DESIGN, DEVELOPMENT, AND USABILITY EVALUATION OF CONTROL ALGORITHMS FOR A MOBILITY ENHANCEMENT ROBOTIC WHEELCHAIR (MEBOT)

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An Electric Powered Wheelchair (EPW) is a key mobility device for people with disabilities providing mobility, independence, and improved quality of life. However, the design of current EPWs remains limited when driving in environments with architectural barriers and uneven terrain, making EPW users susceptible to safety issues - such as tipping or falling - which may lead to serious injury. To overcome these limitations, we developed a series of control algorithms for a novel mobility enhancement robotic wheelchair (MEBot).

MEBot consists of six wheels with pneumatic actuators to control the elevation and inclination of the wheelchair as well as electric actuators in the driving wheel carriage to change its driving wheel configuration. Its controller is comprised of a single board computer, and a sensor package that aids obstacle detection and provides information about joint movements to develop MEBOT's control algorithms. The ability of the MEBot controller to perform control algorithms, such as the dynamic seat leveling, curb climbing, and descending applications, was evaluated and validated in both simulation and a controlled environment for broader accessibility in architectural barriers. A stability analysis showed that while the footprint of the wheelchair changed during the process of its control algorithms when overcoming architectural barriers such as curbs and slopes; MEBot maintained its center of mass within the wheelchair footprint.

Furthermore, a usability evaluation with ten power wheelchair users was conducted to compare the MEBot's controller with that of their own power wheelchair in simulated indoor, outdoor, and advanced (architectural barriers) environments. Results show that MEBot was able to perform a significantly higher number of tasks than currently available commercial power wheelchairs in the advanced environment. In addition, participant's feedback was obtained for further improvement of the device and its control algorithms.

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PREFACE

"The virtue lies in the struggle, not in the prize" – Richard Monckton Milnes

The following PhD work entails years of hard work at the Department of Rehabilitation Science and Technology of the University of Pittsburgh and Human Engineering Research Laboratories of the VA Pittsburgh Healthcare System.

I would like to thank my advisor, Dr. Rory Cooper, for his mentorship and professional guidance throughout the PhD program. Dr. Cooper has inspired me to be an advocate for people with disabilities through the creation of assistive technology to provide them a better quality of life. I would like to thank Rosemarie Cooper for her clinical mentorship to make me think outside of the 'engineer box' and put myself in the 'wheels' of the end-users. I would like to thank Dr. Cheng-Shiu 'Joshua' Chung, Brandon Daveler, Andrea Sundaram, and the 'MEBot team' for their professional assistance in the design and development of the MEBot wheelchair. In addition, I would like to thank Dr. Hongwu Wang, a colleague and a friend who always had an answer for every question I had in regards of school, research and life besides work. Additionally, I would like to thank Deepan Kamaraj for his assistance and full support with subject testing and enlighten me with his writing skills.

My unconditional gratitude to HERL and the machine shop staff, especially Dr. Garrett Grindle and Ben Gebrosky, for the countless hours and patience helping to design, manufacture, and test the MEBot wheelchair. Thanks to all my friends, family and colleagues for their full support throughout these years. To my fiancée Anastasia Martin, my partner and friend who provided me strength and support when I needed it the most.

1.0   INTRODUCTION

This chapter presented the importance of an electric power wheelchair (EPW) for people with mobility impairments and the limited improvements of EPW design to encounter architectural barriers and everyday environments. Furthermore, current technology of commercial and research and development (R&D) mobility robots addressing the problem statement was described as well as their design limitations. At the end of the chapter, the aims of the research were presented.

1.1   THE IMPORTANCE OF AN APPROPIATE ELECTRIC POWER WHEELCHAIR FOR EVERYDAY ENVIRONMENTS

An Electric Powered Wheelchair (EPW) is a mobility device for people with disabilities providing mobility, independence [1], access to communities, satisfaction [2], and improvement of their quality of life [3]. The Centers for Medicare and Medicaid Services (CMS) reported 46,134 EPWs provided to end-users in 2009 [4]. As of 2010, there was an estimate of 400,000 people who benefited from electric powered wheelchairs (EPWs) and it is expected to increase as the baby boom generation grows older [5].

1.1.1 EPW limitations and architectural barriers

However, the wheelchair industry has made minor improvements in EPW design in the past 10 years which has included wheelchair suspension to minimize vibration exposure [6], and expanded user interfaces [7]; while EPW's durability has not shown further improvement [8]. Policy-wise, EPWs are designed for indoor use [9] and limited improvement has been done for driving outside the house. Most users are limited to drive in indoor environments and have difficulties or avoid driving over uneven terrains, steep hills, cross slopes, slippery surfaces, and overcoming architectural barriers [10]. Salatin's study showed that most common accidents while driving an EPW were loss of traction, getting stuck (immobilized) or loss of stability. As result of these accidents, research on wheelchair accidents showed that in 2003, more than 100,000 wheelchair related injuries were treated in emergency departments in US, and tips and falls accounted for 65-80% of injuries [11, 12]; while another study showed that of 600 wheelchair users, 57.4% had completely tipped or fallen from wheelchair and 16% of these accidents occurred outdoors or on ramps [13]. In a survey study reported by Edwards, it was reported that electric powered wheelchairs provided mobility and independence; however, a challenge that EPW users described while driving their EPW was difficulty accessing environmental barriers such as curbs and uneven footpath or ground. Most commonly reported accidents were tipping over which in some cases led to hospitalization [14].

The cause of this driving behavior is mainly due to architectural barriers that do not comply with the Americans with Disabilities Act Accessibility Guidelines (ADAAG) [15, 16] and the lack of safety, stability, and surface/obstacle negotiation capability in current EPWs [17]. A significant challenge is to design an EPW that is suitable for the confined indoor environments of most homes,

highly functional in outdoor built environments, and effective in unstructured outdoor environments. Further, the EPW must provide smooth driving to perform reliable desired functions and accommodate the physical impairments of EPW drivers to include powered seating functions, and alternative controls.

1.1.2 EPWS in the market and R&D mobility robots

Research has reported that EPW users highlighted safety to prevent tips/falls, accessibility in architectural barriers, and proper maneuvering in indoor and outdoor environments as requirements/needs for an adequate assistive mobility device [10, 18] . The mobility-robotics industry has addressed most of user's needs by opting to four types of robot drive modes [19]: wheeled, tracked, legged and a hybrid of wheeled-legged robots (Figure 1). Wheeled robots are characterized by the use of active driven wheels as well as large size wheels and passive suspension to overcome obstacles and rough terrains for accessibility in outdoor terrains. Examples of these robots are the MARS Rovers robot using a rocker-bogie suspension and large diameter wheels (20 inches) to overcome big obstacles [20] and the SHRIMP/SOLERO robot which uses a rhombus configuration with two bogies for steering and a passive suspension to negotiate obstacles [21].

Electric powered wheelchairs are wheeled robots with a suspension linkage mechanism and a controller for steering [17]. Permobil, an EPW manufacturer, offers EPWs with different drive wheel configurations for indoor maneuvering and a passive suspension system in its wheels to overcome small curbs (less than 3") for outdoor driving [22]. The Viking Explorer wheelchair [23] is composed of four driving wheels, high wheel suspension and autonomous self-leveling

fore-after tilting seat to address the accessibility needs, and seat leveling when driving up and down angled slopes. However, its footprint limits its maneuvering to outdoor environments.

Figure 1: Mobility-Robotic designs, wheeled (top-left), tracked (top-right), legged (bottom-left), and hybrid legged-wheel (bottom-right) robots

Tracked robot such as the GALILEO robot and Department of defense (DoD) robots are developed for terrain exploration and bomb de-activation called Packbots. These vehicles use stacked-wheels to drive over rough terrain. Their disadvantages lie in their lack of control for different payloads, difficulty to turn due to lateral forces, high shifts in center of gravity, and low speeds [24]. The GALILEO/VIPeR is another tracked-wheeled robot [25] which is branching out towards assistive mobility vehicles. Limitations of wheeled and tracked robots are mainly overcome by increasing the footprint and use of bigger wheels, which makes them ineffective for indoor use.

Legged robots have been proposed as an alternative mobility device to address accessibility and outdoor maneuvering. These mobile robots use articulated legs with multiple degrees of

freedom, complex software control and higher kinematic requirements to adapt to uneven terrains better when compared with wheeled robots. PetDog, a legged robot from Boston Dynamics [26], uses four air-legged actuators and feedback control to provide high stability and adaptability in uneven terrains. Other robots like the Scout II [27] and RHex [28] have demonstrated similar capabilities with small payloads. Despite their advantages to traverse outdoor environments, legged robots demonstrated to be inefficient when traversing accessible terrains due to their mechanical design and high vibration exposure for the rider. Another limitation is the lack of participatory action design (PAD) and exclusion of user with disabilities since these devices are developed towards ground exploration and weight transportation.

Both wheeled and legged robots show pros and cons which can be combined into a hybrid robot of wheeled and actively articulated vehicles (WAAVs) [29]. These robots control the elevation of the wheels with the use of leg actuators, wheels mechanism, and a position/force control algorithm to drive over uneven terrain. Robots such as the Roller-Walker robot [30], Hylos [31], and PAW robot [32] are examples of hybrid wheeled-legged robots which maintain their posture under discrepancies in the ground surface. Although the latter mobile robots are only used for small loads; it provides the idea of safety by maintaining the robot posture in uneven terrains as well as proper maneuvering in indoor and outdoor environments.

1.1.3   Test-bed step climbing robots

Accessibility in buildings has been a challenge for commercial EPWs due to its limited mechanical design to overcome architectural barriers like steps and building that do not comply with ADA accessibility guidelines [15]. Research in assistive mobility devices using wheeled-legged robots

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has been developed to climb steps. The wheelchair "q" [33] uses 9 wheels and a planetary gear motion to reach steps while the EPW wheelchair from University of La Castilla-La Mancha [34] uses a foot deployed on each step as well as actuated wheels and four bar linkages to climb steps. A similar concept was developed by Nagasaki University who designed an eight-wheel wheelchair with an extendable rear arm to reach high steps [35]. While the need for accessibility is addressed; other user's needs such as maneuvering and safety in uneven terrains are missing.

More advanced prototype designs of electric powered wheelchairs include the RT-Mover robot [36], a self-balancing and climbing robotic wheelchair with one actuator that controls the up/down movement of caster wheels. The RT-Mover provides safety and accessibility for the EPW user; however, its large footprint makes it difficult to maneuver in indoor environments as well as having a slow response time for outdoor driving.

The iBOT3000 [37], no longer on the market, was an EPW with unique combination of capabilities addressing the common issues in electrical powered wheelchairs. Its flexibility allowed the iBOT to balance on two wheels, going up and down steep ramps, drive over outdoor surfaces (e.g., grass, dirt trails) and climbing steps. Unfortunately, the user required good upper range of motion and proper shift in its center of gravity in order to climb steps; in addition, it was unable to accommodate people who required powered seat functions. The TopChair is a climbing EPW only available in the European market which includes the same features as an EPW with the addition of a track under the base which is activated only during a climbing sequence for accessibility [38]. This feature, however, makes the wheelchair heavier than standard EPWs and does not provide information for safety in uneven terrains.

Several researchers have developed EPWs with the ability to drive in uneven terrains for outdoor use or successfully overcome architectural barriers for accessibility; however, these

applications have been demonstrated individually in separate research studies and not yet combined; in addition, these applications require of a complete modification of the classic EPW which results in a large footprint, limited turning ratio and driving performance which makes it difficult for proper maneuvering in indoor use. User's needs such as safety, accessibility and maneuverability for indoor and outdoor use should be taken in account in the design of assistive mobile robots.

1.2   RESEARCH AIMS

The overarching goal of this study is to design, implement, and evaluate the usability of the control algorithms of a novel mobility enhanced robotic power wheelchair (MEBot). The MEBot's purpose is to improve safety in uneven terrains, provide accessibility to overcome architectural barriers and provide proper maneuvering in indoor and outdoor environments that end-users of current EPWs encounter. The methods for achieving the study's goal will utilize the following aims:

Aim 1: To design and implement the necessary electronics and sensory system into the prototype mobility enhanced robotic power wheelchair to meet the following criterion:

1. Modular to incorporate plug-and-play peripherals.

2. Robust to conduct field tests.

3. Real-time control operation for smooth operation.

4. Reliable for the user and researcher.

Aim 2: To develop and evaluate a series of control algorithm models to aid MEBot in navigating slopes, cross slopes and steps using the following design criteria:

1. The controller should be able to detect the angle change in the ground and seat in real-time within error change of +/- 0.2°.

2. The controller should be able to maintain a horizontal leveled seat while ascending-descending 10° slopes and rolling across side-slopes of 5° [15].

3. The controller should be able to maintain a horizontal leveled seat under uneven environments in real-time for an average speed of 0.5 m/s [39]

4. The controller should be able to guide MEBot in climbing curbs of up to 20 cm high. [40]

5. The controller should be able to guide MEBot in climbing curbs within a time frame of 30 seconds (same time needed to cross a street light).

6. Must meet ANSI/RESNA standards Static Stability (Section 2), Dynamic Stability (Section 3), and Maneuvering-Space (Section 5) similar to commercial electric powered wheelchairs [40, 41]

Aim 3: To perform a usability study to compare MEBot with other commercial EPWs in a controlled real-world environment to evaluate the capabilities and limitations of the MEBot's control algorithms.

Aim 4: To evaluate and implement the mobility applications of MEBot based of the participant's feedback and mobility strategies.

The following chapters explain the design process of MEBot and its control algorithms. Chapter Two describes the design, development, evaluation, and implementation of the MEBot wheelchair and its control algorithms. The hardware and software design were addressed in Aim 1 and Aim 2 criteria. The first iteration of the control algorithms was described and evaluated in

both simulation and a controlled environment. A second iteration of MEBot and its control algorithms were presented based on results from its first iteration. As part of the design criteria, wheelchair testing standards were performed to analyze MEBot stability. Chapter Three presents the design and development of the attitude control graphical interface (ACGI). The ACGI was designed to allow end-users to operate the elevation and inclination of the wheelchair through the movement of the wheels as well as through a visual display that provides feedback when the wheels were in contact with the ground. Furthermore, in Chapter four, a usability evaluation with ten power wheelchair users was conducted to compare MEBot's control algorithms with that of their own power wheelchair in simulated indoor, outdoor, and advanced (architectural barriers) environments. MEBot was evaluated in three usability domains according to the ISO 9241-11 definition: effectiveness, efficiency, and satisfaction. In addition, participant's feedback was obtained for further improvement of the device and its control algorithms. In Chapter Five, an exploratory analysis of the driving strategies of the participants when driving architectural barriers was performed. The goal of this chapter was to discover alternative strategies that may ease overcoming architectural barriers for further improvement of the control algorithms in compare to those learnt during the training phase. Chapter Six provides a summary of the research study and future work.

2.0 TOWARDS THE DESIGN AND DEVELOPMENT OF A MOBILITY ENHANCEMENT ROBOTIC WHEELCHAIR (MEBOT)[1]

Participatory action design (PAD) is described as a research approach to the development of technological solutions in close cooperation with end users [42]. The PAD process used iterative cycles involving a plan, action, observation, and revised plan [43] which translates into the design, development, evaluation, and implementation of this project. Chapter Two described the design process of MEBot and its control algorithms towards its final iteration. The design, development, and evaluation of the first prototype of MEBot's control algorithms were presented. As part of the PAD process, a focus group provided feedback of MEBot's capabilities and limitations for further improvement. User's feedback along with revisions from the first prototype were addressed in the following iterations of MEBot and its control algorithms.

2.1 HARDWARE AND ELECTRONICS DESIGN

The first iteration of MEBot consisted of six wheels with air pneumatic actuators on them to elevate/lower the frame as well as a linear actuator in the driving wheels to opt for three different driving wheel configurations: rear, mid, or front wheel-drive mode [44]. Its seat contained the common seating functions of tilt-in-space, recline, and foot rest elevation for pressure relief and

user's comfort [45]. Furthermore, additional seating functions such as seat elevation, lateral tilt and anterior tilt-in-space were provided by the movement of the air pneumatics actuators in the frame. The first prototype of the MEBot controller included an embedded computer EBX-COBRA (Versalogic, OR) connected to a PC/104 computer stack in order to read sensors and output signals to the motor drivers and air manifold as seen in Figure 2. The sensors included membrane position sensors attached in each air pneumatic actuator to calculate the height position of each wheel, an analog six degree of freedom Inertial Measurement Unit (IMU) (O-Navi, CA) to measure the pitch and roll angle change of the seat, and digital incremental encoders attached to both drive wheels to provide the acceleration and linear velocity of MEBot. The MEBot controller was programmed in C/C++ language using the VxWorks real-time operating system.
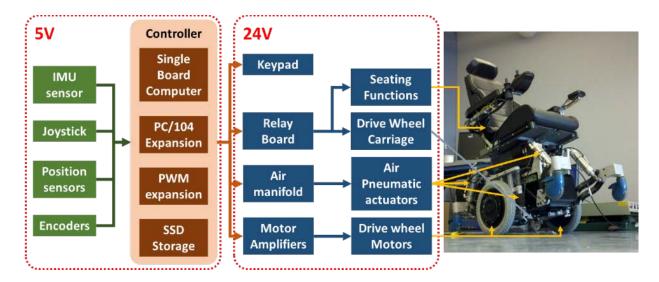
Figure 2: Hardware and electronics components of MEBot 1st prototype

Two motor drivers (50A8DDE, A-M-C, CA) were used to control the speed/direction of driving wheels (GOLDEN Motors, CA) with a 2-axes joystick. The air pneumatic actuators (Clippard Minimatics, Belgium) were connected to an air manifold (SMC, Japan) that regulated the air pressure through a pulse-width-modulation (pwm) signal. The motor drivers and air

manifold were powered by 24V from the batteries. In addition, a DC-to-DC converter transformed

the 24V into a 5V to power the computer and low-power sensors.

2.2   EVALUATION OF THE MEBOT CONTROL ALGORITHMS

By combining the electrical and mechanical design of MEBot we develop a series of control

algorithms to enhance the driving performance of EPW users when driving in all environments.

The control algorithms architecture entails the use of a sensing system along with the kinematics

model of MEBot; these are fed back into a close-loop system to control the movement of the air

pneumatics actuators and drive wheels. The output of the close-loop system aids to the

development of MEBot's mobility applications (Figure 3). The seating posture and mobility

performance of the wheelchair are monitored within the control algorithms for the safety and

comfort of the end-user.
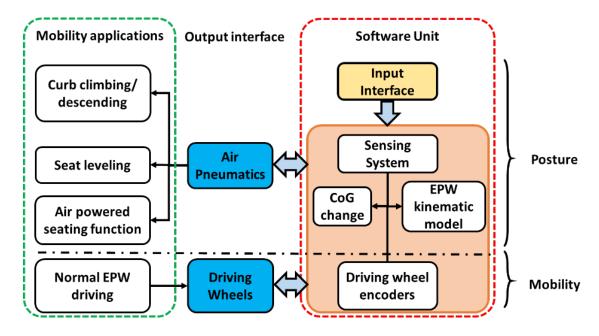
Figure 3: Control algorithms architecture diagram

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2.2.1   Seat leveling algorithm[2]

The current EPW design limits most users to drive in indoor environments with firm and reasonably flat surfaces. Furthermore, research has shown that driving their EPW over outdoor environments that are non-compliant with ADA standards, such as cross slopes (2°max) and ramps (5°max) [15], causes a shift in the EPW center of mass that leads to lack of stability control of the EPW [17], thereby increasing the risk of tips and falls [10, 12, 46]. In order to address this issue, MEBot utilizes the air pneumatic actuators of the wheels along with its sensing system to maintain its seat leveled when driving over these environments [47].

The dynamic seat leveling algorithm is divided into two components. The upper-level control uses the Inertial Measurement Unit (IMU) to determine the pitch/roll angles of the MEBot's seat. The seat angles are used with an internal mathematical model to determine the desired instantaneous position of each pneumatic actuator to maintain the seat orientation. The model reference position is used in a closed-loop low level proportional-derivative (P-D) control for position regulation of each pneumatic actuator. The model is updated based upon the IMU data. Both levels of the seat leveling algorithm are sampled every 1.0 milliseconds.

Upper Level Control:

The IMU detects the angle change in the seat while position sensors detects the actual position of each air pneumatic actuator. This section describes the use of the IMU sensor to obtain the desired

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[2] J. Candiotti *et al.*, "Design and evaluation of a seat orientation controller during uneven terrain driving," *Medical engineering & physics,* 2016.

position of the frame height to compare it with the actual position of the frame height calculated by the position sensors.

Frame height calculation using IMU (desired position):

The IMU sensor ONI-23503 (O-NAVI, CA) is composed of an accelerometer and gyroscope with a range of +/- 2.0g and +/- 150°/s respectively. In order to obtain the pitch, θ, and roll angle, φ, of the wheelchair seat, the IMU sensor data is filtered through a complementary filter (Figure 4a). The filter decreases the high frequency noise of the accelerometer data by passing it through a low pass filter and eliminates the drift over time for the gyroscope in the high pass filter [48]. The complementary filter provides the pitch and roll angles with a sensitivity of ±0.25°.
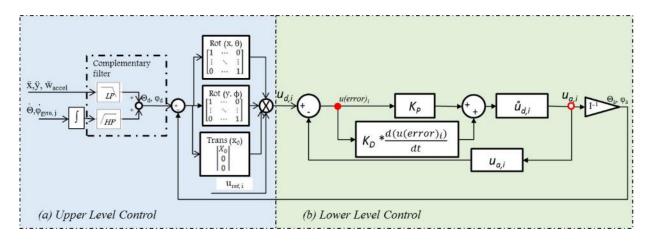
Figure 4: Seat leveling algorithm Diagram: (a) Upper Level Control (b) Low Level P-D Control

Given the angle change in pitch and roll, the desired position of each pneumatic actuator i is calculated to obtain the desired frame height. Figure 4a shows the process diagram to obtain the desired position of each pneumatic actuator where θ_d and φ_d are the desired pitch and roll angles, respectively. u_{ref} represents the reference position of the frame when the seat is flat, and Rot (x, θ), Rot (y, φ), Trans (xo), and Trans (zo) represents the transformation matrix in the pitch, roll, x-axis direction, and z-direction, respectively. $u_{d,i}$ is the desired position of each pneumatic i.

