 1, the wheelchair is compound by 3 basic subsystems: the referential system, traction system and speed estimation and control system.

A. Referential System

The referential system uses, basically, inertial sensors based on MEMS technology. The model applied in this project was the LIS344ALH from STMicroelectronics [7]. This 3 axis analog accelerometer operates with 3.3V power supply and presents a sensitivity of 220 mV/g in full scale mode. The accelerometers functionality, in this project, is applied to the measurement of angles generated by cervical movements executed by the user as shown in Figures 2 and 3.

Analysing Figure 2, it can be noted that the command generated by the referential system for forward movement takes into account the signal provided by the accelerometer positioned in the user's head and the signal from the accelerometer positioned on wheelchair basis used as a reference. The signal generated by the difference between the head accelerometer

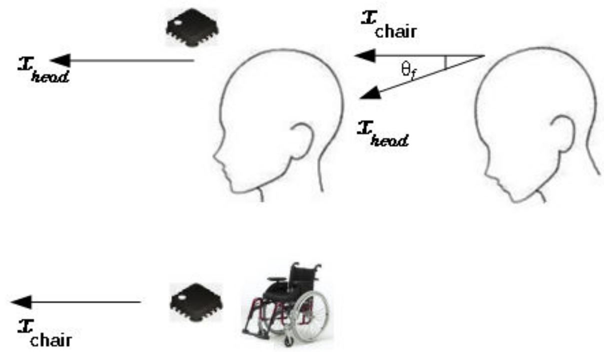

Fig. 2. Generation of reference signal for forward movement command

position and the accelerometer positioned on wheelchair basis is proportional to θ_f.

Taking into account the same principle, the lateral movement of the user's head generates differential signals in relation the wheelchair basis accelerometer making the referential system to provide the command to the wheelchair turn around its own axis, according Figure 3. This differential signal is proportional to θ_t

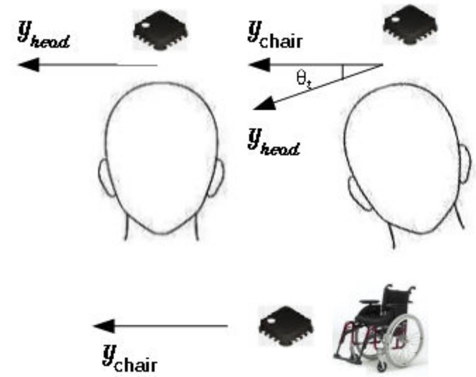

Fig. 3. Generation of reference signal for turn around movement command

Analysing Figure 3, it can be observed that activation signal for wheelchair rotation is proportional to θ_t. Aiming a better comfort in the wheelchair navigation, the angles θ_f and θ_t can be combined providing smooth turns to right and left.

The accelerometers, in this project, are used as inclinometers, thus the vibrations and irregularities related to the ground must affect the referential system. A RC low pass filter was dimensioned to avoid those influences and allow the navigation of the wheelchair on irregular and inclined surfaces. The LIS344ALH accelerometers have one internal resistor of 110 $k\Omega$ per axis output and according to Equation 1 the parameters of the RC low pass filter can be determined [7].

$$f_c = \frac{1.45}{C} \quad (1)$$

Where f_c is the frequency in Hz and C the capacitance in μF.

Considering that only the DC level of the voltage provided by the accelerometers is desired, the cutoff frequency was empirically determined in 1.45 Hz and the capacitance C according to Equation 1, must be 1 μF.

The definition of the angle θ_f takes into account the brazilian standard ABNT NBR 9050 [8] which determines what is the limit of head movements that can compromise the horizon visualization. According to the standard adopted, upward movements of the head can not be greater than 20 degrees, for downward movements the limit is 38 degrees. The angle θ_t, related to the lateralization movements, is limited by 15 degrees angle, being the major reason the limit of the cervical anatomy.

The angle θ_f used as reference for forward movement activation is 10 degrees. It was implemented a hysteresis for a better comfort for user in controlling the chair's movements. The Figure 4 shows how forward activation signal is generated according angle θ_f.