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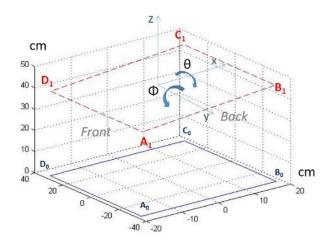
Figure 5: Calculation of desired position for each corner (A1, B1, C1, D1) of the frame using the pitch (θ) and roll (φ) angle measured by the IMU

Figure 5 shows the desired position of each pneumatic actuator (A_1, B_1, C_1, D_1). The equation newMEBot is calculated by the product of the MEBot matrix (eq. 1), which is the initial coordinates of each corner of the frame (A_0, B_0, C_0, D_0), and the rotational/translational transformation matrix IMUangle (eq. 2) with respect to the pitch, roll, driving wheel position (x_0), and height of the top frame (z_0). This operation allows the seat leveling algorithm to extend/compress the pneumatic actuators to reach the highest pitch and roll seat angles. The matrix Translate Z-axis, Trans (z_0), shifts the position reference to the mid-point from the lowest and highest ground clearance of the frame; matrix Translate X-axis, Trans (x_0), is used to perform the seat leveling algorithm at different wheel drive modes (rear-, mid-, or front-wheel drive). Trans (x_0) measures the position of the driving wheel along the frame.

$$\textbf{MEBot} = [\textbf{A}_0 \quad \textbf{B}_0 \quad \textbf{C}_0 \quad \textbf{D}_0] \qquad (1)$$

$$\textbf{IMUangle} = \textbf{Rot}(x, \theta) * \textbf{Rot}(y, \Phi) * \textbf{Trans}(x_0) * \textbf{Trans}(z_o) \qquad (2)$$

$$\textbf{IMUangle} = \begin{bmatrix} \cos\phi & 0.0 & \sin\phi & X_0 \\ \sin\theta\sin\phi & \cos\theta & -\sin\theta\cos\phi & 0.0 \\ -\cos\theta\sin\phi & \sin\theta & \cos\theta\cos\phi & Z_0 \\ 0.0 & 0.0 & 0.0 & 1.0 \end{bmatrix}$$

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A final matrix newMEBot (eq. 3) determines the desired position $u_{d,i}$ of each corner of the frame (A_1, B_1, C_1, D_1) in the local coordinates.

$$\mathbf{newMEBot} = [\mathbf{A_1} \quad \mathbf{B_1} \quad \mathbf{C_1} \quad \mathbf{D_1}] \qquad (3)$$

Frame height calculation using position sensors (actual position):

In order to maintain the seat orientation for any given surface running slope or cross-slope angle, the actual position of the frame height is first calculated by measuring the height of each corner of the frame using the instantaneous stroke length of each pneumatic actuator as seen in Figure 6, and compared with the desired position of the frame height obtain in "***Frame height calculation using IMU (desired position)***".
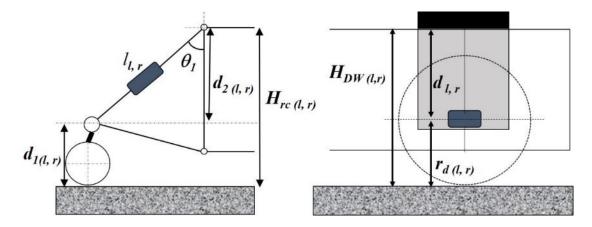
Figure 6: Calculation of height of the Frame w.r.t rear casters and driving wheels

Given the length of the rear casters arms (left and right), $l_{l,r}$, and the angle joint between the caster arms and the frame, θ_1, the distance between the rear top frame and the caster arm joint, $d_{2\ (l,r)}$, can be determined:

$$\mathbf{d_{2\ (l,r)}} = \mathbf{l_{l,r}} * \mathbf{cos\ \theta_1} \qquad (4)$$

In order to calculate the height of the frame at the location of the rear casters, $H_{RC\ (l,r)}$:

$$\mathbf{H_{RC\ (l,r)}} = \mathbf{d_{1\ (l,r)}} + \mathbf{d_{2\ (l,r)}} \qquad (5)$$

where, $d_1 (l, r)$ is the distance between the caster arm joint and ground.

The front edge of the frame is calculated at the location of the driving wheels as it reflects the location of the footprint of the wheelchair. Given the radius of the driving wheels, $r_{d (l,r)}$, and the length of pneumatic actuators plus stroke at the driving wheel arms (left and right), $d_{l,r}$, the height of the frame at the location of the driving wheels, $H_{DW (l,r)}$, is calculated:

$$\mathbf{H_{DW (l,r)} = d_{l,r} + r_{d (l,r)}} \qquad (6)$$

The length of the pneumatic actuator is constant while its stroke is obtained using a position sensor to measure the extension or compression of the actuator. These values are compared with the desired position in each pneumatic actuator and sent into the low-level P-D control to move each pneumatic actuator to the desired position. The actual position of each pneumatic actuator $u_{a,i}$ was used to obtain the actual pitch θ_a and roll angles ϕ_a and feedback into the higher level controller (Figure 4a). The final pitch and roll angles fed into the transformation matrix are the angle errors between the desired pitch/roll and actual pitch/roll angles.

Low level P-D control:

The low level control regulates the position of each pneumatic actuator using the error between the desired position and its actual position. Each pneumatic actuator i is controlled using a P-D control to maintain each desired position as shown in Figure 4b.

$u_{d,i}$ is the desired position for each pneumatic actuator ($i = 1..4$), $u_{a,i}$ is the actual position of the pneumatic actuator i, $\mathring{u}_{d,i}$ is the desired speed of the pneumatic i with maximum/minimum threshold speeds, and K_D and K_P are the derivative and proportional gains, respectively. The gains were calculated through an empirical evaluation The desired speed $\mathring{u}_{d,i}$ of the pneumatic i is converted into a PWM signal which is fed into the air manifold that regulates the air volume going

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into each pneumatic actuator. $\mathring{u}_{d,i}$ is set to a minimum and maximum speed threshold per pneumatic actuator i due to the non-linearity of the system. A linear response was obtained over a duty cycle of 35% to 45%; however, no response was shown at duty cycles lower than the minimum duty cycle threshold. In order to provide an energy-efficient system, the seat leveling algorithm is activated only if the actual pitch/roll angles pass an angle change threshold of $\pm 0.5°$. This way, the system does not consume air and battery power within the angle change threshold.

A unit step response was used to test the target position of a pneumatic actuator in the low-level P-D control with optimized gains of K_P: 6.0 and K_D: 0.002. The settling time for the caster and drive wheel pneumatic actuators were 154.0ms and 283.0ms for a 10% steady-state error, respectively. The settling time difference between actuators were due to a combination of the hardware components, i.e., (1) the delay time in each valve was 20ms and (2) the drive wheels were attached to a one-way air spring actuator to extend it and required an external spring to compress the actuator. Each driving wheel and caster pneumatic actuator is rated to tolerate a pressure of 100 psi and 250 psi, respectively, which was sufficient to neglect the user's weight in the controller. The control system model assumed an unlimited air source, no change in the gas temperature, and constant air pressure.

2.2.1.1 Experimental set-up

MEBot was tested in both static and dynamic experimental set-ups to compare its behavior with and without the activation of the seat leveling algorithm. These tests were performed (Figure 7) within the Computer Assisted Rehabilitation ENvironment (CAREN, MOTEKFORCELINK Medical, Amsterdam) [49], The CAREN was a simulation environment that incorporated a 6 degree-of-freedom (pitch (y'), yaw (z'), roll (x'), surge (x), sway (y), and heave (z) axes) Stewart

platform [50, 51], 10 passive motion capture cameras (VICON Motion systems, Oxford, England) and a split belt instrumented treadmill. The CAREN was able to provide positional data of the wheelchair, which were utilized to calculate the center of pressure of MEBot.

Figure 7: Experiment Setup: MEBot on the CAREN system

The purpose of the static test was to quantify the system response, reliability, and practicability of the algorithm to maintain the seat orientation over nominal slopes as described by the ADA standards for accessible design in ramps and cross-slopes [52]. The static test was composed of four consecutive angles (2, 4, 6, 8, and 10 degrees) in four directions: lateral (roll) right, lateral (roll) left, pitch forward and pitch aft directions, which simulated MEBot driving on cross-slopes and up/down slopes, respectively. The speed of the motion platform was set at 1°/s and it returned to a flat level surface in between each test angle; with the process repeated for each direction. Further, static analysis was conducted to determine the location of the Center of Pressure (CoP) and tipping points of the MEBot when it was placed at different slopes in the static test with

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and without the seat leveling algorithm activated. The motion capture cameras and force plates incorporated with the CAREN measured the magnitude and position of the CoP.

The dynamic test simulated MEBot driving over an uneven surface. In addition to assessing reliability and practicality, the dynamic test was intended to test the limitations in the controller response at different platform speeds with different combinations of pitch and roll angles. To simulate an uneven surface the pitch and roll angles of the CAREN's motion platform was set simultaneously at ± 3.0 amplitude sine and cosine wave, respectively. The wave frequency of the motion platform was initially set at 1.85°/s due to the maximum speed of the CAREN platform and then decreased to 0.61°/sec and 0.37°/s; or linear speed 0.37m/s, 0.12m/s, and 0.07m/s, respectively. The linear speed was determined using the time it takes to drive the length of the wheelchair, while simulating a transition from horizontal ground to an uneven terrain, as shown in the equation below:

$$Linear\ Speed = \frac{CAREN\ angular\ speed}{maximum\ angle} * wheelbase\ length\ (\ 7\ )$$

Four 14mm reflective markers were placed, one at each corner of the seat, to detect the change in seat angle using the motion capture system; the angle of the platform with respect to the horizontal was collected using position sensors in the platform's hydraulic actuators. A test dummy weighting 180lbs was seated in the wheelchair to simulate a person while testing the algorithm. For both tests, it was assumed the wheelchair user drives into the slope at constant speed; therefore, the CAREN platform increased the slope angle at a constant speed as well. Primary outcome measures collected were the CAREN's platform angles (pitch and roll), MEBot's seat angles, and angle error between seat angle and the surface, which was used as the reference angle. Each measure was collected at a sampling frequency of 100Hz.

2.2.1.2 Results

Static and Dynamic test evaluation:

The results of the static test at consecutives angles of 2, 4, 6, 8, and 10 degrees in the lateral (roll)

right, lateral (roll) left, pitch forward and pitch aft directions were shown in Table 1. The results

demonstrated that when the seat leveling algorithm was not activated, the seat angle tilted along

with the angle of the platform. However, when the algorithm was activated the seat stayed

horizontal by maintaining its pitch and roll angles within an angle range of $\pm 0.5°$ as designated

by the limits designed within the control algorithm.

Table 1:Experimental Results: Pitch and Roll results for static test in each direction

Angle (°)	Lateral Left		Lateral Right		Pitch Forward		Pitch Backward	
	Pitch (°)	Roll (°)	Pitch (°)	Roll (°)	Pitch (°)	Roll (°)	Pitch (°)	Roll (°)
2	0.0	0.6	-0.1	-0.3	-0.1	-0.1	-0.1	-0.2
4	0.2	0.3	-0.2	-0.3	-0.3	0.1	0.3	-0.0
6	0.2	0.7	-1.1	-1.5	-0.4	-0.0	0.8	-0.4
8	1.1	1.9	-2.2	-3.7	-0.4	-0.1	2.1	-0.4
10	2.1	4.7	-3.0	-5.7	-3.0	-1.6	4.6	-0.3
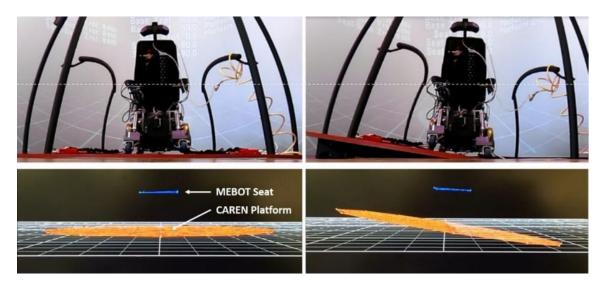
Figure 8: Experimental results: Static test in the roll lateral right direction. Top Fig. shows the transition from horizontal to 8° cross-slope with seat leveling algorithm. Bottom Fig. shows the markers tracked for the MEBot and CAREN platform by the VICON cameras

The experiment showed that MEBot was able to maintain the seat horizontally at roll angle between +5.5° & -4.3° (Figure 8) and pitch angle between +5.5° & -7.0° as shown for 2° and 4° in all directions. The results for 6°, 8°, and 10° show the maximum angle change in the seat due to the extension/compression limitations of the pneumatic actuators. Figure 8 showed the results of the static test in the pitch forward direction at 2°, 4°, 6°, 8°, and 10°, which simulated MEBot driving up slopes. The angle change rate of the platform was moving at 0.25°/s, 0.4°/s, 0.6°/s, 0.67°/s, and 1.0°/s for 2°, 4°, 6°, 8°, and 10°, respectively. As the CAREN platform moved in the pitch direction, the change in the seat roll angle was negligible; while the seat pitch angle changed within the ± 0.5° as designed in the control algorithm except when the CAREN platform went back to horizontal (0°) and at angles higher than 6 degrees. The positive peaks in the seat pitch angle (Figure 9) were due to the limited speed of the controller to level the seat in comparison to the CAREN platform speed and time delay to detect the change in the seat angle.
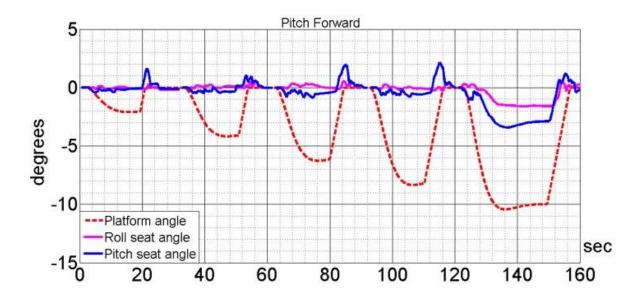
Figure 9: Experimental results: Static test with control activated in the pitch forward direction. Pitch (dotted line) and Roll angle (dash-dot line) of the seat are compared with the angle of the platform (solid line)

The angle error between the pitch/roll seat angle and the horizontal plane (pitch θ_d =0.0, roll ϕ_d=0.0) were partially due to the sensitivity of the IMU sensor in detecting an accurate slope angle and the extension/compression limitation of the pneumatics to reach higher angles. Another type of filter such as the Kalman filter showed similar reading reliability as the complementary filter; however, the latter was used because of its simplicity, code-efficiency and ease of implementation [48].
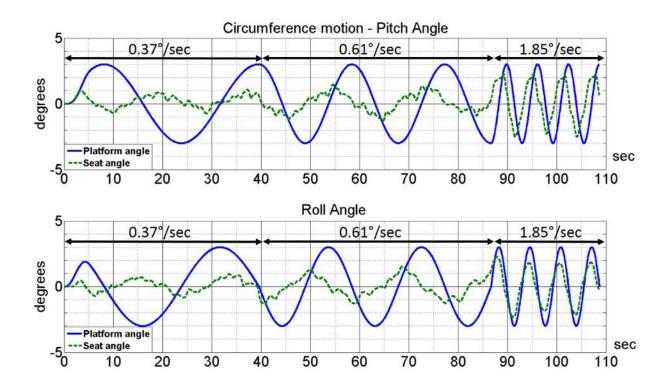
Figure 10: Dynamic test results at platform speed of 0.37°/s, 0.61°/s, and 1.85°/s. (a) Pitch Angle (top) and (b) Roll Angle (bottom). The platform angle is shown in solid line while pitch and roll angles of the seat are shown in dashed line

Figure 10 showed the results of the dynamic test for the pitch and roll seat angle. The results showed that at 0.37°/s, the seat maintained a pitch and roll angle of ± 0.8 degree at all times. However, at 0.61 and 1.85 degree/sec the control algorithm maintained the seat angle at 1.2 degrees and 1.7 degrees, respectively, showing that as the platform speed increased, the response of the controller began to lag. This issue can be in some measure due to the delayed response in the air manifold to move each pneumatic actuator; also, due to the slow response of the air spring actuators in the drive wheels. Another issue that should be taken into consideration for further improvement of the algorithm were the sensitivity of the IMU sensor as it showed a sensitivity of ±0.25°; and the angle threshold of ±0.50° in the controller. Finally, the results in Table II showed

better results in the lateral left than right at 6, 8, and 10° in the roll angle. Also, better results were demonstrated in the pitch forward than pitch backward at 8 and 10°. This behavior may be due to an offset in the calibration of the IMU sensor. Mechanically, the wheelchair may have been slightly tilted toward the lateral left and pitch forward direction due to a camber in the wheels or an air leakage in one or more pneumatic actuators prior to calibrating the IMU sensor. Software-wise, the computer calibrated the angles of the IMU sensor by setting them as zero degrees regardless the position of the pneumatic actuators and seat angle.

2.2.1.3 Practical implications for wheelchair users and the wheelchair design and configuration

Results of the Center of Pressure (CoP) and tipping point estimation demonstrated that the CoP remained within the boundaries of the footprint without a controller activated in every direction except when the wheelchair was tilted over 6° in the forward direction, which it was considered the tipping point of the wheelchair. Figure 11 demonstrated a minimum average movement of 2.4 cm in the center of pressure using the controller, compared to a CoP average displacement of 7.0 cm when the controller was not activated. This shift in center of pressure demonstrated the stability of MEBot when the seat leveling was activated; otherwise, the user would be at risk of falling.
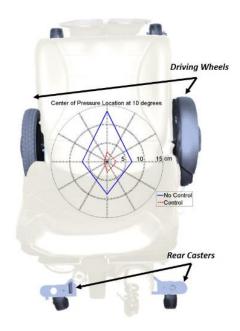
Figure 11: Location of Center of Pressure (CoP) during the static test without seat orientation controller (solid line) and with controller (dashed line)

2.2.1.4 Limitations

As a prototype robotic wheelchair, MEBot showed limitations that needed to be taken into consideration for the next iterations. MEBot was limited to approximately $\pm 5°$ in the roll direction and $-5°$ to $+7°$ in the pitch direction, without considering the capabilities of the seating functions to tilt back-and-forth. In addition, the position of the CoP (wheelchair plus user) limited MEBot from tilting forward further than 6 degrees (without a controller) before tipping, addressing the importance of a dynamic seat leveling control algorithm. During this experiment, MEBot was connected to an air compressor with large source of air. In the next iterations, a portable HPA (high-pressure air) tank will be investigated along with means to conserve gas pressure; in this case, other factors will be taken in account such as volume, pressure and temperature change. Three types of actuators were considered in the design process of MEBot as shown in Figure 12.

Each showed advantages and limitations. Electric actuators provide lifting capabilities and control feasibility; however, they are limited to their duty cycle and slow speed. Typical hydraulic actuators provide high lifting capabilities, as well as speed stroke with an achievable control design. However, they required the use of a hydraulic pump which are usually heavy in weight and difficult to place in the wheelchair. Air pneumatics were used as they provide the lifting capabilities as well as real-time speed stroke to move the wheels. Furthermore, the MEBot wheelchair was tested in a controlled in-lab environment which excluded sudden changes in the terrain such as cobblestones or speed bumps; in addition, the algorithm uses a quasi-static model which does not take in consideration sudden movement of the wheelchair and the user. Future implementation of the algorithm will include the development of a dynamic model to address these issues; thus, experiments will include driving under real-world scenarios to test the performance of the optimized seat orientation controller.

Figure 12: Alternative actuators for the up/down movement of the wheels. Electric (left), Air pneumatic (center), hydraulic (right) actuator

2.2.2   Curb climbing algorithm[3]

The current mechanical designs and control algorithms of EPWs restrict users' mobility from accessing areas with architectural barriers such as steps and where the Americans with Disabilities Act Accessibility Guidelines (ADAAG) criteria are not even met [53]. In order to address this problem, a curb climbing algorithm was designed and evaluated in simulation and in the real-world for curb heights up to 20 cm (7.87 inches) [54]. The curb height was determined based on the EPW testing standards Section 10 for obstacle climbing which determined the ability to climb obstacles of EPWs [40].

2.2.2.1 Curb climbing sequence

The first iteration of the curb climbing sequence consisted of two steps: A manual step performed by the user and an automatic step performed by the controller. Figure 13 showed the curb climbing sequence developed in simulation prior to test it in a real-world environment. The curb climbing sequence was simulated using the software Open Dynamic Engine (ODE) [55]. The curb climbing performed the followed steps:

a) In the manual step, the user drove until the front casters were in contact with the curb. This allowed the algorithm to determine the distance between the driving wheels and the curb through the pressure and position sensors. The user then set MEBot into Climbing Mode.

Climbing Mode would start by driving forward at 0.5 m/s towards the curb until the wheelchair was aligned perpendicular to the curb (Figure 12a).

b) Next, MEBot drove at a slow constant speed (1m/s) in combination with the elevation of the front wheels to place them on top of the curb (Figure 12b1). The rear casters were moved up as well to reach the desired curb height (Figure 12b2).

c) Then, the drive wheels moved back and drive forward to place the wheelchair base on top of the curb. Also, the front wheels move down on top of the curb. When the front wheels were positioned on the curb, they swivel and rotated automatically to prevent the wheelchair from rolling backwards.

d) Next, the rear wheels were moved down and driving wheel moved up which put the driving wheel in the air.

e) The driving wheel carriage moved forward while driving until the driving wheels were on top of the curb.

f) Then, the driving wheel carriage moved back until the wheelchair base was completely on top of the curb. This step tilted the wheelchair forward due to the change in the center of mass.

g) Once the driving wheels and front wheels were on top of the curb, the driving wheels were moved down to put the rear casters on top of the curb.

h) Finally, MEBot would drive automatically until all wheels were in contact with the curb. After this, the MEBot resumed to driving mode and user would have control of the wheelchair.
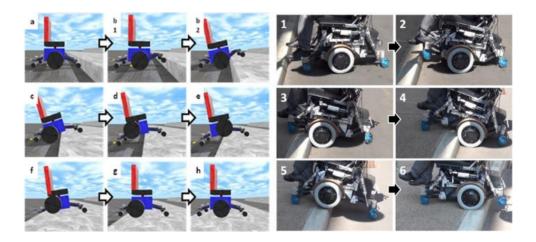
Figure 13: Curb Climbing Sequence evaluated in simulation (Left), and in real-world (Right)

2.2.2.2 Kinematics model

A kinematic model was developed to calculate the center of mass during each step of curb climbing sequence (Figure 14). Furthermore, each step was time-controlled based on the air pneumatics and drive wheel carriage speed. The first step registered the distance of the drive wheels to the edge of the curb in order to time each step of the sequence.
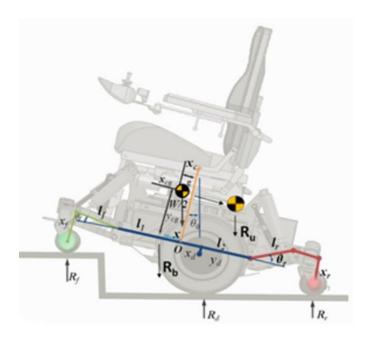
Figure 14: Kinematics and Dynamic model of 1st MEBot prototpype

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Shift in center of mass

The center of mass (CoM) location was calculated to maintain it within the wheelchair footprint and provide safety to the user during the curb climbing sequence. The optimal location of the CoM was calculated by finding the relationship between the users' mass and the minimum driving wheel position. The wheelchair's mass of 136 kg and user weight between 60 - 100 kg was used in the simulation. The initial position of the driving wheels was in mid-position (25.1 cm with respect to the front of the frame). The driving wheels were moved forward 4.3 cm to prevent the wheelchair from leaning forward when the front casters elevate.

The algorithm to shift the center of mass was defined as followed: the position of the center of mass (x_c) must be located between the driving wheels (x_d) and position of the rear wheels (x_r) as shown in equation 8. Also, the force in the rear wheels (R_r) and drive wheels (R_d) must be equal to or greater than the total weight of the user (R_u) and base (R_b) (eq. 9). These requirements were essential to prevent unintentional movements in the wheelchair that can be dangerous to the user.

$$x_c \geq x_r - x_d \qquad (8)$$

$$R_r + R_d - R_u - R_b = 0 \qquad (9)$$

2.2.2.3 Results and limitations

The control algorithm of the curb climbing sequence was first simulated in an Open Dynamic Engine (ODE) simulator using the wheelchair's dimensions and a user weight between 60 - 100 kg. Once the simulation passed the safety concern, the algorithm was tested in real-world environment (Figure 13-Right). Results showed that MEBot was able to climb a step of up to 17.78cm (7 inches) in compare to the proposed simulation of 20 cm (7.87") using the same climbing sequence. The simulation did not take in account the swivel of the caster wheels which

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reduced the length of the wheelchair and therefore reduced the proposed curb height to climb. Despite the climbing limitation, MEBot was able to climb a non-compliant ADA curb height in compare to current EPWs which are limited to climb over obstacles of approximately three inches due to the partial clearance of their wheelchair frame, wheels size, suspension system, and kinematics of the EPW.

Also, the results showed the completion time of the curb climbing application was 2 min and 30 seconds in comparison to the design criteria presented in Aim 2. Extensive number of steps to complete the sequence and hardware limitations such as slow movement of the drive wheels carriage to move from front-wheel to rear-wheel configuration (30sec) and limited elevation of the wheel (3.3 inches height) were areas of concern to be addressed in the next iterations of MEBot.

2.2.3   User's perception towards the idea of MEBot

Additional research was performed to gather feedback from end-user about the design and the control algorithms of MEBot [56]. MEBot's mobility applications were demonstrated to twelve active EPW users to ask their likelihood of using its applications. Participants included experienced users with an average of 16.3 years using an EPW inside and outside of the house and spent an average of 14.6 hours per day in their EPW. Half of the subjects reported to have a spinal cord injury; 50% used a mid-wheel drive EPW and 41% used a forward wheel drive EPW. The results showed most the participants would very likely use the seat-leveling (83%), traction control (83%), and curb climbing (75%), while the selectable driving wheel position and a two-wheel balance potential application were less likely to be used. Their likelihood towards the mentioned applications were related to EPW users' concern of tipping when driving up steep hills or uneven

terrains when the wheelchair stability is jeopardized [57] and concern if curb cuts are not available to access higher ground due to lack of maintenance [58]. EPW users' feedback provided more information for further improvement of MEBot and its control algorithms.

2.3 TOWARDS THE IMPROVEMENT DESIGN OF MEBOT: MEBOT2 AND MEBOT2.5

Two iterations of MEBot were designed and developed based on the evaluation of the previous iteration plus feedback from EPW users. The kinematics model of MEBot was updated with the improvement in the mechanical design. In addition, the electronics design and control algorithms were modified to be more robust and improve MEBot's mobility applications. A stability analysis was performed while evaluating the improvement in the control algorithms [59].[4]

2.3.1 Mechanical design

The new iterations of MEBot are comprised of a 6-wheel design and an EPW seating system with powered seat functions similar as the first prototype. However, improvements in the mechanical design include a higher range of motion in the six wheels as shown in Table 2. This allows the user to elevate MEBot from 3.2 cm up to 23.5 cm above the ground. A high-pressure air (HPA) tank rated for 31.0 MPa is secured at the back of wheelchair seat to provide a transportable air source.

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[4] J. Candiotti, S. A. Sundaram, B. Daveler, B. Gebrosky, G. Grindle, H. Wang, *et al.*, "Kinematics and Stability Analysis of a Novel Power Wheelchair When Traversing Architectural Barriers," *Topics in Spinal Cord Injury Rehabilitation,* vol. 23, pp. 110-119, 2017

The HPA tank is connected to an air pressure regulator to operate the air pneumatics actuators at 0.8 MPA. The drive wheels carriage is modified to allow an independent horizontal movement of the drive wheels along the frame. In addition, the caster wheels are replaced with omni-wheels to improve the pneumatics travel and remove the swivel of common caster wheels (Figure 15). Two MEBot iterations are designed with minimum differences. MEBot2.5 are designed as part of an EPW competition to overcome driving tasks of daily life, such as table approaching, slalom, ramps, obstacle negotiation, tilted ramps, and climbing steps, with advanced robotic technology [60]. The iteration demonstrates a faster horizontal movement of the drive wheels in comparison to MEBot2.0; likewise, its front wheels are removable to add longer front wheel arms that use a ratchet mechanism to prevent the wheelchair from rolling forward when climbing the steps backwards. For the sake of the study, both MEBot use the same front wheel dimensions. Also, both iterations demonstrate similar driving performance and range of motion.

Figure 15: Mechanical improvements of MEBot2.0 (right), and MEBot2.5 (left)

Table 2: Mechanical improvement of MEBot

	MEBot v2.0 and v2.5	**MEBotv1.0**
Drive wheel vertical (cm)	20.3	8.4
Drive wheel horizontal (cm)	35.6	17.8
Front casters vertical (cm)	7.6	7.6
Rear casters vertical (cm)	20.3	7.6

2.3.2 Electronics design

Two PMDC-powered wheels (80ZY24-350D-B; Linix, China) are mounted to the frame via a vertical-horizontal sliding platform, which allow the drive wheels to be moved fore and aft relative to the frame and up and down independently with air pneumatic actuators in parallel with gas springs rated at 108.9 kg. The air pneumatic actuators are supplied by the HPA tank through an air manifold. The electronics design of the second iteration of the MEBot controller are divided into two sections as previously described in Figure 3. The mobility section uses an R-NET wheelchair controller (Curtis-Wright, PA) to control the speed and direction of the drive wheels. The posture section uses a closed-loop control that allowed manual adjustment of the seat height and inclination via potentiometer sliders and switches. The electronics design of the posture section is comprised of a 16-channel 12-bit PWM servo driver (PCA9685, Adafruit, NY) and 16-I/O port expander (MCP23017, Adafruit, NY) to control the chambers of each air pneumatic actuator, two 8-channel 12-bit SAR ADC (LTC2309, Linear Technology, CA) to read the stroke position of the air pneumatics and proximity sensors when wheels are in contact with the ground, and a raspberry PI model 3 single board computer (Adafruit, NY) to design the control algorithms (Figure 16). The 24V from the batteries are converted into 3.3V and 5V using two DC-DC converters (1738-1293,

Digikey, MN) to power the sensors, computer board, and the data acquisition board. The control algorithms are programmed using python language.
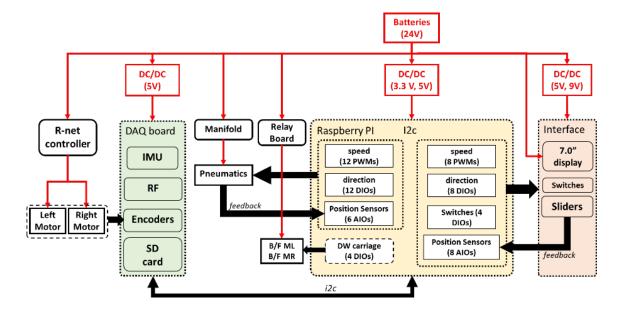
Figure 16: Second iteration of Electronic Diagram of the MEBot controller and interface

2.3.2.1 Data acquisition board

The Data Acquisition (DAQ) Board is a modular sensory system that communicated with the MEBot controller to provide information about the speed, acceleration, seating angle and vibration of the wheelchair (Figure 17). The DAQ board is comprised of an Arduino UNO (Arduino, Ivrea, Italy) microcontroller (5) with a printed circuit board shield to connect with two drive wheel encoders E4T (US Digital, WA) (4), an inertial measurement unit (IMU) Sensor Stick 9 DOF (SparkFun, CO) (1) through I2C communication, a radio-frequency transmitter unit (8) used for synchronization with external systems (i.e., VICON motion cameras unit), and SD card reader (2) to record data (for independent use of the DAQ board). In addition, the DAQ board communicates with the raspberry PI through I2C (6). A DC/DC converter (7) transforms the 24V from the batteries into a 5V to provide power to the DAQ board.

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Figure 17: IMU sensor located under the seat of the wheelchair (Left), DAQ board assembly (Center), Exploded view of the Data acquisition board (Right)

The drive wheels encoders read the number of ticks per second in order to obtain the wheel speed of the wheelchair in meters per second (10). Where rev/#total ticks is the ratio of the drive wheel perimeter in meters per total number of ticks to complete a revolution. Also, the acceleration of the wheels is obtained by the derivation of the drive wheel's speed.

$$speed_{wheel} = \frac{\Delta \#ticks}{\Delta\ time} * \frac{rev}{\#\ total\ ticks} \quad (10)$$

The IMU role is to measure the linear acceleration (m/s^2) and angular velocity of the wheelchair seat (°/s) in 3 axes (Figure 17). These variables are filtered using a complementary filter in order to obtain the pitch and roll seat angles. The filter decreases the high frequency noise of the accelerometer data and eliminates the drift of the gyroscope over time.

2.3.3 Software upgrade

The control algorithms follow the same architecture diagram as presented in Figure 3. In comparison to the previous iteration, the Mobility section is performed by the R-NET commercial EPW controller (Curtis-Wright, PA). However, the speed and acceleration of the wheels are still monitored with encoder gears within the wheels and fed into the MEBot controller. The sensing system, comprised of the DAQ board and position sensors of the air pneumatics, are fed into the

controller. The new center of gravity is calculated using the combination of the sensing system and the updated MEBot kinematics model in order to adjust the position of the pneumatics actuators in the control algorithms.

Furthermore, the low-level control explained in section 2.2.1 was implemented to control both chambers of each air pneumatic actuator. The chambers are exhausted or filled with air to either compress or extend the pneumatic rod to a desired position. The control diagram of the low-level control is described in Figure 18.
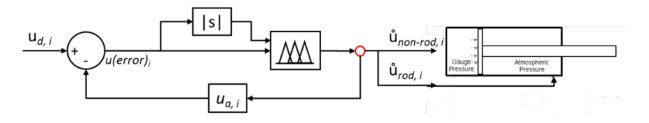
Figure 18: Improvement of low level control of MEBot

$u_{d,i}$ represents the desired position of the pneumatic stroke while $u_{a,i}$ represents its actual position. The desired position is controlled by the user. The difference of the desired and actual position of the pneumatic stroke is calculated as well as its speed; both position and absolute speed value values are fed into a fuzzy logic controller to obtain the desired speed of air filling or exhaustion in both chambers of the pneumatic. The fuzzy logic works as follow: if the position error is less than 1.27 cm (0.5") and absolute speed error is less than 20.54 cm/s, then the non-rod side of the pneumatic is filled with air at full speed and the rod side gradually exhausts air at an initial speed with an increasing speed of 0.3% duty cycle. If the speed error is higher than 20.54 cm/s and less than 25.4 cm/s, the non-rod side continues to be filled at full speed while the non-rod side stops exhausting. The less air pressure in the rod side allows the non-rod side to push faster and increasing the speed stroke of the pneumatic. If the speed error is higher than 25.4 cm/s,

the non-rod side is not filled with air and used momentum to reach the desired position. The opposite behavior occurs when the position error is higher than 1.27 cm; in this case, the non-rod side of the pneumatics exhausts air while the rod side is filled with air. The fuzzy logic diagram is shown in the figure below.
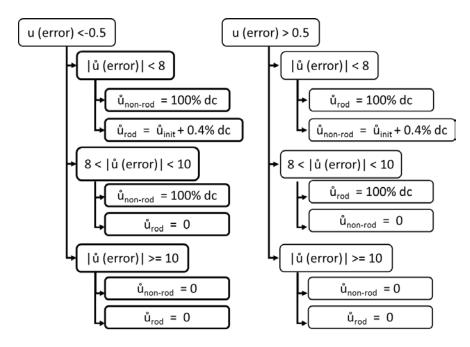
Figure 19: Fuzzy logic diagram of the low-level control

2.3.4   Stability analysis of the MEBot control algorithms

To analyze the stability of the system, the location of the center of mass and its position relative to the wheelbase are calculated for different angles of the chair while the seat level is maintained. The calculations are based on the following assumptions:

- The wheelchair is stationary or slowly driving up, down the slope, and on cross slopes.

- The wheelchair is in front-wheel drive.

- Rear casters and drive wheels are co-planar with the ground.

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To determine the position of MEBot's center of mass relative to the original flat reference frame, the difference angle between the actual pitch and roll values and the true orientation of the wheelbase relative to the frame must be calculated. To calculate the current pitch and roll values of the seat, the local coordinates of the wheels in the wheelchair's reference frame are first calculated using the kinematics model of Figure 20. The kinematic model of MEBot2.0 shows 9 degrees of freedom (DOF); each DOF represents the vertical movement of each wheel, the horizontal movement of each drive wheel, and the rotation of the drive wheels in its own center. The combination of these features provides MEBot with 4 DOF in the inclination (pitch, raw, yaw) and translation (x, y, z) of its seat.
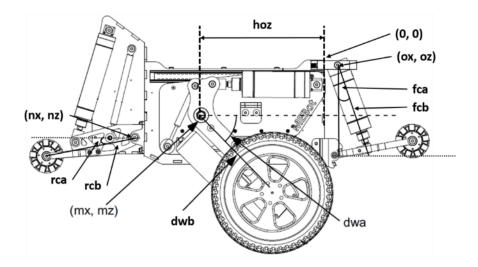
Figure 20: Kinematics analysis of the 2nd iteration of MEBot

$$RL = [nx + rcb * cos(rca), -rcy, nz - rcb * sin(rca)] \qquad (11)$$

$$RR = [nx + rcb * cos(rca), rcy, nz - rcb * sin(rca)] \qquad (12)$$

$$ML = [(mx + dwb * cos(dwa), -dwy, mz - dwb * sin(dwa)] \qquad (13)$$

$$MR = [(mx + dwb * cos(dwa), dwy, mz - dwb * sin(dwa)] \qquad (14)$$

Where *RL*, *RR*, *ML*, and *MR* are the Cartesian coordinates of the left caster, right caster, and left and right drive wheel, respectively. *Nx*, *nz*, *mx*, and *mz* were the x-axis and z- axis location

of each wheel arm's pivot point with respect to the origin point (0, 0) in the chair. *Rca* is the joint angle between the rear caster arm and the horizontal x-axis, and *dwa* is the angle between the drive wheel arm and the horizontal x-axis. *Rcb* is the length of the rear caster arm, and *Dwb* is the length of the drive wheel arm.

The orientation of the MEBot's wheelbase is found by taking the cross product of the vectors between any 3 of its wheels. We choose the vectors between the wheelchair's right caster and right drive wheel and between its right caster and left drive wheel. Φ is the resulting pitch angle and θ is the resulting roll angle.

$$u1 = MR - RR; \; u2 = ML - RR; \; u = \overrightarrow{u1} \; x \; \overrightarrow{u2} \qquad (15)$$

$$\phi = -\tan^{-1}\left(\frac{u(1)}{u(3)}\right); \; \theta = -\tan^{-1}\left(\frac{u(2)}{u(3)}\right) \qquad (16)$$

Determining the position of the center of mass over the ground plane requires calculating the difference between the wheelchair frame orientation and the pitch and roll values of the ground, *pin* and *rin*. The difference angle, *dphi* and *dtheta*, between the frame orientation and ground plane are shown below:

$$dphi = \phi + pin; \; dtheta = \theta + rin \qquad (17)$$

Prior to calculating the location of the center of mass in the simulation, the wheelchair is placed on a force plate (Bertec Corporation, OH), both flat and incline, to measure the actual position of the prototype's center of mass (cm1, cm2, cm3) (Figure 20)

$$newcm = [cm(1,1) + cm(1,3) * sin(dpi), cm(1,2) + cm(1,3) * sin(dtheta), cm(1,3) *$$
$$cos(dpi) * cos(dtheta)] \qquad (18)$$

Returning to the simulation, *newcm* calculates the new location of the center of mass using the obtained angles about the wheelchair frame. To obtain the intersection of the center of mass

with the ground plane, *s1* is used to account for the new orientation of the ground relative to the initial reference frame. *gg* shows the intersection point of the gravity vector extending downward from the center of mass with the ground plane.

$$ng = [sin(pin), sin(rin), cos(pin) * cos(rin)] \qquad (19)$$

$$s1 = (ng \cdot ([0, 0, -5.5] - newcm)) / (ng \cdot [0, 0, -1]) \quad (20)$$

$$gg = s1 * [0, 0, -1] + newcm \qquad (21)$$

2.3.5   Results

Seat leveling algorithm

The seat leveling algorithm allows MEBot to keep its seat leveled when traversing over ramps and cross slopes. Driving in these uneven environments has been shown to cause shifts in the center of mass that lead to lack of stability EPWs. This feature prevents tips and falls in these environments by detecting the inclination of the ground through the IMU sensor and moving the pneumatics actuators to a desired position to maintain the seat as flat. In Section 2.2.1, the seat leveling algorithm was described and evaluated [47]. While the software algorithm remains the same, the geometry of the wheelchair changed as shown in Figure 20 and was tested in simulation [61]. Limitations such as a restricted range of motion and load-lifting capabilities are addressed in MEBot 2.0. The MEBot 2.0 prototype was tested to ANSI/RESNA standards [40, 41] defined in Sections 1, 2, 5, 6, and 10 of ISO 7176 as shown in Table 3.

Section 1 of the ANSI/RESNA standards determines the static stability of EPWs by placing them on a tilting platform. MEBot was tilted in 4 directions: lateral left, right, backward, and forward direction. For each direction, the tipping angle was recorded when the platform tilted until

the uphill wheels left the ground. Results showed a maximum angle of 27° on cross slopes without

the algorithm activated and an improvement to 37° using the seat leveling algorithm. For upward

slopes, the center of mass remained within the footprint at a 50° angle (maximum angle of the

tilting platform) with the seat leveling algorithm de-activated in front-wheel-drive mode. Even

though the seat leveling algorithm was not required to maintain stability in this test, its ability to

keep the frame level up to 15° would improve user comfort.

No changes in stability were noted with and without the seat leveling algorithm when the

platform was tilted forward, simulating driving down the slope. The distance between the center

of mass's gravity vector and the front of the wheelbase was reduced when adjusting for downward

slopes due to the kinematics of the mechanism shifting the drive wheels backward relative to the

frame at a higher ground clearance. Again, although it did not change the stability margin for these

extreme slopes, the ability to keep the frame leveled on slopes up to 15° may improve user's

comfort.

Table 3: Characteristics of MEBot and ANSI/RESNA wheelchair standards test results

	Dimension		Highest Ground Clearance	Lowest Ground Clearance
Section 5: Overall Dimensions	**Length**		1150 mm	1300 mm
	Width		665 mm	
	Turning Diameter		1250 mm	1670 mm
	Ground Clearance		241 mm	38 mm
	Required Corridor Width for Side Opening	**Entering**	760 mm	990 mm
		Exiting	760 mm	1140 mm
	Wheelchair Mass		414 lb	
Drive wheel movement	203 mm			
Power	24V, 51Ah			
Maximum velocity	5.0 mph (2.23 m/s)			
Section 1: Static Stability	**Direction**		**Passive**	**Active**
	Forward		30.8°	28.4°
	Rearward		50.7°	---
	Sideways	**Left**	25.8°	37.7°
		Right	27.5°	36.3°

Section 2 of the ANSI/RESNA wheelchair standards determines the dynamic stability of EPWs by driving them at maximum speed forward and reverse and turning in a slope of 0°, 3°, 6°, 10° and suddenly stopping to test stability when brakes are applied. The scoring system quantified as follow: 0 = full tip, 1 = stuck on anti-tip, 2 = less than 3 wheels remain on the test plane, and 3 = at least 3 wheels remain on the test plane at all times. MEBot passed all the dynamic stability tasks with a score of 3 using the assistance of its wheels' height adjustments. It was shown that MEBot required the assistance of the front casters when driving down the 10° slope and in front-wheel-drive mode to increase its footprint and stability margin. Alternatively, the allocation of the drive wheels to rear-wheel-drive mode would optimize the stability of the system.

For this chapter, the location of the center of mass was calculated and evaluated when MEBot 2.0 was driven up, down, and across a 20° slope using the seat leveling algorithm as shown in Figure 21. The wheelchair was driven by the researcher who weighed 81.6 kg. As part of the calculations, it was assumed the footprint consisted of the area between the rear wheels and drive wheels when driving in front-wheel-drive mode. The results showed that the center of mass remained within the footprint of the wheelchair during each task, even when the area of the footprint changed with the wheelbase due to the movement of each wheel to compensate for the seat angle adjustment. Driving down the slope showed insufficient stability, as it was likely to maintain fewer than 3 wheels on the ground when brakes were applied and the center of mass approached the front of the wheelchair footprint.
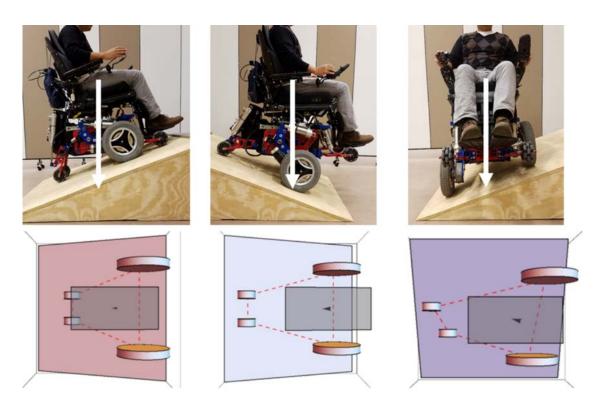
Figure 21: Results of the seat leveling algorithm and location of the center of mass in tilt forward, tilt back, and lateral tilt when driving a 20° slope

To provide an extra safety feature during this configuration, the frame was lowered down using the pneumatic actuators as well as the front casters to act as anti-tippers to provide 6 points of contact to the ground as demonstrated during the Section 2: Dynamic Stability test of the ANSI/RESNA wheelchair standards. The seat angle in this configuration was -6.6° without the use of the powered seating functions. By combining the results from the static stability, dynamic stability, and the center of mass calculation, the second iteration of MEBot showed high stability when using the seat leveling algorithm and minimum change in the seat angle except when driving down a slope.

2.3.6   Curb climbing and descending application

Accessibility remains a limitation for wheelchair users. Commercial power wheelchairs are rated to climb up to a 7.6 cm curb height facing perpendicular to the obstacle and drive at full throttle; otherwise the user is at risk of tipping. In addition to the warning of this limitation, there is a lack of safety or adequate process when climbing or descending a curb. These criteria were considered when performing the curb climbing and descending application. To provide safety and stability during climbing and descending curbs, the application must follow the requirements and guidelines below:

- The center of mass must remain within the footprint of the wheelchair. In order to prevent tipping:
  - The seat angle should maintain a horizontal level or
  - Must not pass the maximum tilting angles obtained in the Section 1 test of the ANSI/RESNA wheelchair standards.
- The wheelchair should be able to climb/descend a maximum curb height of 20.32 cm.
  - Section 10 of the ANSI/RESNA wheelchair standards determines the ability to climb and descend obstacles of EPWs, which can be varied in height from 1.0 cm to a height of 20.0 cm.