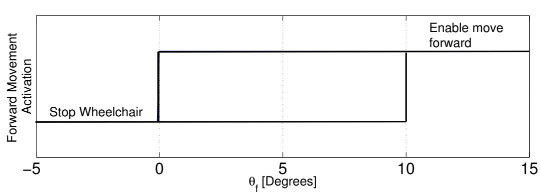

Fig. 4. Forward activation Signal

The same principle was used for θ_t angle. The reference angle for rotation or smooth curve movements is 5 degrees for left or right. It was implemented a hysteresis of 5 degrees for a better behavior of referential system.

For a better processing of signals provided by the accelerometers, it was experimentally obtained the response of accelerometers relative to inclination of the helmet. The essay consists in vary gradually the θ_f and θ_t angles, measure by an inclinometer and capture the voltage signals produced by accelerometers located on the chair and on helmet respectively. The helmet, inclinometer and accelerometer is shown in Figure 5 .

The differential voltages $V_\Delta(\theta_f)$ and $V_\Delta(\theta_t)$ based on angles of inclination θ_f and θ_t are shown in Figure 6.

The data related to $V_\Delta(\theta_f)$ and $V_\Delta(\theta_t)$ can be approximated by a linear regression according to Equations 2 and 3.

$$V_\Delta(\theta_f) = 0.009818\theta_f + 0.03182 \quad (2)$$

$$V_\Delta(\theta_t) = -0.006887\theta_t - 0.005294 \quad (3)$$

With $V_\Delta(\theta_f)$ and $V_\Delta(\theta_t)$ in Volts and θ_f and θ_t in degrees.

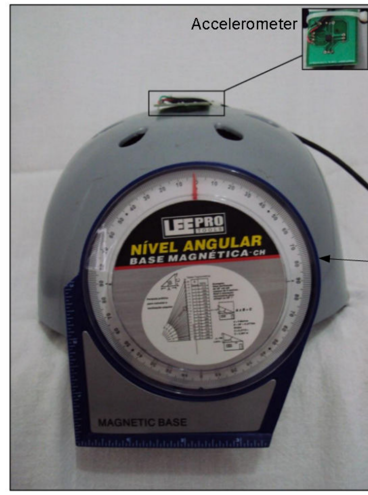

Fig. 5. Helmet, accelerometer and inclinometer

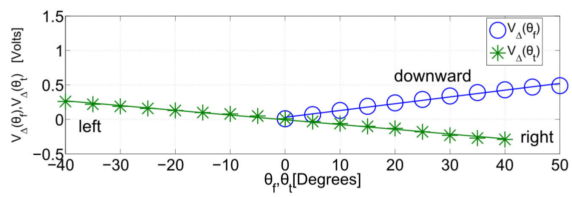

Fig. 6. Differential Voltages $V_\Delta(\theta_f)$ e $V_\Delta(\theta_t)$

The Equation 2 has a R^2 factor of 0.9895 in relation to experimental data, while Equation 3 presents a R^2 factor of 0.9938 demonstrating convergence from equations to experimental data.

B. Traction System

The traction system is composed by two 12V DC brushed motors with permanent magnets, linked mechanically to reducers of worm drive type. Each motor/reducer was linked directly to each wheel of the wheelchair with the objective to traction it. For a better knowledge of the motor/reducer assembly it was estimated the behavior of current, speed and efficiency in function of torque. First, the armature resistance was estimated by the blocked rotor test [9], then the no load test was executed to determine the behavior of the assembly with no load. The characteristics of the assemblies is shown in Figures 7 and 8.

Analysing the data presented by Figures 7 and 8 it can be noted the low efficiency of motor/reducer assembly. According [10] the nominal values of the motor, model 101400112 produced by Imobrás, related to efficiency, current, speed and torque are 70%, 13 A, 3000 RPM e 0.4 Nm. The assembly of the motor with the reducer model IBRQ030 [11], worm drive type, shows for motor nominal condition a efficiency around 25% which demonstrates that reducer has a efficiency around 35% for considered motor operation.

The motor drive is performed by two circuit boards based

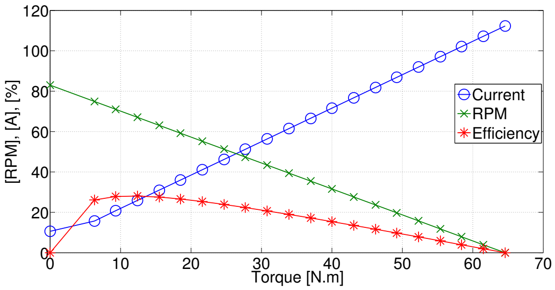

Fig. 7. Characteristics of Motor/Reducer 1

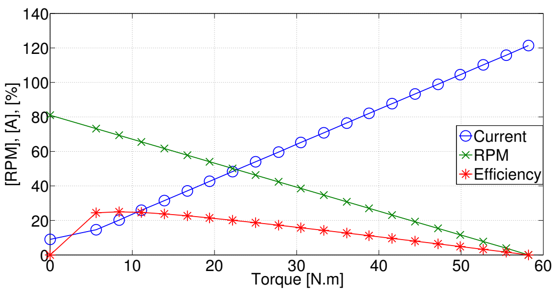

Fig. 8. Characteristics of Motor/Reducer 2

on integrated circuit BTN7960 [12]. The BTN7960 is a half bridge driver with several functionalities embedded as active freewheeling, automatic overtemperature and undervoltage shut down, current sense capability and PWM capability of up to 25 kHz. The continuous drain current of BTN7960 reaches up to 44 A.

C. Control and Sensing

The speed control of the wheels is a key feature desired by the project. The estimation of speed is achieved through the use of a incremental encoder, model E40S produced by Autonics [13], which has as main characteristics the generation of 1000 pulses per rotation, supply voltage and output in 5 V_{dc}.

The wheel's speed behaviour were mapped experimentally. Each wheel had the speed increased gradually and the frequency of the signal generated by encoder was measured by a digital oscilloscope, model Agilent DSO1072B, posteriorly, the wheel velocity was measured by a digital tachometer model MDT-2238A manufactured by Minipa. The data produced by the experimental test is shown in Figure 9.

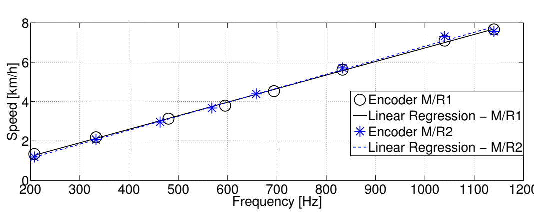

Fig. 9. Speed estimation using the encoder signal frequency

The data presented by Figura 9 can be approximated by linear regression by the following Expressions 4 and 5.

$$v_{MR1}(f_{e1}) = 0.006885.f_{e1} - 0.1614 \tag{4}$$

$$v_{MR2}(f_{e2}) = 0.00711.f_{e2} - 0.2997 \tag{5}$$

Where $v_{MR1}(f_{e1})$ and $v_{MR2}(f_{e2})$ are the speeds in km/h of right and left wheels respectively.

The Equation 4 has a coefficient of determination R^2 of 0.9987 and Equation 5 has a R^2 of 0.9969.

The control algorithm applied in the speed control was the PID algorithm. The motivation in the use of this algorithm is the simplicity and effectiveness in controlling applications with dominant dynamics of first and second order [14] . The algorithm can be summarized by Equation 6.

$$u_{PID}(e(t)) = K\left(e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt}\right) \tag{6}$$

Where $u_{PID}(e(t))$ is the control signal in Volts, $k_p = K$ is the proportional gain, $k_i = K/T_i$ is the integral gain and $k_d = K.T_d$ is the derivative gain. The variable e(t) represents the error produced by the difference between the speed reference v_{ref} and instantaneous speed which is estimated by the microcontroller using, first, the capture feature to determine the frequency of the signal provided by the encoder and then using it for the speed estimation by Equations 4 and 5.

The definition of the constants k_p, k_i and k_d were established by the step response method presented by Ziegler and Nichols and described in [14]. Posteriorly, the same constants were obtained by a method developed by Chien, Hrones and Reswick also described in [14]. The methods use the system response to a step input, in an open-loop configuration, and by means of a tangent line to the inflection point determines the constants used in the calculus of PID parameters. To turn possible the method implementation, it was effectuated a step response on each wheel to capture its dynamics and these data were applied for the estimation of a system model utilized in obtention of PID parameters. The system model obtained by the approximation of step response is shown in Equation 7.

$$\frac{V_{MR_{12}}(s)}{U(s)} = \frac{0.55e^{-0.022s}}{0.1s+1} \tag{7}$$

Where $V_{MR_{12}}(s)$ represents the Laplace transform of the speed of wheels 1 and 2 and $U(s)$ represents the Laplace transform of step function. It must be noticed that the difference between the dynamics presented by wheels 1 and 2 is less than 1% and because of that it was neglected and only the model described by Equation 7 was used. The voltage level defined in step input was 7.2 V and the final speed achieved by the wheels were around 3.79 km/h.