The curb-climbing and descending process was performed with MEBot2.0. Also, the wheelchair was manually controlled by the researcher. To demonstrate the kinematics of the chair, the application was used to climb a curb height of 20.32 cm on a runway with 16 motion capture cameras to detect 24 reflective markers placed on the wheelchair at each corner of the seat, at each corner of the curb platform, at the center of each of the 6 wheels, and at each joint of the 6

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pneumatics within the frame. The seat angle and each wheel joint motion were monitored at 100

Hz frequency and presented in Figure 22.
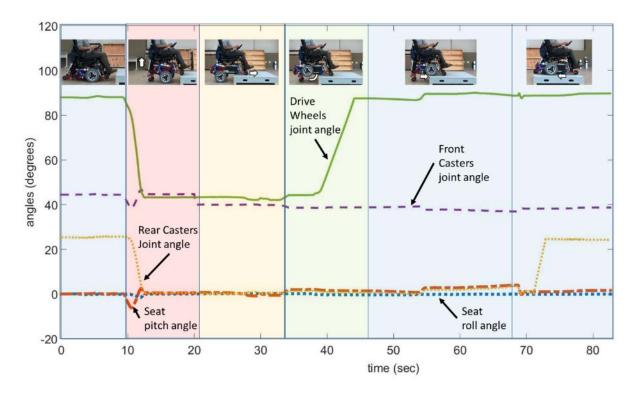
Figure 22: Curb climbing sequence (top); angles of seat and wheel joints when ascending a curb (bottom)

The curb-climbing sequence consisted of 5 main steps:

a) When approaching the curb, the user elevates the wheelchair to the highest ground clearance in order to place the front casters on the curb. The ground clearance increases to 24.1 cm to overcome the maximum ADA curb height of 20.32 cm as stated in Section 10 of the ANSI/RESNA wheelchair standards. The highest ground clearance configuration maintains the center of mass within the footprint without using the front casters as shown in Figure 23b. When the wheelchair elevates, the front casters move forward due to the mechanical design of the wheelchair to rise as a "scissor lift" and reach the top of the curb.

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b) The frame moves forward to place the drive wheels on top of the curb. Two DC motors (BDWG319NP-207-24-45-FL-C6-W3; Anaheim Automation, CA) drive the horizontal carriage from front to back in 12 seconds. MEBot2.5 completed this task in 5.5 seconds in compare to MEBot2.0. In this step, the wheelchair is in rear-wheel-drive mode with casters on the ground, increasing its stability margin as shown in Figure 23b and maintaining its center of mass in the center of the footprint.

c) Once the carriage is moved back, the drive wheels are elevated to clear the curb height, changing its joint angle from 43° to 85° as shown in Figure 22. In this configuration, the radius of the drive wheels is higher than the remainder of the curb height, and the wheelchair can drive over the curb. At this moment, the wheelchair is resting on its casters, keeping the center of mass in the center despite the reduction in the stability margin sideways as shown in Figure 23c.

d) The drive wheels move to front-wheel drive using the horizontal carriage. At the same time, the drive wheels spin and their brakes unlock to prevent them from getting caught on the edge of the curb.

e) The rear casters are elevated to drive all the wheels over the curb.

The curb-climbing sequence was completed in 75 seconds. The seat roll angle was 0° while the pitch angle read ±4.0° when the wheelchair was elevated to its highest ground clearance and when the drive wheels were on top of the curb. However, the wheelchair remained in a static posture during the entire process and the wheelchair had 4 points of contact throughout the curb-climbing sequence. This, in combination with the results in the static stability test, demonstrated that the center of mass remained within the footprint of the chair.
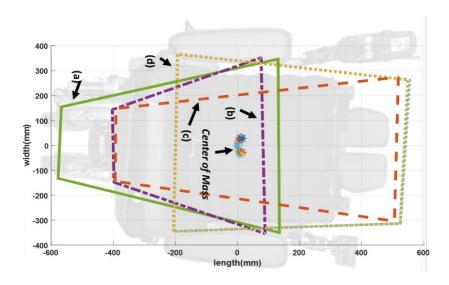
Figure 23: Location of the center of mass when climbing a curb in different footprint configurations: (a) lowest ground clearance, (b) highest ground clearance, (c) only front and rear wheels on the ground, and (d) only drive wheels and front wheels

A secondary test was performed on a force plate to locate the center of mass of the entire system (wheelchair plus user) for different footprint configurations in the curb-climbing process. During this test, the user leaned as far as possible for 5 seconds in the left and right directions when the wheelchair was static to demonstrate the stability of the system when the user moves in the seat, as shown in Figure 23. This stability test was limited to leaning sideways as the center of mass was closer to the sides of the wheelbase than the back or front in each configuration. The results showed a change of ±3.0 cm when leaning sideways, while remaining well within the footprint. For front-wheel-drive mode, it was observed that the highest ground clearance is the least stable configuration, as the center of mass is 8.1 cm closer to the front of the wheelchair than at the lowest ground clearance (Figure 23b). While the center of mass remained within the footprint, it is suggested that, depending on the mobility application, the front wheels should be lowered to increase the stability margin or the maximum speed to be reduced up to 1.5 m/s when driving in this configuration on a flat surface to prevent tipping.

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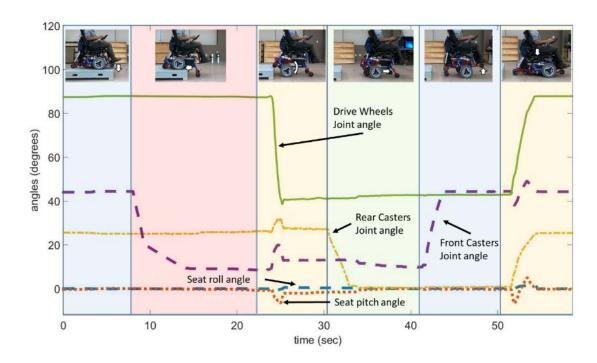
Figure 24: Curb descending sequence (top); angles of seat and wheel joints when descending a curb (bottom)

The curb-descending sequence used the same requirements as when climbing a curb. The sequence was completed in 5 steps as shown in Figure 24:

a) The front casters are lowered on top of the curb to align the wheelchair perpendicular to the curb.

b) Once the front casters drop off the curb, the frame is moved forward while the front casters are lowered to the ground to maintain a footprint area.

c) Then, the wheelchair drives forward to lower the drive wheels to the ground. The wheelchair is in rear-wheel-drive mode in this step and the rear casters are lowered to the ground as well.

d) The drive wheels are moved forward to front-wheel-drive mode while front casters are elevated.

e) The wheelchair is lowered to its lowest ground clearance.

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The seat roll angle remained completely flat while the pitch angle showed a ±5° change when the drive wheels moved from the curb to the ground and in the transition from highest to lowest ground clearance. The footprint configurations in the curb-descending process were similar to the curb climbing, which maintained the center of mass within its footprint.

2.3.7   Conclusions

The mobility applications of the MEBot 2.0 – curb climbing/descending and seat leveling algorithm– were introduced and evaluated through a stability analysis. The results showed that the position of the center of mass remained within the footprint of the wheelchair on slopes of different angles and while climbing and descending a curb. It was also discovered that the least stable configurations of the wheelchair were in high ground clearance and when driving down the slope in front-wheel drive. To compensate for instability, it was recommended that the front casters be used as anti-tippers. In addition, MEBot includes powered seating functions that can be used to adjust its seat inclination when driving up or down slopes up to 60°. Further work will include an optimization of the kinematics and seat leveling algorithm in different wheel drive configurations and wheel height positions to maintain the seat leveled.

Even though the completion time of the curb climbing/descending process was not the objective of the study, it could be improved with automation of each wheel motion in every step of Figure 22 and Figure 24. R&D climbing wheelchairs have reported to climb 1 step every 300 seconds. However, the study demonstrated the capabilities and stability of MEBot when climbing over ADA-compliant steps (20 cm high) in comparison to commercial EPWs, which are limited to climb curb heights not exceeding 7.6 cm and lack safety when overcoming architectural barriers.

The location of the center of mass can be obtained with the wheelchair angle and the position of the wheels. This equation can be used for further development of the automation and potential safety failure analysis of the mobility applications.

3.0 DESIGN AND DEVELOPMENT OF AN ATTITUDE CONTROL GRAPHICAL INTERFACE TO OPERATE THE MEBOT FEATURES

3.1 RATIONALE

The goal of this chapter was to design and develop an attitude control graphical interface (ACGI) in order to: 1) allow users to navigate through the mobility features of MEBot, 2) control the elevation and inclination of the MEBot seating system for the user's safety and comfort and 3) understand the users' driving strategies when traversing different environments using the MEBot wheelchair. Attitude control is an engineering term used to describe the orientation of a body in space [62]. This term was used to define the seat orientation of MEBot in relation to the movement of its wheels and the ground. Also, a graphical user interface (GUI) is the displayed system of icons, and other features that allows the user to select and access information through the computer in the wheelchair. GUIs are essential to the proper functioning of EPWs and user approval of the wheelchair in general. Part of the design process was the development of design criteria by understanding the end-user's desires and favorable aesthetics in order to provide an intuitive device control [63] of the system and maximize user functionality [64]. The results describe the final product of the attitude control graphical interface (ACGI)

3.2 DESIGN CRITERIA

The design criteria were based on the unique features of MEBot, as well as input from our research group members which included clinicians, engineers and experienced wheelchair users:

User interface:

- The interface should display the movement of the wheels with respect with the frame in a 2D/3D view that represents the wheelchair dimensions

- The interface should display when the wheels are in contact with the ground using a color grouping (green in contact, red in the air)

Software:

- The ACGI controller should have built-in algorithms to save the movement of the wheels and selected features by the user at a 100 Hz sample rate

- The ACGI controller must control the direction and position of the wheels individually or combined

- The ACGI controller should provide a real-time display of the wheels movement and location

- When one feature is selected, the ACGI controller should disable the other features.

Hardware:

- The ACGI should be easy to control the wheels movement for people with low dexterity with the use of sliders or long buttons.

- The hardware should be powered by the 24V wheelchair battery.

- The ACGI should provide a visual representation of the selected features as well as the wheels

- The ACGI dimensions must fit within the wheelchair footprint and not be on the way of the user especially for easy transfer. Regular EPW joystick dimensions were used as reference.

- The hardware should not expose wiring and must enclose its electronic components

- The hardware must be easy to mount in left or right side of the wheelchair

- The hardware should be able to withstand vibration when driving in all environments

3.3   RESULTS

3.3.1   Hardware

The ACGI controller was composed of a monitor for visual feedback (XENARC TECH, CA), four SPDT switches (450-2269-ND, Digikey, MN) and eight motorized slide potentiometers (PSM01-082A-103B2-ND, Bourns, CA). Each switch was assigned to the MEBot features; the sliders controlled the direction and position of the six wheels: Front Right (FR), Front Left (FL), Middle Right (MR), Middle Left (ML), Rear Right (RR), and Rear Left (RL) and the Drive wheels horizontal movement. The eighth slider on the side of the interface controlled all the sliders and their corresponding wheels in the base when Switch 1 was activated. The components within the ACGI enclosure included a 16-channel 12-bit PWM servo driver (PCA9685, Adafruit, NY) to control the motorized sliders, one 8-channel, 12-bit SAR ADC (LTC2309, Linear Technology, CA) to read the analog position of the sliders, a 16-I/O port expander (MCP23017, Adafruit, NY) to read the switches inputs, and the single board computer raspberry PI model 3 (Adafruit, NY) used to design the built-in algorithms of the ACGI controller and communicate with the MEBot controller. The sliders were powered through a 9V DCDC Converter (DCDC-USB-200, Mini-box,

CA) while the rest of the components used a 3.3V and 5V DC-DC converter (1738-1293, Digikey, MN) that converts the 24V from the battery.

3.3.2   ACGI enclosure

The switches were placed on top for easy access and level to the interface to avoid any involuntary pushes. The enclosure was built to fit seven sliders in an array and facing towards the user at an angle of 10 degrees (Figure 25). The eighth slider that controls the elevation was placed on the left side of the enclosure. Each slider was named from left to right based on the orientation of the wheels in the frame. In addition, the slider knobs were colored to the side of the wheels (i.e., yellow – left, red – right). The color classification also represented the sliders to be used for the selected features (i.e., switch 2 was colored in yellow to use the left side of sliders; switch 3 was colored in green for the slider in the center). The dimensions of the enclosure (15.24"Lx12.7"Wx12.7"H) were designed to fit within the footprint of the wheelchair and avoid collisions with doors. The monitor was placed at an angle of 70° degree in relation to the switch plane to reduce light reflection. An output plug powered the ACGI interface from a DC/DC converter that converted the 24V EPW battery; also provided communication with the MEBot controller within the base through I2C.

Figure 25: 3d model exploded view of the ACG Interface (Left), ACGI mounted in the MEBot wheelchair (right)
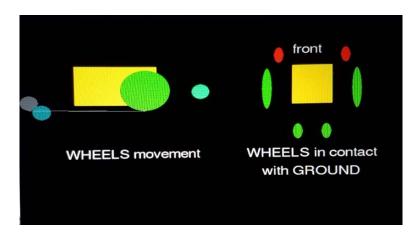
Figure 26: ACGI display of the wheels movement (left) and wheels in contact with the ground (right)

3.3.3   Software

The attitude control graphical interface was designed using python and the pygame library. The interface display provided information about the movement of the wheels in relation to the frame from a 2D side view of MEBot as well as a color representation when the wheels were in contact with the ground (green) or in the air (red) from a top view of MEBot (Figure 26). The ACGI displayed a unique system by which users could negotiate through the MEBot features.

3.3.4   Features of the attitude interface

As mentioned in the previous chapter, a sequence to climb and descend curbs was developed based on what the research team thought was appropriate to complete the sequence in an effective and efficient manner. However, the user's strategy to overcome curbs was also useful to develop different methods steps that can be created from the model sequence. Therefore, a set of features in the attitude interface was designed to record the user's strategies (Figure 27):

Independent movement of wheels (No Switch): The direction and position of each wheel was controlled through the sliders. When the slider was moved back, its corresponding wheel moved down which elevated that side of the wheelchair; and when it moved forward, the wheel moved up toward the frame.

Elevation (Switch 1): When switch 1 was activated, the user controlled the elevation of MEBot using the slider on the side of the interface. When the elevation slider moved up, all the wheels moved down which elevates the wheelchair; and vice versa when the slider moved down. In addition, the sliders corresponding to each wheel moved automatically to the desired position of the elevation slider.
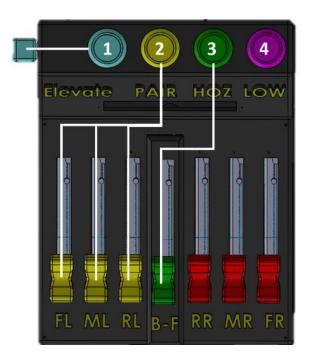
Figure 27: The MEBot features are represented by the switches and colored coded with the sliders

Paired wheels (Switch 2): This feature controlled either both front wheels, drive wheels or rear wheels. The switch was color coded to use the yellow sliders. When a slider moved forward, its assigned paired wheels moved up to the desired position (i.e., FL slider moved both front wheels, ML slider moved both drive wheels, and RL slider moved both rear wheels). In addition, the red sliders that represent the wheels on the right side of the wheelchair, moved in parallel to their mirrored yellow sliders.

Drive wheel carriage (Switch 3): This feature allowed the user to move the drive wheels in a horizontal carriage along the frame. The switch was color coded use the green slider at the center of the interface. The slider worked as a toggle switch which controlled the translational direction of the drive wheels. When the slider moved forward, the drive wheels moved to the front of the wheelchair; when the slider was released, it returned to the center and the drive wheels stopped to their last position. When the slider moved backward, the drive wheels moved to the back of the

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wheelchair. Furthermore, this feature allowed the MEBot to be configured as a front-, mid-, or rear-wheel drive wheelchair.

Home button (Switch 4): This feature moved the wheelchair to its lowest ground clearance by moving all the wheels up and the drive wheels to front wheel drive configuration.

3.4   CONCLUSIONS

In this chapter, we described the design and developed of the attitude graphical user interface following the hardware and software design criteria. Due to the limited speed processor of the single board computer to record and display MEBot features in real-time, the interface displayed a 2D view of the wheelchair rather than a 3D view. A user's satisfaction questionnaire will be performed to gather EPW user's perception in regards of ease of operation, visual display and improvements of the interface. In addition, the interface will be used to record the movement of the wheels and users' driving strategies when traversing different environments.

4.0   USABILITY EVALUATION OF THE MOBILITY ENHACEMENT ROBOT

4.1   INTRODUCTION

The International Organization for Standardization (ISO) defines usability as '*the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use'* [65]. A usability evaluation was performed to obtain feedback from active EPW users after using MEBot. Participants compared MEBot's driving capabilities to their own commercial EPWs in a controlled real-world environment. Usability was evaluated based on the effectiveness and efficacy of the wheelchair to complete a series of driving tasks and user's satisfaction toward MEBot. The gathered information was analyzed to improve MEBot's capabilities if necessary.

4.2   HYPOTHESES

The three domains of usability evaluation were defined in three Specific Aims:

Specific aim 1: To determine if the MEBot wheelchair could perform driving tasks of everyday environments (Effectiveness)

1. **Hypothesis 1:** End-users will complete a significantly higher number of driving tasks when using MEBot in comparison to their own EPW when driving in indoor, outdoor, and advanced (architectural barriers) environments.

Specific aim 2: To determine how well the MEBot wheelchair is able to complete driving tasks of everyday environments (Efficiency)

2. **Hypothesis 2:** End-users will score significantly higher scores in the Power Mobility Capacity Driving Assessment (PMCDA) tool when using MEBot wheelchair in comparison to their own EPW when driving in indoor, outdoor, and advanced (architectural barriers) environments.

   a. **Hypothesis 2. 1.** End-users will score a significantly higher score of adequacy-efficacy in the PMCDA tool when using MEBot in comparison to their own EPW in indoor, outdoor, and advanced (architectural barriers) environments

   b. **Hypothesis 2. 2.** End-users will score a significantly higher score of safety in the PMCDA tool when using MEBot in comparison to their own EPW in indoor, outdoor, and advanced (architectural barriers) environments

3. **Hypothesis 3:** End-users will show a significant difference in safety, adequacy, and efficacy between environments when using the MEBot wheelchair

4. **Hypothesis 4:** End-users will show a significant difference in safety, adequacy, and efficacy between environments when using their own wheelchair

Specific aim 3: To determine user's perception toward the MEBot wheelchair and its attitude control graphical interface (ACGI) (Satisfaction)

5. **Hypothesis 5:** A significant difference in comfort, safety, and operation will be shown when using MEBot in comparison to their own EPW when driving in indoor, outdoor, and advanced (architectural barriers) environments.

6. **Hypothesis 6:** A significant difference in the NASA-TLX outcome measures will be

shown when using the MEBot wheelchair in comparison to their own EPW when driving

in indoor, outdoor, and advanced (architectural barriers) environments.

4.3 METHODS

4.3.1 Study design

4.3.1.1 Subjects

Ten active EPW users were recruited to compare the driving capabilities of two iterations of

MEBot and their own EPW in a controlled environment. Inclusion criteria included participants

who were 18 years old or older, weight less than 113.4 kg, able to tolerate sitting for six hours, and

at least 1 year of experience using an EPW in indoor and outdoor environments. Participants with

pressure sores or back, pelvic or thigh pain were excluded from the study. The study was conducted

at the National Veterans Wheelchair Games in Cincinnati, Ohio and the Human Engineering

Research Laboratories (HERL) in a controlled simulated real-world environment. The study

protocol was approved by the University of Pittsburgh and Veterans Affairs Institutional Review

Board (IRB).

4.3.1.2 Protocol

For each participant, the session consisted of a single visit of 6 hours total with a time break

between device changes if necessary. Each participant completed the inform consent process and

a questionnaire, which includes general questions about demographics (i.e age, gender, ethnicity) and their own wheelchair (Figure 28). Following the questionnaire, participants' EPW driving skills were evaluated using the Powered Mobility Clinical Driving Assessment Tool (PMCDA) in their own EPW and in MEBot prior to use of any advanced features in MEBot. This baseline EPW driving evaluation ensured that MEBot's configuration did not affect the users' driving capacity. If the participant was unable to perform a task of the PMCDA, he/she would receive training to improve his/her wheelchair skills.
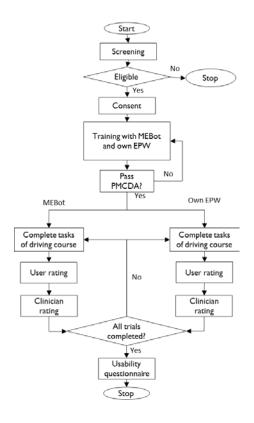
Figure 28: Flowchart of the study protocol

Following the baseline skills evaluation, participants were transferred into MEBot2.0 or MEBot2.5 wheelchair (Figure 29). MEBot2.5 provided a faster movement of the drive wheels carriage in comparison to MEBot2.0; however, both MEBot iterations provided same driving performance and wheels' movement. Participant were asked if modifications in the seating system

were required to provide comfort. In addition, the driving parameters (e.g. speed, turning speed, acceleration) were adjusted to the participant's preference. An experienced researcher in the use of MEBot provided an overview and training of MEBot's advanced mobility features including climbing and descending a curb (Appendix A) to participants. The curb climbing and descending applications were demonstrated in a video as well as walk-through until participants were able to perform it by themselves. The training time was approximately 30 minutes and each participant performed the curb climbing application until they felt confident with their skills and received approval from the researcher.

Figure 29: MEBot2.0 (left), MEBot 2.5 (center), and a test commercial EPW (right)

Then, participants were asked to drive a MEBot and their own EPW (3 trials each) through a driving course with obstacles that simulated real-world environments (Figure 30). The order of starting MEBot vs the participants' wheelchair was neglected since the number of completed tasks was more important than the completion time. The driving obstacles were categorized in indoor, outdoor and advanced environments. Indoor environments represented obstacles within the home or apartments. This environment included 13 tasks: (1) Drives forward (15ft) in a straight line in a 36" hallway, (2) Turn 180° in place to the left, (3) Drives backward 10ft in a straight line in 36" hallway, (4) Turn 90° while moving backward, (5) Turn 90° and enters a doorway, (6) Ascend 3°

incline, (7) Descend 3° incline, (8) Turn 90° while moving forward, (9) Drive forward 30ft in 30s, (10) Negotiates over 1 in door/mock threshold, (11) Drive in carpet, (12) Passes through 36" doorway, and (13) Approaches an accessible sink. Outdoor environments represented obstacles outside the house. The environment consisted of 12 tasks: (14) Avoids therapy balls approaching from left and right, (15) Can safely maneuver in-between 2 chairs 32 in apart (16) Stops on command (emergency stop), (17) Approaches a transfer surface (bed or chair), (18) Ascend 6° incline, (19) Descend 6° incline, (20) Drive 3° cross slope, (21) Ascend 10° incline, (22) Descend 10° incline, (23) Drive through speed bump, (24) Drive over a slippery surface, and (25) Drive over an unpaved surface (2" bumps). The advanced environment included architectural barriers such as curbs and steep slopes present in the real-world. The tasks included (26) Ascend 2" curb, (27) Descend 2" curb, (28) Drive 10° cross slope (rough slope), (29) Ascend 4" curb, (30) Descend 4" curb, (31) Rolls 10ft across 6° side-slope, (32) Ascend 6" curb, (33) Descend 6" curb, and (34) Drive 10° cross slope. The curbs' dimensions were 8x4 square-feet. The obstacles were determined based on the Power mobility capacity driving assessment (PMCDA) tool [66] which used a content and face-validity to recognize driving tasks that EPW users encounter in daily basis. The slope angles and curb heights were obtained based on the ADA standards for accessible slopes, Section 2 of the ISO/RESNA standard wheelchair test: Determination of Dynamic Stability and Section 10: Determination of Obstacle climbing ability [40, 53].