The controllers provided by Ziegler-Nichols and CHR methodology were tested individually on the system model described by Equation 7. The best result, taking into account the lower overshoot and shortest settling time, was chosen as wheelchair speed controller. The controller which presented the best system performance was the PI defined by CHR set point response method to 0% overshoot. The constants k_p and k_i are, respectively, 2.894 and 24.117. The system model response considering $v_{ref} = 3.79$ km/h in a closed loop configuration and with a PI controller actuation is shown by Figure 10.

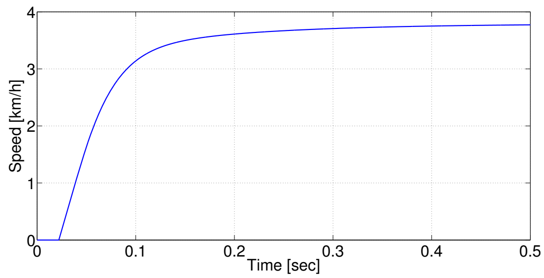

Fig. 10. System model response to a PI controller with $K_p = 2.894$, $K_i = 24.117$ and reference $v_{ref} = 3.79[km/h]$

The Tustin approximation [15] was used in the discretization of continuous PI established for the control system. The Equations 8, 9 and 10 demonstrate how control signal provided by discrete PI is estimated.

$$P(n) = k_p.e(n) \tag{8}$$

$$I(n) = I(n-1) + k_i.\frac{T_{sampling}[e(n) + e(n-1)]}{2} \tag{9}$$

$$u_{PI}(n) = P(n) + I(n) \tag{10}$$

Where P and I are, respectively, the proportional and integral portions of control signal, the u_{PI} is the control signal itself, $T_{sampling}$ corresponds to the sampling period and n is the index of the sample.

According to [15] the sampling period of the discrete PI controller $T_{sampling}$ can be defined respecting the condition 11:

$$0.1 \leq T_{sampling}/T_i \leq 0.3 \tag{11}$$

The sampling time $T_{sampling}$ was defined as 0.02 seconds that satisfies the condition 11, resulting in $T_{sampling}/T_i = 0.167$.

The central processing unit of the system is the evaluation kit STM32VL Discovery [16] based on the 32 bits ARM Cortex-M3 microcontroller STM32F100RB, produced by STMicroelectronics. This microcontroller has several features like A/D channels of 12 bits resolution, D/A converters, PWM channels, digital inputs/outputs, USART, SPI and I2C communication interfaces. The microcontroller firmware was developed using the Coocox free/open ARM cortex MCU development tools [17] which is based on Eclipse IDE and GCC compiler.

The functional test of wheelchair controlled by cervical movements is shown in Figure 11.

Fig. 11. Functional test of wheelchair controlled by cervical movements

IV. Results

In order to provide better security to the user, the wheelchair was defined to work at a constant speed, with the speed control system generating a acceleration ramp at the beginning of the movement and a deceleration ramp in braking. A speed of 3.2 km/h for the operation of wheelchair was adopted. In implementing the response of both sets motor/reducer proved identical. Tests were performed to verify whether the gains of PI system were in line with expectations, since the controller design was performed in countertop without charge. The ramp response of the wheels is shown in Figure 12.

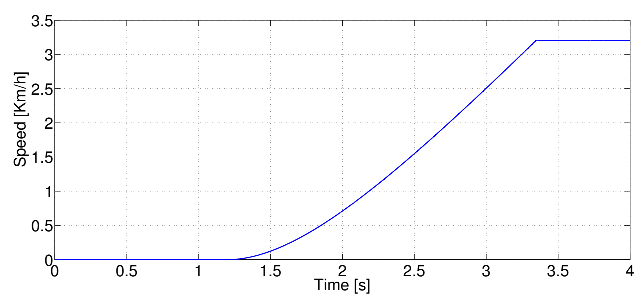

Fig. 12. Ramp response of wheels

The wheelchair has shown constant velocity on commands move forward, turn left and right smoothly and rotation to the left and right. It was implemented a test where the angle θ_f was achieved 30 times and the movement of the chair was checked in the horizontal plane. Afterwards, the lateralization head movement was executed 30 times, with the wheelchair in forward movement, achieving the angle θ_t and the smooth turn left and right was checked. The last test was made with the wheelchair stopped and the angle θ_t being achieved by the head lateralization movement and the rotation movement of the wheelchair was checked. In a total of 30 forward commands, the wheelchair moved forward 30 times, achieving 100%