Each participant was asked to drive straight at their comfortable speed on each of the tasks. A clinical investigator and two spotters followed each participant throughout the course to bring the wheelchair to an immediate halt if a risk to the participant was perceived or assistance was requested by the participant. After each trial, participants rated the EPW's safety, comfort, ease of use on a Likert scale and completed the NASA Task Load Index (TLX) to provide a gauge of the

workload while operating the EPW. Simultaneously, a clinician (with over fifteen years of experience in EPW provision) rated the participant's EPW driving performance using the PMCDA. After the driving trials, participants completed a usability questionnaire, regarding the use of MEBot's unique technical features and its attitude control graphical interface (ACGI). The protocol lasted approximately 6 hours.

1	Drives forward (15ft) (in a straight line) in 36" hallway
2	Turn 180° in place to the left
3	Drives backward 10ft in a straight line in 36" hallway
4	Turn 90° while moving backward
5	Turn 90° and enters a doorway
6	Ascend 3° incline
7	Descend 3° incline
8	Turn 90° while moving forward
9	Drives forward 30ft in 30s
10	Negotiates over 1 in door/mock threshold (piece of wood)
11	Drive in carpet
12	Passes through 36" doorway
13	Approaches an accessible sink
14	Avoids therapy balls approaching from left and right
15	Can safely maneuver in-between 2 chairs 32 in apart
16	Stops on command (emergency stop)
17	Approaches a transfer surface (bed or chair)
18	Ascend 6° incline
19	Descend 6° incline
20	Drive 3° cross slope
21	Ascend 10° incline
22	Descend 10° incline
23	Drive through speed bump
24	Drive over a slippery surface
25	Drive over an unpaved surface (2" bumps)
26	Ascend 2" curb
27	Descend 2" curb
28	Drive 10° cross slope (rough slope)
29	Ascend 4" curb
30	Descend 4" curb
31	Rolls 10ft across 6° side-slope
32	Ascend 6" curb
33	Descend 6" curb
34	Drive 10° cross slope

Figure 30: Indoor environment (Left), Outdoor Environment (Center), Advanced Environment (Right)

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4.3.2   Variables

MEBot was evaluated in three usability domains according to the ISO 9241-11 definition: effectiveness, efficiency, and satisfaction. The number of driving tasks completed in each environment was used as a measure of effectiveness. The PMCDA scores were used as a measure of efficiency from a clinician's perspective while the NASA TLX and user evaluation questionnaire were used as a measure of efficiency from the users' perspective. A usability questionnaire was administrated to participants which served as a measure of user satisfaction and answered questions from a semi-structured interview regarding the use of MEBot's unique technical features and its attitude control graphical interface (ACGI).

4.3.2.1 Demographics questionnaire

The questionnaire (Appendix B) asked basic information which included demographic information such as age, gender, veteran status, disability, education, job status, and marital status. In addition, the questionnaire asked details about the participant's current EPW such as make/model, time with current EPW, accessories, wheel drive configuration as well as experience with past training and time using an EPW.

4.3.2.2 PMCDA driving skills and modified PMCDA

The PMCDA developed by Karamaj et al [66], was a validated training method for power wheelchair users who needed/wanted to improve their ability to safely and effectively use a wheelchair. The PMCDA tool was used by a clinician who assessed the participant's driving skills in a scale of 1 to 3 in the areas of adequacy-efficacy (AE) and safety. In the AE area a score of 1

meant the participant required physical assistance or cannot complete the task; a score of 2 was given if the participant required verbal or auditory hints but no physical assistance, and a score of 3 is given if the participant completed the task without help. In the safety assessment, a score of 1 meant that the participant drove unsafe, a score 2 meant moderately safe, and a score of 3 meant safe driving. The PMCDA was modified to fit the tasks of the advanced environments (Appendix C) and able to use the same rating score. The total score in each environment was collected by the clinician.

Other assessment tools for evaluating EPW driving capacity were created without using a sort of validity or limiting their scoring system with a pass or fail such as the Wheelchair Skills Test (WST) [67], developed by Kirby et al, the Power Mobility Indoor Driving Assessment (PIDA) [68] and Power Mobility Community Driving Assessment (PCDA) [69], developed by Dawson et al, and Letts et al, respectively. The PMCDA used face-validity, content validity as well as the scoring tool similar to the Performance Assessment of Self-care Skills (PASS), a valid and reliable tool to measure occupational performance of daily life tasks [70].

4.3.2.3 NASA TLX

The NASA-Total Load Index (TLX) [71] was a reliable measure of workload imposed by a given task and related to subjective usability. It was comprised of six dimensions related to the workload demands on the user and the user's interaction with the task. These dimensions were mental demand, physical demand, temporal demand, performance, effort, and frustration. Participants first rated these six dimensions in a 0-100 scale and then weighted with 15 pairwise comparisons to obtain the workload score of each dimension. Higher scores indicated higher workload was contributed.

4.3.2.4 User evaluation

The user evaluation measured participants' perception of each EPW in terms of safety, comfort, ease of use. Comfort was defined as the quality of ride and seated well-being; Safety was defined as the users' level of control of the wheelchair and his/her feeling of stability when driving the wheelchair. Operation was the ease or difficulty of use of the wheelchair. Each measurement used a Likert scale of 1-5 where a score of 1-not satisfied at all, 2-Not very satisfied, 3-More or less satisfied, 4-Satisfied, and 5-Very satisfied (Appendix D).

4.3.2.5 Data analysis

Due to the novelty of MEBot, a learning effect was expected in participants; therefore, the latter trial for each environment was analyzed which represented the wheelchair's best performance [72]. Initial statistical analyses included a descriptive analysis of the data using standard descriptive summaries (e.g., means, median, standard deviation, percentiles, and ranges) and graphical techniques (e.g., histograms, scatter plots). The data were analyzed for normal distribution using Shapiro-Wilk in order to use a parametric or non-parametric statistical analysis. A paired sample t-test was performed if the data was normally distributed. If the data did not fit the normality assumption, Wilcoxon Sign-rank test was performed between types of wheelchairs (MEBot and commercial EPW) for each environment (indoor, outdoor, and advanced) with respect to the number of tasks completed, PMCDA scoring system, comfort, safety, operation and NASA TLX outcomes. The level of significance was set at $p < 0.05$ for all comparison. In addition, Friedman's test was performed to compare the efficacy and safety level of each EPW within the type of environments. If results were significant, a post-hoc analysis with Wilcoxon signed-rank test was

conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.017$. The statistical analyses were performed in SPSS (SPSS Inc., Chicago, IL)

4.4   RESULTS

The study recruited twelve subjects. Two participants did not complete the study due to back pain and unable to stay awake during the training phase. Ten power wheelchair users (8 male, 2 female) of an average age of 54.7 ± 10.9 years completed the study. The most common disability for using their EPW was spinal cord injury with 70% (Table 4). Participants reported an average of 16.3 ± 8.1 years of EPW driving experience and an average weight of 82.8 ± 16.1 kg (Table 5). Among the ten commercially available EPWs owned by the users, five were front-wheel drive EPWs, four were mid-wheel drive EPWs, and one was a rear-wheel drive EPW.

Table 4: Demographics information of participants

Gender	80% Male 20% Female
Ethnic Origin	70% White 20% African-American 10% Hispanic
Education	50% Bachelor 30% High School/GED 20% Masters
Work Status	30% Unable to work because of disability 30% Working full time 10% Volunteer 20% Working part-time 10% Retired
Marital Status	60% Married 30% Single 10% Living with someone
Diagnosis	70% SCI 10% Double BK amputee 10% MS 10% CP w/spastic

Table 5: Information about participants' electric power wheelchair

Subject	Age	Weight (kg)	Wheelchair Model (Type)	Years using a EPW	Years using current EPW	Hours in EPW per day
1	62	80.7	Q6 (Mid-wheel)	15	2	6
2	59	83.0	F5 (Front-wheel)	22	4	14
3	69	73.9	M400 (Mid-wheel)	20	4	11
4	57	72.6	S646-SE (Rear-wheel)	34	4	10
5	51	93.4	C300 (Front-wheel)	4	4	13
6	31	95.3	C400 (Front-wheel)	10	5	16
7	50	99.8	M300 (Mid-wheel)	12	5	18
8	56	71.7	F5 (Front-wheel)	20	3	18
9	37	52.2	F5 (Front-wheel)	23	1	14
10	70	105.7	TDX-SP (Mid-wheel)	20	1	16
	54.7±10.9	82.8±16.1		16.3 ± 8.1	3.5 ± 1.5	13.0 ± 3.6

4.4.1 Effectiveness

A Wilcoxon signed rank pairwise comparison analysis was performed to compare the percentage of tasks completed between EPWs in indoor, outdoor and advanced environments (Figure 31). The number of completed tasks were divided by the total number of tasks per environment to obtain the percentage of tasks completed. There was no significant difference in tasks completed between MEBot and participants' EPW in the indoor ($p=1.000$) and outdoor environments ($p=0.083$). However, results showed that users were able to perform significantly higher number of tasks ($p=.004$) while using MEBot rather than their own EPW when driving in the advanced environments demonstrating the effectiveness of MEBot.
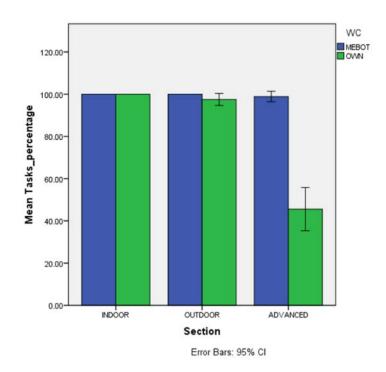
Figure 31: Comparison of percentage of completed tasks by EPW in indoor, outdoor and advanced environments

4.4.2   Efficiency

PMCDA scores

A Wilcoxon signed rank pairwise comparison was performed to compare the adequacy and safety of the EPWs to complete driving tasks of everyday environments. Results showed no significant difference in the adequacy-efficacy (p=.317) and the safety (p=.317) domains in the PMCDA between MEBot and participants' EPW when driving in indoor environments. Likewise, no significant difference was reported in the adequacy-efficacy (p=.221) and the safety (p=.141) domains between MEBot and participants' EPW when driving in outdoor environments. However, results showed significantly higher scores in both the adequacy-efficacy (p=.005) and the safety

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(p=.005) domains in the PMCDA while using MEBot rather than their own EPW when driving in the advanced environments demonstrating the efficiency of MEBot.

Friedman's test was used to compare participants' adequacy-efficacy and safety when using MEBot across the indoor, outdoor and advanced environment. Likewise, the adequacy-efficacy and safety of participants when using their own EPW were compared across the three environments. A post-hoc analysis with Wilcoxon signed-rank test was conducted with a Bonferroni correction applied, resulting in a significance level set at p <0.017. There was a significant difference in participant's adequacy-efficacy when using MEBot depending on the type of environment (χ^2 (2)=12.162, p=0.022). Results showed participants scored significantly higher in adequacy-efficacy when driving in indoor environments in compare to outdoor environment (p=0.013), and advanced environments (p=0.008). The Friedman's test did not show a significant difference in safety across indoor, outdoor and advanced environments when driving MEBot (χ^2 (2)=3.063, p=0.216). These results may be due to limited time learning MEBot's features and to practice curb climbing and descending; nonetheless, MEBot provided safety regardless the encountered environment. On the other hand, participants showed a significant difference in safety (χ^2 (2) =17.684, p=.000) and adequacy-efficacy (χ^2 (2)=17.684, p=.000) when using their own EPW across environments. A post-hoc analysis with Wilcoxon signed-rank test was conducted with a Bonferroni correction applied, resulting in a significance level set at p <0.017. Results showed significantly higher scores in safety when participants used their own EPW in indoor environment in compare to outdoor environments (p=0.016) and advanced environments (p=.004). In addition, participants scored higher in safety when using their own EPW in outdoor environments in compare to advanced environment (p=.005).

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Participants scored significantly higher in adequacy-efficacy when using their own EPW in indoor environment in compare to outdoor environments (p=0.016) and advanced environments (p=.004). Also, participants scored higher in adequacy-efficacy when using their own EPW in outdoor environments in compare to advanced environment (p=.005). As the difficulty level of environment increases, the adequacy-efficacy and safety of commercial EPWs decrease.

4.4.3   Satisfaction

NASA TLX and User Evaluation

A Shapiro-Wilk normality test was performed for the mental, physical, temporal, effort, performance, and frustration workload weights and comfort, safety and ease of operation for each EPW and environment. Only the performance workload using MEBot (p=.357) and own EPW (p=.053) in advanced environments showed normal distribution.

Wilcoxon signed-rank test was performed to compare participants' self-score in the NASA TLX and User evaluation outcomes when driving MEBot and their own EPW in different environments. Participants self-scored a higher performance workload mean score using their own EPW (27.5±5.6) in compare to MEBot (22.5±9.7) in indoor environments. However, a Wilcoxon signed-rank test showed no significant difference in the NASA TLX and user evaluation outcomes between the two EPWs when driving in indoor environments as shown in Table 6. In addition, results showed no significant difference when driving through outdoor environments, indicating the overall workload while operating MEBot and their own EPWs were similar in indoor and outdoor environments.

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Participants reported significantly higher scores in mental demand (p=.005) and effort (p=.022) while using MEBot in the advanced environments (Figure 32). This could be attributed to the increased demand that MEBot requires in order to remember and execute the steps of the curb climbing and descending sequences. In addition, participants reported that if these sequences were to be automated, operating MEBot would be considerably easier and more user friendly. Furthermore, participants self-reported higher performance workload means scores using their own EPW (19.8±12.7) in comparison to MEBot (11.9±7.6) when driving in advance environments. Even though no significance score was shown in performance workload (p=0.117), participants self-reported higher performance for completing the tasks allowed by their EPW despite of not being able to climb or descend the curbs. Overall, there were no significant differences in comfort, safety and ease of operation of MEBot in comparison to their own EPW demonstrating MEBot's comfort and safety while driving through any type of environments is comparable to commercial EPWs.

Table 6: Mean and Standard Deviation results of the NASA TLX and User Evaluation

Mean ± SD	Indoor			Outdoor			Advanced		
	MEBot	OWN Chair	p-value	MEBot	OWN Chair	p-value	MEBot	OWN Chair	p-value
Mental	.3±.4	.2±.3	.593	.5±.8	.5±1.1	1.0	12.7±7.5	.8±1.2	.005
Physical	.3±.4	.5±.9	.285	.4±.6	.2±.3	.066	3.6±6.2	2.2±4.3	.310
Temporal	1.2±3.1	.3±.5	.465	.6±.7	.6±1.1	.786	3.9±5.0	1.9±3.5	.398
Perform	22.5±9.7	27.5±5.6	.128	27.7±7.4	25.4±7.1	.599	11.9±7.6	19.8±12.7	.117
Effort	1.6±3.7	.4±.7	.168	.6±1.0	.6±1.1	.785	9.8±8.0	2.0±3.5	.022
Frustration	.0±.0	.0±.0	1.0	.0±.0	.0±.0	1.0	9.0±11.3	1.3±4.0	.063
Comfort	4.7±.5	4.3±1.1	.336	4.3±.8	4.4±1.0	.785	4.4±1.0	4.4±1.0	.891
Safety	4.8±.4	4.5±1.0	.414	4.7±.5	4.4±1.0	.480	4.1±1.0	3.9±1.1	.607
Operation	4.8±.4	4.6±.7	.414	4.7±.5	4.5±.7	.480	4.0±.9	4.2±1.0	.672

Table 7: Median and Interquartile range results of the NASA TLX and User Evaluation

Median (IQR 1-3)	Indoor		Outdoor		Advanced	
	MEBot	**OWN Chair**	**MEBot**	**OWN Chair**	**MEBot**	**OWN Chair**
Mental	.1 (.0 - .6)	.0 (.0 - .5)	.1 (.0 - .6)	.0 (.0 - .4)	12.0 (6.7 - 17.7)	.2 (.0 - 1.2)
Physical	.1 (.0 - .6)	.0 (.0 - .6)	.1 (.0 - .6)	.0 (.0 - .3)	.3 (.0 - 7.2)	.0 (.1 - 3.2)
Temporal	.1 (.0 - .7)	.0 (.0 - .8)	.3 (.0 - 1.4)	.0 (.0 - .7)	1.5 (.2 - 8.3)	.3 (.0 - 2.3)
Perform	21.5 (13.3 - 32.7)	28.8 (20.0 - 32.8)	31.0 (19.8 - 33.3)	26.7 (20.0 - 32.7)	13.5 (3.5 - 18.9)	19.2 (5.6 - 33.3)
Effort	.3 (.0 - 1.0)	.0 (.0 - .7)	.2 (.0 - 1.0)	.0 (.0 - .8)	7.7 (2.5 - 18.7)	.3 (.0 - 3.3)
Frustration	.0 (.0 - .0)	.0 (.0 - .0)	.0 (.0 - .0)	.0 (.0 - .0)	3.5 (.0 - 17.0)	.0 (.0 - .0)
Comfort	5.0 (4.0 - 5.0)	5.0 (3.8 - 5.0)	4.5 (3.8 - 5.0)	5.0 (4.0 - 5.0)	5.0 (4.0 - 5.0)	5.0 (4.0 - 5.0)
Safety	5.0 (4.8 - 5.0)	5.0 (4.0 - 5.0)	5.0 (4.0 - 5.0)	5.0 (4.0 - 5.0)	4.0 (3.8 - 5.0)	5.0 (3.0 - 5.0)
Operation	5.0 (4.8 - 5.0)	5.0 (4.0 - 5.0)	5.0 (4.0 - 5.0)	5.0 (4.0 - 5.0)	4.0 (3.8 - 5.0)	4.5 (3.8 - 5.0)
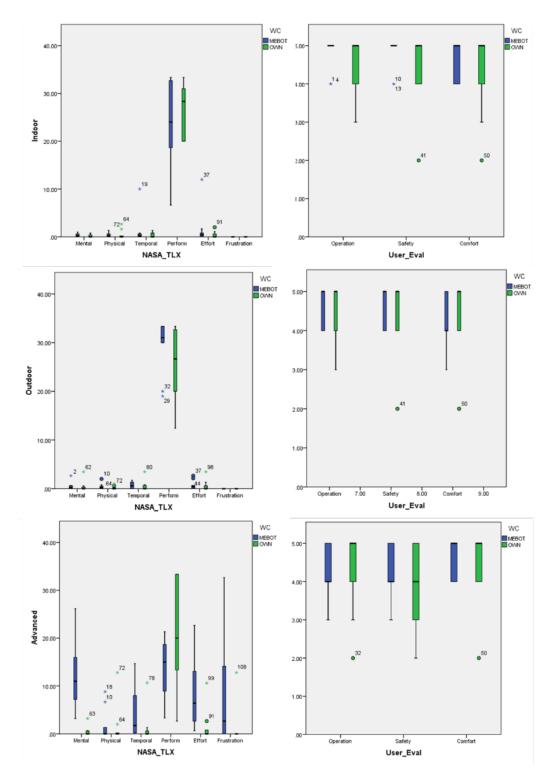
Figure 32: Comparison of NASA TLX (Left) and User Evaluation (Right) results between MEBot and participants' EPW when driving in the Indoor (Top), Outdoor (Middle), Advanced environment (Bottom)

4.4.3.1 User's perception towards the attitude control graphical interface

Regarding the ACGI features, 70% of the participants agreed that the visual representation of wheel position was useful and clear to interpret (Figure 33). Half of the participants agreed that it was easy to locate the functions on the interface and that it is aesthetically pleasant (Figure 34). However, 50% were neutral when asked if the interface had all the function and capabilities they needed, indicating that the ACGI needed further improvement to make its functionalities more user-friendly. While all participants managed to operate the sliders; end-users with low dexterity would have a hard time to control the interface and complete the curb climbing sequence.

The interface did not show the distance between the wheel and the ground regardless of providing a visual movement of the wheels and contact with the ground. Four participants noted this limitation and recommended rear-view cameras similar to the ones in on-road vehicles and audio feedback in addition to the visual display would be helpful to know the position of the wheels with respect to ground. One participant stated the ACGI would be in the way when transferring due to the size of the interface. The integration of the ACGI into the wheelchair joystick could provide a more compact interface. Participants reported that learning MEBot's features plus the curb climbing and descending sequence was a concern. In addition, 30% disagree that the interface was easy to learn how to use it while 40% were neutral about it. As future goal, the interface would be solely integrated switches to activate the mobility applications and a computer aid display (CAD) of each movement of the wheelchair instead of a 2D view as proposed in Chapter 3. The automation of the mobility applications may benefit the learning process of the interface as it will significantly simplify steps within the curb climbing/descending sequence that are repetitive.
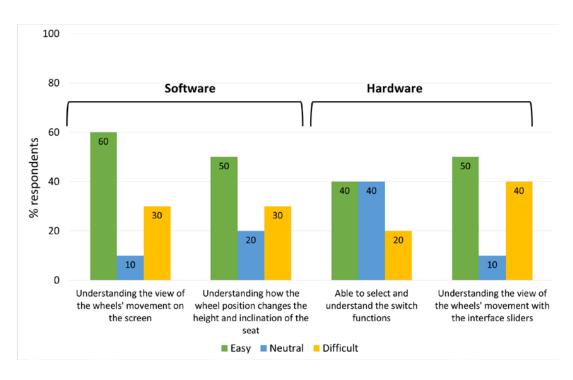
Figure 33: User Perception of the Attitude Interface
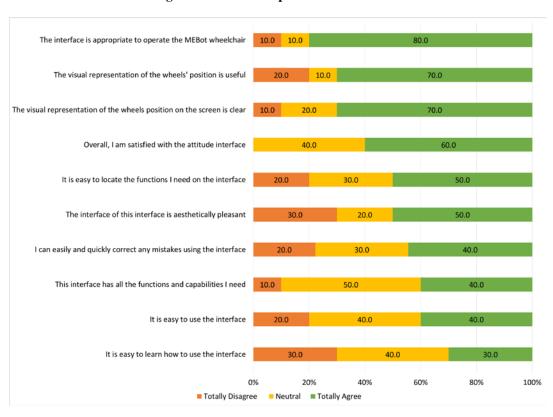
Figure 34: User Satisfaction of the Attitude Interface

Table 8: Response of the usability questionnaire about the Attitude Interface

Questions/Answers
What are your thoughts related to potential problem(s) and concerns about using the attitude interface?
P1: "Depth of rear casters"
P2: "The amount of sequences to remember needs to be simpler. 1,2,3 labeling the sequence"
P3: "Water-proofing of interface (sliders) and entire electronics of the chair, confused about which button to push (e.g., push forward I expect to go front for HOZ switch; too many steps to control the sliders; would not travel on flight airlines (everything needs to be sealed); concerned with compressed air tank"
P5: "Graphical display needs improvement (put cameras on the screen to show what happens in the wheels while moving the sliders); will be hard to drive into a car (interface on the way)""
P6: "Bigger air tank; too much equipment (overwhelming technology)"
P8: "Guessing the intended position is difficult. Not having caster brakes is a concern"
P9: "Slider location and marking, i.e., slider wheels should be located the same way as wheels in the footprint and close to each other"
P10: "Great potential if a bit simplified for end-user"
P11: "A low rear view mirror to help the person see the location of the wheels and know if the casters are making contact. A special Velcro-strap to place over feet so they can stay in place while the chair changes position"
P12: "Stressful to remember each step of the curb climbing and descending sequence"
What are your recommendation to improve the use of the attitude interface?
P2: "Prove an actual visual of the ground and curbs through the use of a camera"
P3: "Chair needs to sit lower, especially to get under desks and under tables for dinning; pneumatics need to be smoother down the sides as well (very jerky); 'add-on' seat support and modifications, e.g. transfer handle; touch screen interface for sliders; back light screen sensitivity; a joystick operation would be better than the slider"
P8: "Cameras would help"
P9: "Mounting screen option/size of screen (smaller) - it increases the footprint, RF/RR + LF/LR sliders for angled surface leveling"
P10: "Auditory cues for correct movement; Video display; cheat sheet for CC/CD application; automated sequences; also, possibly use of one button for a common set of steps"
P11: "Requires more training to learn the sequence and features"
P12: "Improvement of sliders into just a button for each sequence step of the CC and CD. (i.e., for CC a total of 11 buttons to do each step automatically, rather than using sliders)"

4.4.3.2 User's perception towards MEBot's applications

In the usability questionnaire, 80% indicated that the curb climbing and descending applications were extremely useful and 60% felt the same for the seat-leveling application in uneven terrains (Figure 35). These results complement the 80% who agree that MEBot felt stable when driving up and down slopes as well as when climbing and descending curbs (Figure 36). Furthermore, all participants indicated that the air powered seating functions were moderate to extremely useful due to its fast movement in comparison to the electric actuators available in commercially available

EPWs. Similarly, 70% of the participants indicated that the selectable driving wheel position was moderate to extremely useful for optimal maneuvering, particularly when transitioning from indoor to outdoor environments.

The movement of the air pneumatic actuators allowed the wheelchair to maintain its seat leveled during uneven terrains and provide accessibility to curbs. To operate the pneumatics also caused significant noise in the wheelchair; however, 60% of participants agree that the noise was acceptable; especially since these applications would be commonly used in outdoor environments where the ambient noise would be less noticeable. On the other hand, one participant stated the noise may not be acceptable in places such as a library or church where silence is golden. In addition, one participant stated that MEBot can be useful for outdoor usage but it would need improvement for noise cancellation especially for recreational sports such as hunting where silence is important.
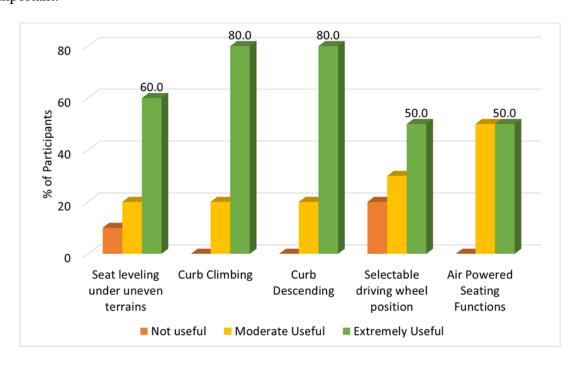
Figure 35: User's perception of MEBot's applications

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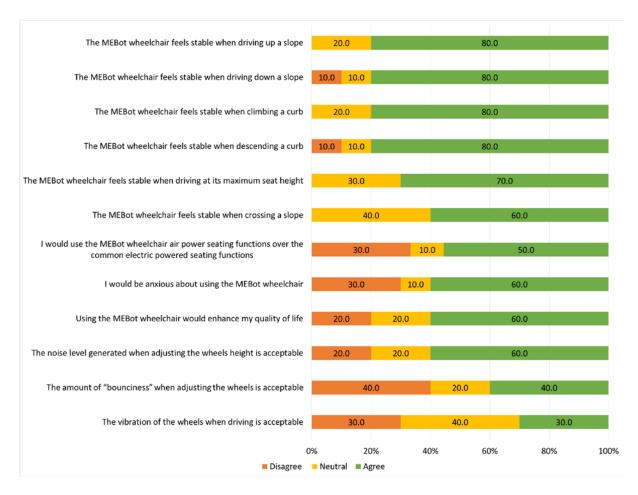
Figure 36: Users' Satisfaction with MEBot's applications

The questionnaire also highlighted the limitations of MEBot. One of the participants occasionally experienced spasms when the wheelchair was moving fast. The participant mentioned that a reason would be due to the vibration caused by the omni-wheels. The advantage of the omni-wheels allowed the caster wheels to move sideways without swivel; but more importantly they were used to gain ground clearance and increase the travel of the air pneumatics. However, it was noticed that the vibration of wheelchair was due to the shape of the omni-caster wheels. 30% of participants disagree that the vibration of the wheelchair was acceptable while 40% were neutral about it. 'Bounciness' was defined as the settling time of the pneumatic actuators to reach the desired position. This effect caused the wheelchair to move up and down without the use of the

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controller due to the air variability within the air pneumatics actuators. Participants showed disagreement regarding the 'bounciness' of the wheelchair at which 40% disagree that the effect was acceptable while another 40% agreed to be acceptable. The 'bounciness' effect can be beneficial or useless when driving uneven terrains as it can act as a passive suspension or increase the damping of the wheelchair. Improvements in the control algorithms are necessary to address the limitations of MEBot.

Participants provided useful feedback in regards of the curb climbing and descending application. Participants recommended a single button to start the curb climbing/descending sequence rather than asking them to learn the 6-11 steps. Also, all of the participants favored automated applications or the use of a few buttons to perform the mobility applications rather than using the sliders. While autonomous applications are essential, the involvement of end-users is important because they can detect obstacles that the wheelchair does not expect in the environment and therefore stop the application in unusual events [73]. In general, scalable autonomy is recommended for future improvement of the control algorithms.

The major feedback was the addition of rear cameras or mirrors to observe the position of the wheels. The interface provided information when the wheels were in contact with the ground and the movement of the wheels; however, it did not provide information about the distance of the wheels from the curb or ground. The use of obstacle detection and environment recognition can improve the visual feedback and even automation of the mobility applications. In addition, the use of cameras and other sensors to be aware of the wheelchair movements was recommended. The use of an interface that provides multiple channels of data provide a fair degree of situational awareness especially in close proximity [74].

The fore-aft movement of the drive wheels was confusing to most of the participants. When the drive wheels were in the ground, the wheelchair moved forward as the slider controlling the fore-aft movement moved backward along with the drive wheels; however, if the drive wheels were in the air, the drive wheels moved with the direction of the slider. For future improvement, the interface would allow the user to select between front-, mid-, or rear-wheel drive configuration instead of using a slider to simplify the interface.

Hardware limitations such as the high use of air and air filling concern were also addressed. The HPA air tank allowed MEBot to climb and descend a curb three times until running out of air. Then, it would require 7 minutes to fill the air tank again; using an external tank to fill the tank was also useful; however, the maximum volume would be less over time. Other alternatives, such as electric and hydraulic actuators were considered for future improvement.

Table 9: Response of the usability questionnaire about MEBot mobility applications

Questions/Answers
What would be the potential problem(s) and/or concerns to use the MEBot wheelchair?
P1: "Learning curve"
P2: "Remember the sequence of operation, potential problem of traveling without air in airlines"
P5: "Running out of air; overwhelming technical features and equipment; battery replacement; wiring and pneumatics lines leaking"
P8: "Air filling, Repair costs, making adjustments for specific user, noise factor (inside the church, hunting)"
P10: "Different curb heights require steps; got confused when moving middle wheels back/forth rather than frame back/forth"
P11: "Tipping over, mirrors/cameras to see the wheels, straps to keep the feet in place"
P12: "Because of the many ramps and accessible areas, it is not necessary the CC and CD application"
What are your recommendation to improve the applications of the MEBot wheelchair?
P2: "Install a camera to see the terrain to gain access to"
P5: "Power seating functions; flip switch to change functions to one joystick"
P10: "Auditory cues, cheat sheets or cues on screen"
P11: "Elevation sliders in both sides of interface, cheat sheet for CC/CD steps"
P12: "No more than four buttons for each application, improvement in interface for people with lack of dexterity"
Would you recommend a "MEBot" to a friend and/or family member?
50% "Yes"; 10% "Yes – Specifically for outdoor usage"; 10% "If the final product has all the bugs addressed" 10% "After you get all the bugs out of it"; 10% "After improvements"; 10% "Not yet"

4.5 STUDY LIMITATIONS

Hawthorne effect refers to the change of behavior in participants to their awareness of being observed. Participants were aware of being observed by researchers and other potential participants when conducting the study at the National Veterans Wheelchair Games (NVWG). The presence of other individuals may have caused participants to perform different than their normal driving behavior. Likewise, using a different EPW than their own, such as MEBot, probably changed their driving behavior. To eliminate the influence, participants were recommended to use as much time to complete the driving tasks since time was not an outcome measure. Also, participants performed the driving course three times in the case of getting familiar or frustrated with MEBot and their own wheelchair in the first two trials. The latter trial was used for comparison and analysis.

A second limitation was the amount of training time with MEBot. Participants reported many years of driving experience with their own EPW in comparison to a single day using MEBot. To reduce favoritism toward their own device, MEBot's seating system and driving parameters were adjusted prior to the study to be as similar as their own EPW. Also, a driving skills evaluation was performed prior to the start of the study to obtain a driving performance baseline. Scores in the PMCDA, NASA TLX and User Evaluation demonstrated the similarities of MEBot and their own EPW in the indoor and outdoor environments. However, the limited time for training in the curb climbing/descending application and other features of MEBot affected participant's self-report outcomes in the advanced environment. Participants self-reported higher scores in the mental (12.7 ± 7.5) and effort ($.8\pm1.2$) workload when using MEBot in compare to their own EPW (9.8 ± 8.0 and 2.0 ± 3.5, respectively). The time constraint of the study and extensive number of MEBot features demonstrated during the training were a limitation of the study. A longer training

time may have improved the self-report NASA TLX scores of participants. Future improvements should involve the reduction of inputs to operate the MEBot interface, automation of the mobility applications to decrease the training time and provision of an intuitive interface.

Another limitation was that participants rated the EPWs based on the type of environment using the NASA TLX. Ideally, the participant would rate the use of each EPW per driving task to have a better understanding of participants' workload for each driving task. On the other hand, this could exhaust or frustrate the participant which could lead to a withdrawal of the study.

The sample criteria included active EPW users and excluding people with pressure sore or pain in lower back. This might limit our generalization to a broad EPW user population. In addition, half of the participants were veterans who are more active using their EPW than civilians (non-veterans) [39]. These criteria were selected to prevent attrition or drop out in the study due to the exposure to vibration when driving in the driving course and unable to complete the course.

The driving course simulated indoor and outdoor environments in an in-lab controlled setting. This type of setting eliminated distractions, weather, and other variables that could affect the user's driving performance. A future study design will include in-home trials using the final product of MEBot after improvement are addressed.

4.6   CONCLUSIONS

Overall, this usability evaluation demonstrated that the clinician's assessment and the users' perception indicate that MEBot was effective, and efficient to use in indoor, outdoor and advanced environments. Participants demonstrated similar driving performance with MEBot and their own

EPWs in indoor and outdoor environments, and significantly better performance in advanced environments where curb and cross slopes were present. Few key limitations of the current design such as the vibration and 'bounciness' of the wheelchair were highlighted by the participants and will be taken in account for further improvement of user satisfaction with the device.

Further, the mental workload of participants was affected by the number of steps to perform the curb climbing and descending sequence and the limited time for learning these sequences to use the novel applications of MEBot. Users identified that automating the curb climbing and descending sequences with additional visual and auditory feedback would make the device intuitive and user-friendly. The next version of MEBot will incorporate these design suggestions along with the use of alternative motors and power sources such as hydraulic actuators aimed to reduce the power consumption of the system, prolong the battery life and improve the performance of MEBot's mobility applications.

5.0 EXPLORATORY ANALYSIS OF MOBILITY STRATEGIES FOR A NOVEL ROBOTIC WHEELCHAIR WHEN FACING ARCHITECTURAL BARRIERS

In this chapter, we analyzed the different movements of the wheels performed by the participants when completing the driving tasks in the advanced environments. The purpose of this chapter was to explore different mobility strategies when climbing and descending curbs as well as when driving through slopes and cross slopes in comparison to those during the demonstration and training of MEBot. These strategies were analyzed to improve MEBot's control algorithms in order to developed semi-automated mobility applications. Results showed that steps in the curb climbing and descending sequence can be combined and shortened to reduce the completion time, air consumption and improve user's satisfaction. Also, potential sensors to complement the mobility strategies were discussed.

5.1 INTRODUCTION

In the usability study, participants reported that the number of steps in the curb climbing and descending process was extensive which was associated with the high level of frustration and mental demand in the NASA-TLX when driving in the advanced environment. Another comment included that different curb heights required extra steps in the sequence which were not taught during the training. The training asked the participant to climb the highest curb which involved moving the wheels to their maximum stroke. In addition, participants stated the lack of visual or

auditory feedback whenever the wheels contact the ground. Performing a usability study on MEBot's performance in the driving course allowed us to gather participant's feedback to find limitations in the control algorithms. The goal of this chapter was to combine participant's feedback with quantitative data collected when driving through the architectural barriers in the advanced environment for further improvement of MEBot and its control algorithms.

5.2   METHODS

5.2.1   Study design

The study followed the same protocol as the previous chapter. The inclusion criteria included participants who 18 years old or older, weight less than 113.4 kg, able to tolerate sitting for six hours, and at least 1 year of experience using an EPW in indoor and outdoor environments. The study was conducted at the Human Engineering Research Laboratories (HERL) in a controlled simulated real-world environment. The study protocol was approved by the University of Pittsburgh and Veterans Affairs Institutional Review Board (IRB). Participants were transferred in one of the MEBot iterations; MEBot2.0 or MEBot2.5. Modifications in the seating system were applied as requested by the participant to offer the best comfort. Participants received an overview and training of MEBot's advanced mobility features including climbing and descending a curb (Appendix A) and later they were asked to demonstrate the learned skills. Participants complete the driving tasks of the advanced environment in MEBot three times. The driving tasks included climbing and descending curbs with heights of 5.1 cm (2"), 13.1 cm (5.15"), and 19.1 cm (7.5")

with a length and width of 2.44x1.22 meter-sq., respectively; as well as driving through a cross slope of 6 degrees, 10 degrees and a 'rough' cross slope of 10 degrees that simulated an uneven surface. The slope angles and curb heights were within ADA standards for accessible slopes [15] and the ISO/RESNA wheelchair testing standards Section 10: obstacle climbing [40].

Participant's mobility strategies to complete each driving task were recorded, analyzed and compared with the curb climbing and descending sequence demonstrated during the training phase. These training sequences were created by the research team including clinicians, engineers, and end-users. The curb climbing completion time for MEBot2.0 and MEBot2.5 were 68 seconds and 42 seconds, respectively. The steps of the curb climbing and descending sequence were shown in Figure 37 and Figure 38, respectively along with the moving wheels and completion time for each step. The dash lines represented a pause in the sequence. As mentioned earlier, the MEBot2.5 provided a faster horizontal travel of the drive wheel of 5.5 seconds along the frame in compare to MEBot2.0 (12 seconds). Despite the improvement, both MEBot iterations shared the same range of motion, driving performance, and control algorithms.
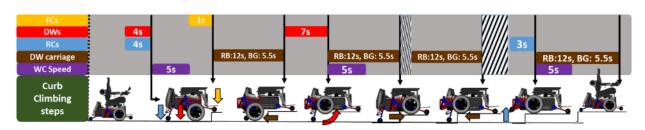
Figure 37: Curb Climbing Sequence demonstrated during training
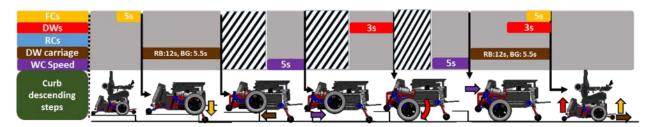
Figure 38: Curb Descending Sequence demonstrated during training

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5.2.2 Variables

The study collected and analyzed the quantitative data of the movement of the wheelchair and the selection of MEBot features by the participants in the three trials. The quantitative data included the following:

Table 10: Quantitative variables to analyze mobility strategies

Variables	Description	Unit
Actual Pneumatic Position	Position sensors measured the stroke of the pneumatic to elevate or lower the wheels in a scale from 3.2 to 23 cm for the drive wheels and rear casters. These measurements were the distance from the bottom of the frame. Front caster stroke ranges from -2.5 to 23 cm.	Centimeters (cm)
Desired Pneumatic Position	Slider potentiometers in the attitude interface recorded the pneumatic position selected by the participant in the same scale as actual pneumatic positions	Centimeters (cm)
Switches	Four switches represented each feature of MEBot: Elevation, Paired wheels, Drive wheel carriage, and home switch. No switch selected represented the individual use of wheels	0-1
Pitch, Roll	An IMU sensor placed under the seat measured the seat angle of the wheelchair. Positive pitch represented the wheelchair tilting backward; a positive roll, represented the wheelchair tilting to the right	Degrees (°)
Drive Wheels Speed	Encoder gears attached to the drive wheels measured the speed of each drive wheel	Meters per second (m/s)
Drive wheels carriage	Encoder gears attached to a rack and pinion mechanism that moved each drive wheel horizontally along the frame for 36 cm. The BG MEBot travelled the full distance in 5.5 seconds while the RB MEBot travelled it in 12 seconds.	Centimeters (cm)
Time	Completion time of each step of the curb climbing and descending sequence was measured	Seconds (s)
Air pressure difference	The air pressure difference before and after the completion of each task was recorded	Mega Pascal (MPa)

5.3 RESULTS

Each participant completed the 9 driving tasks in the advanced environment. The average time to complete all the tasks was 13.4 ± 3.6 minutes with an average air pressure difference of 10.8 ± 1.6 MPa used throughout the advanced environment. Each participant's seating angle was different at the start of the study due to the participant's comfort. Therefore, the results of the seating angle were calibrated by subtracting the initial seating angle. Both MEBot iterations showed a high dynamic stability in each driving task demonstrated as well in the static stability analysis.

Table 11: Seat angles, time, and air pressure difference of the advanced driving tasks

Task (Mean ± 2SD)	Pitch (degrees)	Roll (degrees)	Time (sec)	Air pressure difference (MPa)
Climb 5.1 cm (2")	.0 ± 2.0	.0 ± 1.4	26.5 ± 13.7	2.6 ± 1.3
Descend 5.1 cm (2")	.0 ± 3.7	.0 ± 1.7	12.9 ± 6.0	
6° cross slope	.0 ± 6.7	.0 ± 5.0	21.6 ± 8.0	0.5 ± 0.7
Uneven 10° cross slope	.0 ± 5.5	.0 ± 11.0	29.5 ± 13.1	2.6 ± 3.2
10° cross slope	.0 ± 9.4	.0 ± 7.7	26.9 ± 14.2	1.8 ± 1.8
Climb 13.1 cm (5.15")	.0 ± 4.5	.0 ± 1.5	232.8 ± 80.0	9.6 ± 3.9
Descend 13.1 cm (5.15")	.0 ± 6.2	.0 ± 1.1	127.4 ± 48.3	5.0 ± 2.3
Climb 19.1 cm (7.5")	.0 ± 2.8	.0 ± 1.0	197.7 ± 30.6	7.6 ± 1.6
Descend 19.1 cm (7.5")	.0 ± 2.6	.0 ± 0.9	130.5 ± 37.4	6.6 ± 2.9

Slopes:

Participants moved the drive wheels down to an average of 8.13 ± 2.0 cm to increase the ground clearance (Figure 39). The ground clearance of both MEBot iterations were as low as 3.18 cm; MEBot2.0 had the front casters as low as the frame while MEBot2.5 had the front casters 5.08 cm above the ground; however, since the hard stop of the front casters were only 1.27 cm above the

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ground, participants required to move the drive wheels to clear the slopes especially at the rough 10° slope. Results showed an average pitch and roll angles of $.0 \pm 6.7°$ and $.0 \pm 5.0°$, respectively when driving through a 6° cross slope; an average of $.0 \pm 9.4°$ and $.0 \pm 7.7°$ driving through a 10° cross slope and an average of $.0 \pm 5.5°$ and $.0 \pm 11.0°$ driving through an 10° cross slope (rough slope) (Table 11).