of success, in 60 smoothly turn commands the wheelchair succeeded 28 times to left and 29 times to right. The rotation movements had the worst results achieving 23 successes in 30 commands (left) and 21 successes in 30 commands (right). The same tests were executed on slope relief and the commands produced similar responses over the system.

An experiment was performed to test the effectiveness of the RC filter. In Figure 13 is shown the θ_f estimated by the measurement of the signal provided by the accelerometer positioned in the helmet. These experimental data were obtained positioning the helmet in a surface producing, initially, a 5 degrees angle between the sensor and surface. The system used in this experiment is equipped with a motor and springs responsible for producing the vibration.

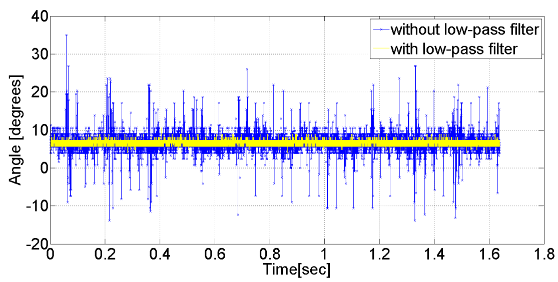

Fig. 13. Vibration effect over θ_f estimation

The Figure 13 shows that several times, in absence of low pass filter, the θ_f angle estimated based on the accelerometer signal exceeds 10 degrees, which would make the system recognize a forward movement command while the effect of vibration is suppressed by the presence of the low pass filter.

V. Discussions and Conclusions

The wheelchair controlled by cervical movements has shown that people with tetraplegia can have more independence and, consequently, better quality of life. This project has presented an additional feature on the generation of wheelchair commands (move forward, turn/rotation left and right) which is the use of two accelerometers. One accelerometer is applied as a reference on the wheelchair basis and the second is used as an inclinometer on the top of the user's head. The use of 2 accelerometers allows the wheelchair system to use the signals provided by the accelerometers in the differential form, facilitating the use of the wheelchair by a tetraplegic user on different reliefs. A secondary concern of the project was avoid that vibrations from ground irregularities interfered on commands generation, so, a RC low pass filter was implemented to give greater robustness on the wheelchair commands generation and have shown effectiveness in noise suppression.

The commands have shown the success ratio that follows: move forward, 100%, turn left and right softly, 93% and 97% respectively and rotation to left and right 77% and 70%. The decay on effectiveness of the wheelchair response to the commands is explained by the positioning of the user's head accelerometer, which has shown to be critical. The displacement of the user's accelerometer can compromise the commands generation.

The worm drive reducer must be substituted by a more efficient one, since the set composed by motor/reducer has only 25% of efficiency for nominal operation. Maybe a helical reducer, which is frequently used in commercial motorized wheelchairs is the most suitable for this application.

Some mechanical adjustments must be made since the mechanical transmission is linked directly to the center of the wheel and the wheel used in this project is from a manual wheelchair, with a radius around 30 cm which provides a high moment of inertia, overloading the motor/reducer.

Another improvement that could be cited is the use of a dedicated microcontroller in the speed estimation since the input capture feature of STM32100RB could estimate with precision, in this project, frequencies above 200 Hz. This behavior produces a deadzone in the speed estimation that can disturb the control system.

The telemetry system would improve the system performance significantly since all parameters of the wheelchair could be monitored in real time. This type of resource would allow the study of more efficient algorithms to control the wheelchair and would make the development of a calibration system easier which could assist patients with different degrees of cervical mobility.

Acknowledgment

The authors would like to thank Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPQ) for financial support, the Imobrás company for the donation of motors/reducers, the STMicroelectronics for the donation of accelerometers and microcontrollers and Ortobrás for the donation of the wheelchair.

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