Three participants performed seat leveling when driving on the cross slopes for one trial by moving the drive wheel down closer to the flat ground. However, the participants' weight plus the wheelchair weight was leaned toward the moving wheel which increased the moving time of the wheel. In addition, the moving wheel reached its desired position by the time the participant completed the cross slope which caused an 'echo' effect; meaning, the wheelchair replicated driving a cross slope by leaning to the opposite side of the extended drive wheel. While six participants responded in the usability questionnaire that the self-leveling application was extremely useful, participants were able to overcome the cross slopes without performing the seat leveling application. Although participants did not require to use the application, research has shown that tips and falls often occurs in slopes and curb cuts; particularly during the transition between flat ground and angled surface [10]. EPW users tend to decelerate causing the system to shift its center of mass, creating a tipping moment [12]. Driving in a steep cross slope can be as risky as driving in slopes; since the center of mass moves closer to the sides of the wheelchair footprint. For future improvement, the seat leveling application would be performed automatically when slopes, crossing slopes, and uneven terrains to prevent tips and falls. In addition, the lifting capabilities will be improved with the use of hydraulics actuators which decreases the delay in the controller to move the wheels.
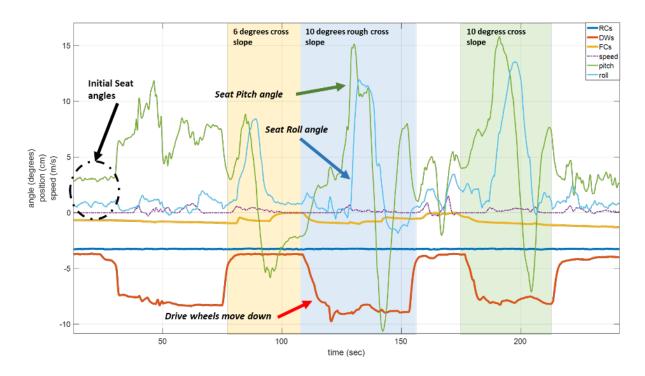
Figure 39: Participant #2 mobility strategy when driving 6° cross slope (yellow area), 10° rough cross slope (blue area), and 10° cross slope (green area)

Curbs:

Participants were asked to climb and descend a 5.1 cm curb with their own mobility strategies (Figure 40). The average completion time to climb and descend a 5.1 cm curb were 26.5 ± 13.7 and 12.9 ± 6.0 seconds, respectively. As first step, participants lined up perpendicular towards the curb to obtain as much contact of the drive wheels with the curb (step 1). Then, the drive wheels were move down to elevate the front side of the frame at an average of 8.1 ± 2.0 cm above the ground (step 2). This step allowed the wheelchair to prevent the frame from hitting the curb. In addition, this step tilted the wheelchair back an average of 3.0 ± 1.9 degrees in the pitch direction. Participants followed to climb and descend the curb with an average speed of 0.6 ± 0.3 m/s (step 3-4). The total completion time for climbing and descending a curb of 5.1 cm were 26.5 ± 13.7

seconds and 12.9 ± 6.0 seconds, respectively. MEBot tilted three more degrees in the pitch direction when the drive wheels were driving over the curb due to the air suspension in the wheels.
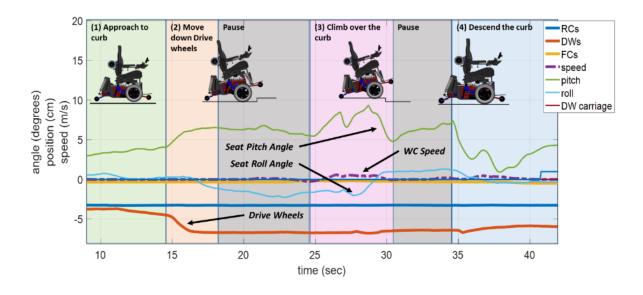
Figure 40: Subject #2 climbing and descending strategy in a curb height of 5.08 cm (2")

A similar mechanism is found in commercial EPWs which uses a passive spring-loaded suspension mechanism to climb curb up to 10.2 cm (4") according to the manufacturer [22]. The standard mobility strategies to climb this curb height with commercial EWPs are driving at full speed and move their center of mass back before climbing the curb. In theory, the climbing ability depends mainly upon the wheels radius, where the maximum obstacle height is limited by the wheel radius, not taken in account the required force and wheelchair weight [75]. In addition, it was suggested to approach the curb at angles less than 25°; otherwise, there was a risk of tipping over [76]. However, attempting to climb curb over 5.1 cm using this mobility strategy can damage the EPW or put the user at risk of injury.

Two participants attempted to climb the curb by moving down the six wheels 9.1 cm above the ground. This mobility strategy required less speed because the weight was distributed among all the wheels and the drive wheels used less traction to overcome the curb. In addition, the seat

angles varied 1 degree in compared to the previous mobility strategy; however, it required 38.3 seconds to complete the task.

Curb Climbing:

For curbs higher than 5.1 cm, participants performed the curb climbing and descending sequence demonstrated during the MEBot training. While most participants followed the sequence learned during the training phase; other participants showed other mobility strategies that could improve the sequences as shown in Table 12. The average completion time to climbing a 13.1 cm and 19.1 cm curb was 232.8 ± 80.0 seconds and 197.7 ± 30.6 seconds, respectively. In addition, the air pressure difference used in both curbs were 9.6 ± 3.9 MPa and 7.6 ± 1.6 MPa, respectively. Results showed a slow movement of the wheels due to participants' adjustments to move the wheels to the curb height and a response delay in the control algorithm due to the participant's weight. In addition, the movement speed of the wheels was reduced within the control algorithm to provide a smoother and safer movement.

The grey areas in Figure 41 showed a participant stopping during the curb climbing sequence to think through the next steps or alternative strategies. All the participants paused during the climbing process which increased the completion time. Six participants elevated the wheelchair to its highest ground clearance when climbing the 13.1 cm curb; while the other four participants showed a better understanding of the environment and MEBot features; therefore, these participants elevated the wheelchair to the curb height. During step 2 and 4, most participants moved the front casters and drive wheels, respectively, all the way up and then lower these wheels to the curb until the control algorithm detected when they were in contact with the curb. This trial and error added time to the curb climbing process.
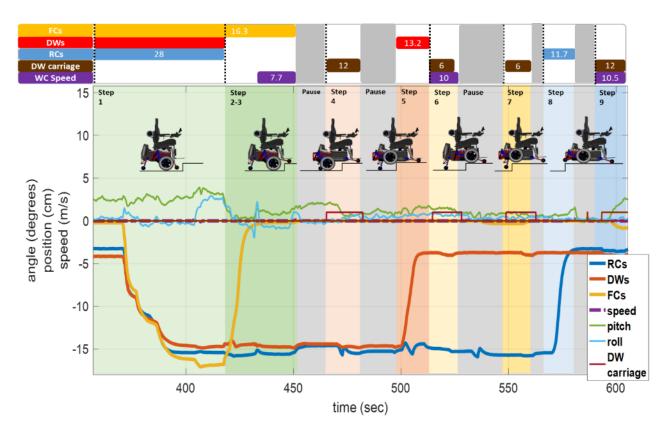
Figure 41: Curb climbing strategy used in a 13.1 cm (5.15") curb

The low upper movement of participants limited their visibility of the position of the wheels in relation to the ground. Even though, the interface displayed the contact of the wheels with the ground, participants recommended the use of cameras near the wheels for a better visual feedback. During step 6, participants moved the drive wheels carriage forward halfway until the drive wheels were on top of the curb compared to moving to its extreme as shown during the training. This step reduced the climbing process by 12 seconds for MEBot2.0 and 6 seconds for MEBot2.5.

A difference in both MEBot iterations were the movement of the front casters. The front casters in MEBot2.0 were at the same plane of the bottom of the frame when its pneumatics were fully compressed; compared to MEBot2.5 which required to move down 5.7cm to clear the curb and hard stops. During steps 7, 8, and 9 MEBot's footprint was on top of the curb and showed a

high stability which allowed the participant to combine these steps. The control algorithms can be further improved by knowing the completion time of each step and the center of mass based on the position of the drive wheels carriage. Also, step 1 and 2 can be combined with sensors that detect the curb height ahead of time.

Table 12: Curb Climbing steps difference between training and participant's strategies

	Assigned wheels	Steps from Training	Mobility strategies by participants
1	FCs, DWs, RCs	Move all wheels down/Elevate MEBot to highest ground clearance	All wheels were moved down to elevate MEBot to the curb height.
2	FCs	Front casters move up to the curb height	Front casters moved up to the curb height
3	DW-HOZ	Move drive wheels carriage backwards to its extreme travel	Drive wheels carriage was moved back to its extreme travel
4	DWs	Move drive wheels up to the curb height	Drive wheels moved up to the curb height
5	DW-HOZ, DW-drive	Move drive wheels carriage forward to its extreme travel while driving	Drive wheels carriage was moved forward until the drive wheels were on top of the curb (Drive wheels were 14.5 cm away from the front of the frame)
6	DW-HOZ	Move drive wheels carriage backwards to its extreme travel	Drive wheels carriage was moved backward to its extreme travel.
7	RCs	Move rear casters up to the curb height	Rear casters were moved up to the curb height while driving forward until all the wheels were on top of the curb. Also, the home button was pressed during these steps which moved all the wheels up and the drive wheels carriage forward to its extreme.
8	DW-drive	Drive forward until all wheels are on top of the curb	
9	DW-HOZ	Move drive wheels carriage forward to front-wheel drive	

Curb descending:

Two strategies were demonstrated for curb descending. The first strategy showed participants combining steps of the trained descending sequence as shown in Table 13. The average completion time to descending a 13.1 cm and 19.1 cm curb was 127.4 ± 48.3 seconds and 130.5 ± 37.4 seconds, respectively. In addition, the air pressure difference used in both curbs were 5.0 ± 2.3 MPa and 6.6 ± 2.9 MPa, respectively.

The curb descending sequence requires six steps. However, participants demonstrated the use of combined steps to reduce the completion time. Step 3-4 were used at the same time followed by the combination of steps 5 and 6. After driving off the curb (step 2), moving the drive wheels carriage backwards (step 3) was performed in unison while moving the drive wheels down (step 4). In the same manner, once MEBot was in rear-wheel drive and fully elevated; the participant drove the rear casters off the curb (step 5) while lowering MEBot to its lowest ground clearance (step 6) as shown in Figure 42. The combination of steps and repetitive movement of the wheels provided insight for automation of the sequence and improvement of the mobility algorithms.

Table 13: Curb Descending steps difference between training and participant's strategies

	Assigned wheels	Steps from Training	Mobility strategies by participants
1	FCs	Move front casters down until they are in contact with the ground	Front casters were moved down until interface showed the wheels were in contact with the ground
2	DW-HOZ	Move drive wheels carriage backward to its extreme	Participants used steps 2 and 3 in different order. Driving off the curb may provide more room to prevent the wheelchair from rolling completely off the curb
3	DW-drive	Drive forward until drive wheels are off the curb	
4	DWs	Move drive wheels down until they are in contact with the ground	Some participants combined step 3 and 4. Furthermore, other participants combined step 2 and 4 after the drive wheels were off the curb.
5	DW-drive	Drive forward until rear casters are off the curb	Step 5 and 6 were combined which improved the completion time to descend the curb
6	FCs, DWs, DW-HOZ	Press home button: Lower MEBot to its lower position and move drive wheels carriage forward to its extreme	

Figure 42: Curb descending strategy used in a 19.05 cm (7.5") curb

The second mobility strategy showed a faster curb descend sequence of 42.6 seconds as shown in Figure 43. This sequence required the participant to tilt MEBot backwards by moving the drive wheels down (step 1). This step moved the center of mass of the user to the back of the wheelchair. The front casters were moved down as well to be used as anti-tippers to prevent the participant from tipping forward (step 2). Then, participants drove off the curb slowly until the drive wheels were on the ground (step 3). The wheelchair tilted forward, making the seat flat to the ground. The rear casters were moved down (step 4) 5.1 cm to increase the suspension before driving them off the curb (step 5). After descending the curb, the participant pressed the home button to move all the wheels to the lowest ground clearance. For automation, step 1, 2, and 4 can be combined which would reduce the completion time by 12 seconds. Furthermore, participant would require to drive once in compare to performing step 3 and 5. This sequence was only

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performed with the 13.1 cm curb for safety reasons. Higher curbs may cause the wheelchair to tilt

more forward, thus putting the participants at risk of falling.
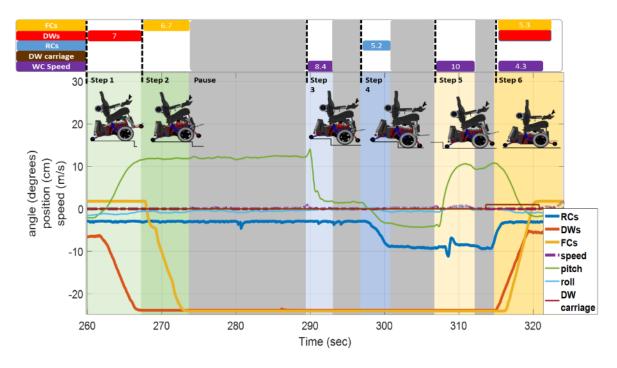
Figure 43: Second curb descending strategy used in a 13.1 cm (5.15") curb

The lack of visual or auditory feedback prove the need of sensors for obstacle detection

and environment recognition to automate the climbing and descending process. Sensor as such

could measure the distance from the curb as well as identify the curb height in order to provide a

variety of options to overcome the recognized obstacles. In addition, safety failures will provide a

second layer of safety by providing full control of the application to the user to roll-back the curb

climbing/descending sequence or home position. Furthermore, the seat angle will be monitored to

maintain the center of mass within the safety boundaries of the wheelchair during the sequence.

An issue when descending curbs was the lack of brakes in the casters wheels. After moving

the front casters down onto the ground, participants were required to drive off the curb which set

the drive wheels in the air; this step caused the wheelchair to roll forward depending on the

wheelchair speed. To prevent the wheelchair from rolling off the curb completely, participants were asked to drive at the slowest speed of 0.22 m/s. Due to the controlled environment, we did not take in consideration curbs with small slopes for water drainage. A recommendation is the design of caster brakes or motorized wheels to prevent rolling off the curb.

The approaching and departure angle for the curb climbing and descending were always perpendicular to the curb. During each trial, participants were guided whenever the wheels were either in contact with the curb when climbing or at the edge of the curb when descending. It was suggested to approach the curb at angles less than 25°; otherwise, there was a risk of tipping over [76].

5.3.1 Completion tasks comparison between MEBot 2.0 and MEBot 2.5

The two latest iterations of MEBot were compared in regards of completion time for each task of the advanced environment as well as the air pressure difference used to complete the advanced environment. An independent sample t-test analysis was performed to compare the completion time individual and combined tasks of the advanced environment as well as the air pressure difference between MEBot2.0 and MEBot2.5 (Table 14). Results showed no significant difference between both iterations of MEBot when completing each task. However, MEBot2.5 showed significant less air pressure difference in compare to MEBot2.0 to complete the advance environment. An interpretation of this result may be a finer operation of the movement of the wheels to climb and descend the curbs which can be associated with a better completion time. In Table 14, it was reported that MEBot2.5 was able to climb and descend the curbs in less time than MEBot 2.0 which can be due to the speed improvement to move the drive wheel along the

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frame. However, MEBot 2.0 was slightly faster than MEBot 2.5 to complete the cross slopes; possibly because participants using MEBot2.5 were more careful to drive through these tasks (i.e, two participants used the seat leveling applications with MEBot2.5).

Table 14: Completion time comparison of MEBot 2.0 and MEBot 2.5

Completion Time (Mean ± SD)	MEBot2.0	MEBot2.5	p-value
Climb 5.1 cm (s)	32.1 ± 16.1	21.0 ± 13.1	.708
Descend 5.1 cm (s)	14.6 ± 7.2	11.4 ± 7.0	.999
6° cross slope (s)	19.7 ± 8.3	24.0 ± 6.8	.664
Uneven 10° cross slope (s)	29.9 ± 17.9	29.4 ± 13.8	.484
10° cross slope (s)	24.1 ± 10.0	33.0 ± 15.2	.565
Climb 13.1 cm (s)	260.1 ± 95.9	213.5 ± 78.7	.791
Descend 13.1 cm (s)	157.2 ± 42.5	107.6 ± 53.0	.738
Climb 19.1 cm (s)	207.8 ± 40.1	201.5 ± 22.9	.054
Descend 19.1 cm (s)	148.1 ± 40.5	126.3 ± 37.0	.858
Total time (s)	14.9 ± 4.17	12.8 ± 3.6	.665
Air pressure difference (psi)	1725 ± 206.2	1412.5 ± 103.1	.009
User weight (lb)	172.3 ± 22.5	175.8 ± 48.8	.080

5.4   CONCLUSIONS

Participants' mobility strategies to navigate different curb heights and degree of slopes were analyzed. When driving through cross slopes, participants did not perform a seat leveling. If the application was performed, a side effect caused the wheelchair to tilt to the angle of the cross slope after its completion due to a delay in the control algorithm. The weight distribution of participants within the wheelchair was a limitation in the control algorithm to move the wheels to the desired position; for that reason, the time to perform this action increased with the user's weight. Future improvements of the algorithms would include an active suspension through automated movement

of the wheels for self-leveling when driving through slopes and cross slope as well as a passive suspension for smaller obstacles than 5.08 cm height and uneven terrains. For the seat leveling there were two strategies; as proposed in MEBot1.0 the chair can adjust its seat angle co-planar to the ground and using the IMU sensor. The other strategy is the independent movement of actuators as shown by the participants; however, the latter may require force sensors in each actuator to give more preference to which actuator to move if the application is performed automatically.

The mobility strategies and participant's feedback were extremely beneficial for the improvement of the control algorithms of MEBot. The combination of steps and repetitive movement of the wheels provided information for automation of the sequences. The use of rear cameras and sensors that could scan the environment may be useful for obstacle detection and terrain recognition [77] in order to provide available mobility features to the user ahead of time. In addition, such sensors can semi-automate the control algorithms; while still allowing the user to be in control of the wheelchair throughout the climbing and descending process. An improvement in the control algorithms also means improvement of the comfort and safety for the EPW user and ease of use of the MEBot wheelchair.

6.0   CONCLUSIONS AND FUTURE WORK

A series of control algorithms in the MEBot wheelchair were designed, developed, and evaluated to address non-compliance ADA environments and the design limitations of EPWs when driving through these environments. Environments as such make EPW users susceptible to safety issues - such as tipping or falling - which may lead to serious injury. The purpose of MEBot was to improve safety and overcome architectural barriers that end-users of current EPWs encounter. In addition, the design criteria of MEBot was developed to meet policy regulations [9] by including the seating system and drive wheel configuration within the frame.

Chapter two described the design process of the MEBot wheelchair and its control algorithms towards its final iteration through a participatory action design (PAD) in close cooperation with end-users. The control algorithms provided dynamic seat leveling, curb climbing, and descending applications which were evaluated and validated in both simulation and a controlled environment for broader accessibility in architectural barriers. A focus group was performed with twelve active EPW users to ask their likelihood of using MEBot's applications. The results showed most the participants would very likely use the seat leveling and curb climbing, while the selectable driving wheel position were less likely to be used. Their likelihood towards the mentioned applications were related to EPW users' concern of tipping when driving up steep hills or uneven terrains when the wheelchair stability is jeopardized [57] and concern if curb cuts are not available to access higher ground due to lack of maintenance. User's feedback along with design revisions from the first prototype were addressed in MEBot2.0 and MEBot 2.5. The control algorithms were modified by improving the movement of the wheels through a proportional

control by the users. The kinematics of the new MEBot iteration was also updated to obtain the location of its center of mass when performing each mobility application. The major improvement was the completion time of the curb climbing and addition of the curb descending application in compare to the first iteration of MEBot. Chapter three described the importance of an attitude control graphical interface (ACGI) to operate the MEBot's features and obtain further insight of end-user mobility strategies when traversing different environments.

In Chapter Four we performed a usability evaluation to gather user's response towards MEBot's applications and its attitude graphical interface. The usability evaluation demonstrated that MEBot was effective, and efficient to use in indoor, outdoor and advanced environments. Participants demonstrated similar driving performance with MEBot and their own EPWs in indoor and outdoor environments, and significantly better performance in advanced environments where curb and cross slopes were present. Participants also reported that MEBot applications such as curb climbing, curb descending, and the seat leveling application in uneven terrains were extremely useful; participants felt stable when driving up and down slopes as well as during climbing and descending curbs. However, participants were neutral when asked if the interface had all the function and capabilities they needed, indicating that the ACG Interface needed further improvement to make its functionalities more user-friendly. Few key limitations of the current control design such as the vibration and 'bounciness' of the wheelchair were highlighted by the participants. User's feedback was taken in account for further improvement of the MEBot's hardware and control algorithm design. In addition, participants addressed that the number of steps to perform the curb climbing and descending sequence were extensive.

MEBot was a research prototype with room for improvements. Chapter Five addressed alternative mobility strategies of participants when driving through the driving course. The

combination of steps and repetitive movement of the wheels when climbing and descending curb provided information for automation of the sequences. The use of rear cameras and sensors that could scan the environment may be useful as well for obstacle detection and terrain recognition [77] in order to provide available mobility features to the user ahead of time. When driving through cross slopes, participants did not perform the seat leveling application. If the application was performed, a side effect was observed where the wheelchair tilted to the angle of the cross slope after its completion due to a delay in the control algorithm. The design improvement of control algorithms must take in account the user weight plus the wheelchair and the location of its center of mass when performing the mobility applications.

Technology has improved since the beginning of this work. Alternative actuators to provide smoother up/down movement of the wheels and lifting capabilities should be considered as well. The current air actuators required 24V input, lift capabilities of ~1500N, and a travel stroke of 7.6 cm. Compact hydraulic actuators provide a miniature compressor which facilitates the attachment into the current MEBot iterations. The improvements of the wheel actuators can improve the lifting capabilities of the new iteration of the MEBot wheelchair as well as its control algorithms for real-time response when traversing uneven terrains and climbing and descending curbs.

As future work, the seat leveling algorithm will be optimized using a dynamic model which takes in account the location of the center of mass and the inertia force to maintain the wheelchair stable while driving through the environments. Safety failures will add an extra layer of safety by monitoring the seat angle for sudden movement of the user and actuators to prevent tipping while performing MEBot applications. In addition, MEBot should be evaluated in other advanced tasks, besides curbs and slopes, that EPW user tend to encounter such as stepper slopes and logs of different heights that simulate uneven terrains as presented during Cybathlon, the first competition

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where people with physical disabilities compete against each other at tasks of daily life, with the aid of advanced assistive devices including robotic technologies [60].

The design criteria of Aim 1 were evaluated through the usability evaluation of MEBot. In regards of Aim 2, the design specifications were achieved in simulation; however, the completion time of the tasks when performing in the controlled environments was longer in compare to the simulation. The simulation did not take in consideration mechanical issues such as partial camber, air compression in the pneumatics and drive wheels, user's involuntary movements and also the ground friction or contact between the wheel and ground.

Due to the prototype stage of MEBot, the demonstration and training of its features were performed by an experienced researcher in the use of the wheelchair. The future goal of MEBot is the optimization of its applications to reduce the training time as well as the commercialization of MEBot to provide training to other stakeholders such as clinicians, wheelchair providers, and especially end-users. In addition, the Appendix A checklist would be modified to aid clinicians assess participant's use of MEBot along with the power mobility capacity driving assessment (PMCDA) tool for everyday indoor and outdoor tasks.

APPENDIX A

MEBOT TRAINING SCRIPT

Driving training:

- Toggle switch on the left to change driving profiles. Each profile progressively increases speed.

- Knob on the right, changes your max speed

- Caution: Whenever approach a curb, toggle to slowest profile and speed

Individual Pneumatic Function (Sliders):

- Sliders control the up/down movement of each wheel individually

- Sliders are mirrored

- Yellow controls the left wheels and red controls the right wheels

- Show the symbols of each wheel

- Ask user to move the different wheels

Emergency Switch:

- If the last switch is pressed, all the wheels will come down. *try it

Wheelchair Elevation Function:

- If first switch is pressed, the six wheels are controlled together.

- Use the slider (on the side) to go up and down.

- You have two options to lower the chair, except the first switch controls the elevation

Pair pneumatics Function:

- Second switch pairs the wheels.

- When second switch is pressed, Yellow sliders control the up/down movement of the paired wheels

- Caution: be very slow when controlling the wheels, rear casters can tip you forward if controlled without caution

- Tip: You can use it when driving ramps.

- Move middle wheels, bring them down, do front, bring them back, and do rear slowly to know how far the wheelchair can push forward

Middle Wheels Position:

- Third switch moves the middle wheels back and forth.

- Green slider controls the back and forth movement of the middle wheels.

- Slider in the center stops the middle wheels. Slider forward, moves the middle wheels forward. Slider back, moves the middle wheels backward. Move slider back to center to stop wheels.

- Caution/tip: After finishing an obstacle, always bring the middle wheels to front wheel position. Position changes the center of gravity.

Training for curb climbing: Ask participant to perform each step

- Elevate the chair

- Drive chair until middle wheels touches the curb. Drive back up enough to elevate middle wheels

- Put front caster down in the curb

- Move middle wheels backwards – frame forward

- Move middle wheels up

- Move middle wheels forward until they are over the curb

- Move front casters up so middle wheels are touching the ground

- Move middle wheels back

- Move rear casters up

- Drive forward

☐ Press home switch

Training for curb descending: Ask participant to perform each step

☐ Drive to edge of the curb

☐ Put front caster down to the ground

☐ Move middle wheels backwards – frame forward

☐ Drive until middle wheels go off the curb

☐ Move middle wheels forward

☐ Move middle wheels down until touching the ground

☐ Move middle wheels backwards

☐ Drive until rear casters go off the curb

☐ Press home switch

APPENDIX B

DEMOGRAPHICS QUESTIONNAIRE

PART A - Personal Demographics

Gender: ☐ Male
        ☐ Female

Age: _____

Ethnic Origin: ☐ Black or African-American   ☐ American Indian
               ☐ Hispanic or Latino   ☐ White or Caucasian
               ☐ Asian   ☐ Native Hawaiian
               ☐ Two or more races   ☐ Other:_____
                                                    ____

What is your impairment/disability?_____

Date of onset or injury: _____/_____/_____

What is the highest degree you received?

☐   High School Diploma or GED
☐   Associate Degree
☐   Vocational/Technical School
☐   Bachelors Degree
☐   Masters Degree
☐   Doctorate, Law, Etc.

Which statement best describes your CURRENT work status?

☐   Working full-time, outside the home
☐   Working part-time, outside the home
☐   Working full-time, inside the home
☐   Working part-time, inside the home
☐   Retired because of disability
☐   Retired, but not because of disability
☐   Housekeeper, homemaker
☐   Disabled: unable to work because of disability
☐   Unemployed
☐   Other: please specify: _____

Please indicate which best describes your marital status:

☐   Single
☐   Married
☐   Living with someone as if married

Part B: Current Wheelchair Information

1. Model	
2. Manufacturer	
3. Date received	
4. Other Characteristics	
5. Control Method (i.e. joystick, head array, etc.)	
6. Additional Equipment (i.e. seat elevator, elevating leg rests, tilt-in-space)	
7. Front-wheel, mid-wheel, or rear-wheel drive?	

How long have you been using a power wheelchair? _____ years

How long have you been using your current power wheelchair? _____ years

In a typical day, how many hours are you in your wheelchair? _____ hours

How many days of the week are you driving your wheelchair outside your house?
_____ days per week

Part C: Power Wheelchair Training and Accidents

How much training did you receive when you obtain your current power wheelchair?

☐   Less than 30 minutes   ☐   Between 30 and 60 minutes

☐   More than one hour   ☐   Do not remember

☐   No training

Did you practice driving outside at all during your training?

☐   Yes   ☐   No   ☐   N/A

Did you have to take any kind of driving test to see if you could safely drive a power wheelchair?

☐   Yes   ☐   No   ☐   N/A

APPENDIX C

MODIFIED PMCDA DRIVING EVALUATION

The Power Mobility Clinical Driving Assessment Tool (PMCDA)

		AE (1-3)	Safety (1-3)	Comments
	Indoor			
1	Drives forward (15ft) (in a straight line) in 36" hallway			
2	Turn 180° in place to the left			
3	Drives backward 10ft in a straight line in 36" hallway			
4	Turn 90° while moving backward			
5	Turn 90° and enters a doorway			
6	Ascend 3° incline			
7	Descend 3° incline			
8	Turn 90° while moving forward			
9	Drives forward 30ft in 30s			
10	Negotiates over 1 in door/mock threshold (piece of wood)			
11	Drive in carpet			
12	Passes through 36" doorway			
13	Approaches an accessible sink			
	Indoor/Outdoor			
14	Avoids therapy balls approaching from left and right			
15	Can safely maneuver in-between 2 chairs 32 in apart			
16	Stops on command (emergency stop)			
17	Approaches a transfer surface (bed or chair)			
18	Ascend 6° incline			
19	Descend 6° incline			
20	Drive 3° cross slope			
21	Ascend 10° incline			
22	Descend 10° incline			
23	Drive through speed bump			
24	Drive over a slippery surface	NA	NA	
25	Drive over an unpaved surface (2" bumps)			
	Outdoor			
26	Ascend 2" curb			
27	Descend 2" curb			
28	Drive 10° cross slope (rough slope)			
29	Drives in soft surface (sand)	NA	NA	
29	Ascend 4" curb			
30	Descend 4" curb			
31	Rolls 10ft across 6° side-slope			
32	Ascend 6" curb			
33	Descend 6" curb			
34	Drive in pea gravel surface	NA	NA	
35	Drive 10° cross slope			
	TOTAL			

Scoring System for the Adequacy and Efficiency (AE) assessment

Score of 1: if the driver requires physical assistance or cannot complete the task, a score of 1 is given.
Score of 2: if the driver requires verbal or auditory hints or cues but no physical assistance, a score of 2 is given. Score of 3: if the driver completes the task without help, then a score of 3 is given.

Scoring System for the Safety assessment

Score of 1: Unsafe

Score of 2: Moderately safe

Score of 3: Safe

Instructions

- You may provide visual or auditory clues along with verbal instructions to complete tasks.
- Tasks can be completed in any order.
- Control interface settings should be adjusted for safety and at discretion of the trainer and driver

APPENDIX D

DRIVING TRIAL USER EVALUATION SCORING SHEET

Driving Trial User Evaluation:

	Not satisfied at all	Not very satisfied	More or less satisfied	Satisfied	Very satisfied
WC:					
Trial 1					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 2					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 3					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
WC:					
Trial 4					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 5					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 6					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5

Comfort: Seating, Quality of ride

Safety: Feeling in control of chair; Feeling of stability during operation

Operation: Ease/difficulty of use

	Not satisfied at all	Not very satisfied	More or less satisfied	Satisfied	Very satisfied
WC:					
Trial 7					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 8					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 9					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
WC:					
Trial 10					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 11					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 12					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5

Comfort: Seating, Quality of ride

Safety: Feeling in control of chair; Feeling of stability during operation

Operation: Ease/difficulty of use

	Not satisfied at all	Not very satisfied	More or less satisfied	Satisfied	Very satisfied
WC:					
Trial 13					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 14					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 15					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
WC:					
Trial 16					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 17					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5
Trial 18					
Comfort	1	2	3	4	5
Safety	1	2	3	4	5
Operation	1	2	3	4	5

Comfort: Seating, Quality of ride

Safety: Feeling in control of chair; Feeling of stability during operation

Operation: Ease/difficulty of use

APPENDIX E

USABILITY QUESTIONNAIRE

MOBILITY ENHANCEMENT ROBOTIC WHEELCHAIR (MEBOT)

Attitude Interface:

Each item below describes how you perceived and interacted with the attitude interface when driving the MEBot wheelchair. Please put an X in the appropriate box to show how easy you feel it is to use the interface

Software Visualization	Very Easy	Easy	Neutral	Difficult	Very Difficult
Understanding the view of the up/down and back/forth movement of the wheels on the screen is:					
Understanding how the wheel position changes the height and inclination of the seat is:					
Hardware Visualization	Very Easy	Easy	Neutral	Difficult	Very Difficult
Able to select and understand the switch functions is:					
Understanding the view of the up/down and back/forth movement of the wheels with the interface sliders is:					

Which features do you like about the attitude interface (check all that apply)?
☐ Graphical Display of the position of the wheels
☐ Use of sliders to control the wheels height
☐ Visual feedback of wheels height with automated sliders
☐ Safety button (move wheelchair to lowest ground clearance)
☐ Other, please specify_____

What are your thoughts related to potential problem(s) and concerns about using the attitude interface?
_____
_____
_____

What are your recommendation to improve the use of the attitude interface?
_____
_____
_____
_____

On a scale of 1-5, 1 being totally disagree and 5 being totally agree, please circle the number to rate your answer for each question:

Question	Totally Disagree		Neutral		Totally Agree
It is easy to learn how to use the interface	1	2	3	4	5
It is easy to use the interface	1	2	3	4	5
The interface of this interface is aesthetically pleasant	1	2	3	4	5
The visual representation of the wheels position on the screen is clear	1	2	3	4	5
The visual representation of the position of the wheels is useful	1	2	3	4	5
It is easy to locate the functions I need on the interface	1	2	3	4	5
I can easily and quickly correct any mistakes using the interface	1	2	3	4	5
The warning messages on the interfaces are helpful and effective to stop any unsafe action	1	2	3	4	5
This interface has all the functions and capabilities I need	1	2	3	4	5
Overall, I am satisfied with the attitude interface	1	2	3	4	5
The interface is appropriate to operate the MEBot wheelchair	1	2	3	4	5

Driving Performance:

This section asks your perception of the mobility applications of the MEBot wheelchair.

On a scale of 1-5, 1 being totally disagree and 5 being totally agree, please circle the number to rate your answer for each question

Question	Totally Disagree		Neutral		Totally Agree
Using the MEBot wheelchair would enhance my quality of life	1	2	3	4	5
I would be anxious about using the MEBot wheelchair	1	2	3	4	5
I would choose to use the MEBot wheelchair air power seating functions over the common electric powered seating functions	1	2	3	4	5
The amount of "bounciness" when adjusting the wheels is acceptable	1	2	3	4	5
The vibration of the wheels when driving is acceptable	1	2	3	4	5
The noise level generated when adjusting the wheels height is acceptable.	1	2	3	4	5
The MEBot wheelchair feels stable….					
… when driving at its maximum seat height	1	2	3	4	5
… when climbing a curb	1	2	3	4	5
…when descending a curb	1	2	3	4	5
…when crossing a slope	1	2	3	4	5
…when driving up a slope	1	2	3	4	5
…when driving down a slope	1	2	3	4	5

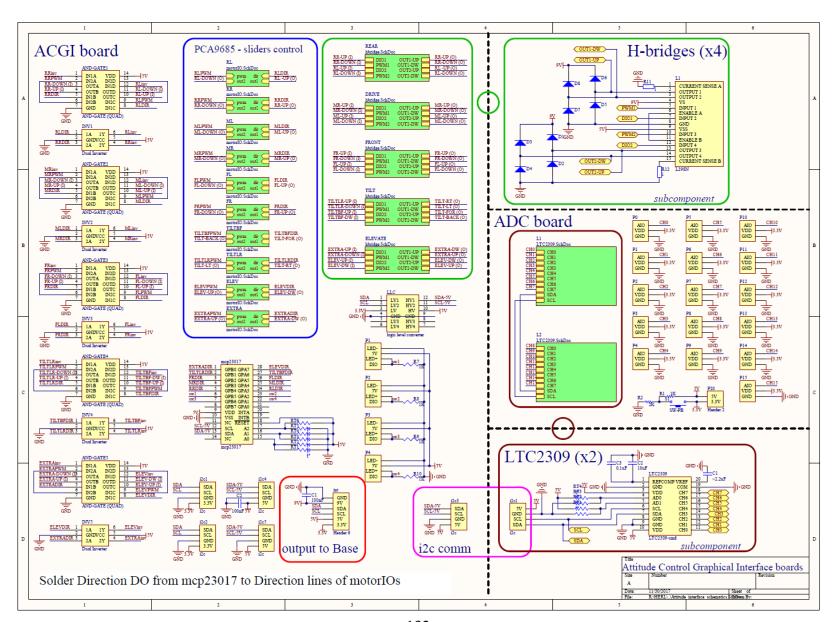Which features do you like about the MEBot wheelchair (check all that apply)?
☐ Seat leveling in uneven terrains (i.e. slopes, cross slopes)
☐ Curb Climbing/Descending
☐ Change of Drive wheels configuration (i.e. front-, rear-, mid- wheel drive)
☐ Air Powered Seating Functions (Seat Elevation, Lateral/Back/Forward Seat Tilt)
☐ Safety button (move wheelchair to lowest ground clearance)
☐ Other, please specify_____
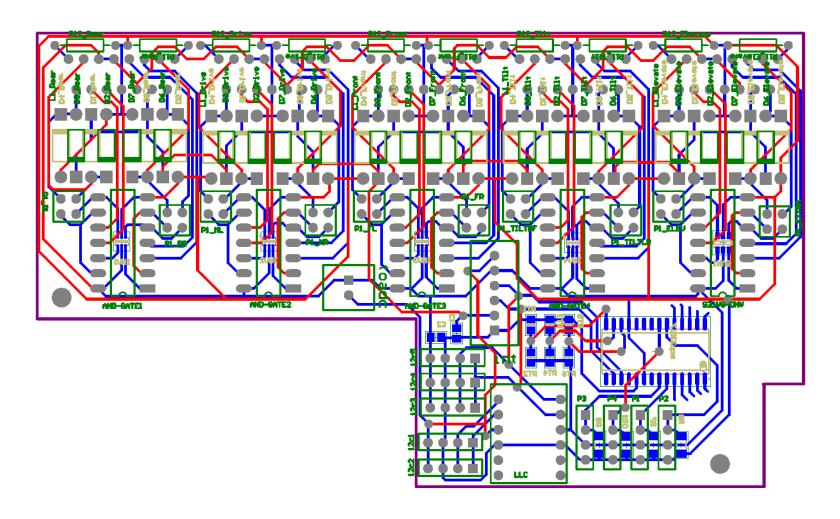
Please put a check in the box describing the likelihood you would use each of the MEBot applications in the table below.

Question: How do you rate the usefulness of the MEBot applications	Not useful	Slightly useful	Moderate Useful	Very useful	Extremely useful
Seat leveling under uneven terrains (slopes, cross slopes)					
Curb Climbing					
Curb Descending					
Selectable driving wheel position					
Air Powered Seating Functions					

What would be the potential problem(s) and/or concerns to use the MEBot wheelchair?

_____
_____
_____
_____
_____
_____

What are your recommendation to improve the applications of the MEBot wheelchair?

_____
_____
_____
_____
_____
_____

Would you recommend a "MEBot" to a friend and/or family member?

_____
_____
_____
_____
_____

APPENDIX F

ELECTRONICS SCHEMATICS OF MEBOT2.0 AND MEBOT2.5

Attitude Control Graphical Interface boards

Solder Direction DO from mcp23017 to Direction lines of motorIOs
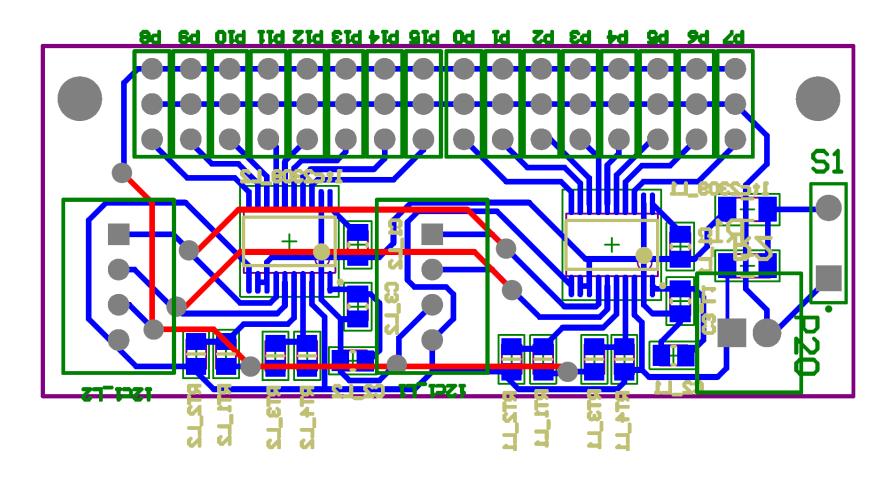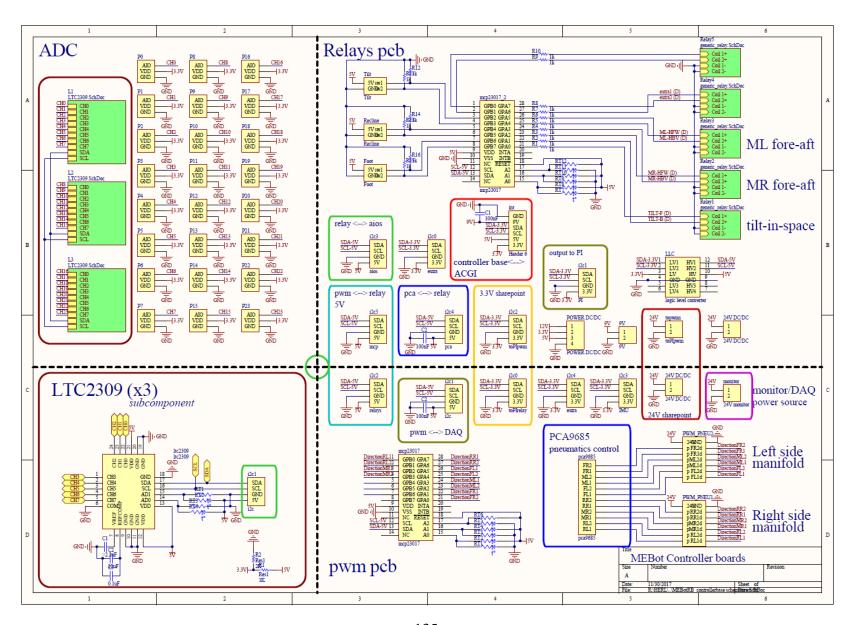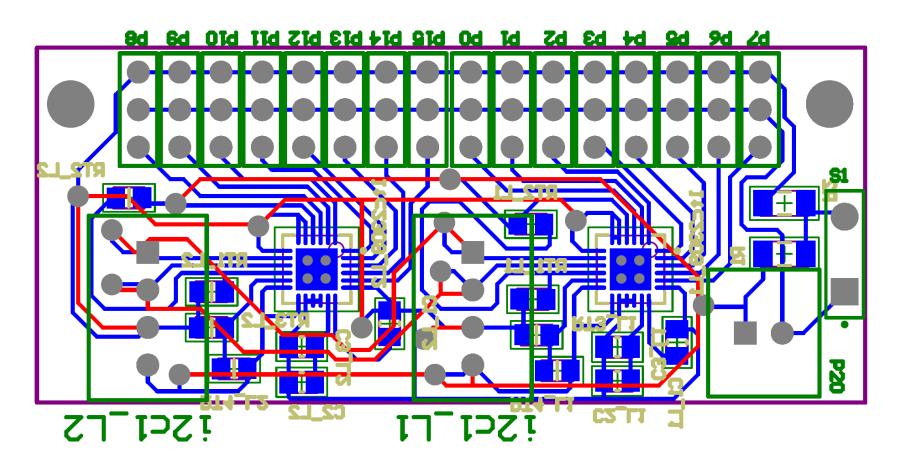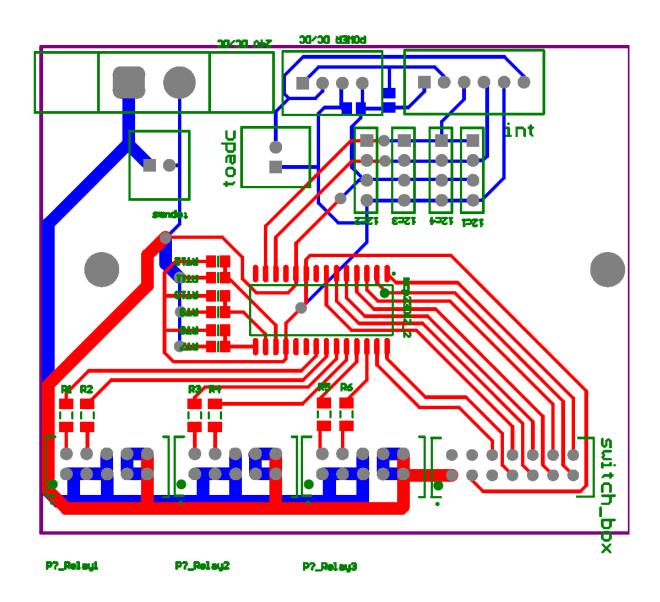
ACGI PRINTED CIRCUIT BOARD

ADC PRINTED CIRCUIT BOARD

ADC

LTC2309 (x3)
subcomponent

Relays pcb

relay <--> aios

controller base <--> ACGI

output to PI

pwm <--> relay 5V

pca <--> relay

3.3V sharepoint

pwm <--> DAQ

PCA9685
pneumatics control

ML fore-aft

MR fore-aft

tilt-in-space

monitor/DAQ power source

Left side manifold

Right side manifold

pwm pcb

logic level converter

POWER DC/DC

24V DC/DC

24V sharepoint

Title
MEBot Controller boards
Size Number Revision
A
Date: 11/30/2017 Sheet of
File: R:\HERL\...\MEBotRB controllerbase schematics.SchDoc

ADC PRINTED CIRCUIT BOARD

RELAYS PRINTED CIRCUIT BOARD
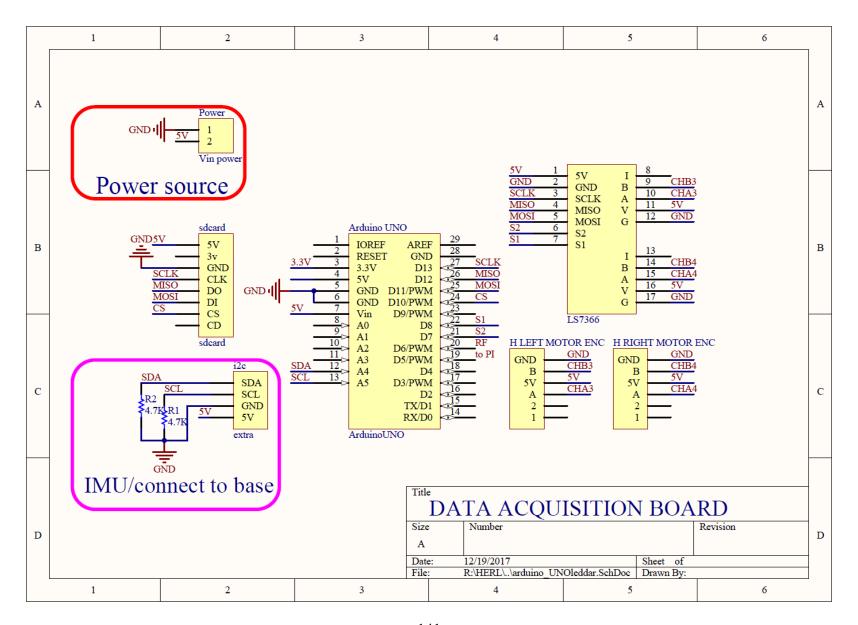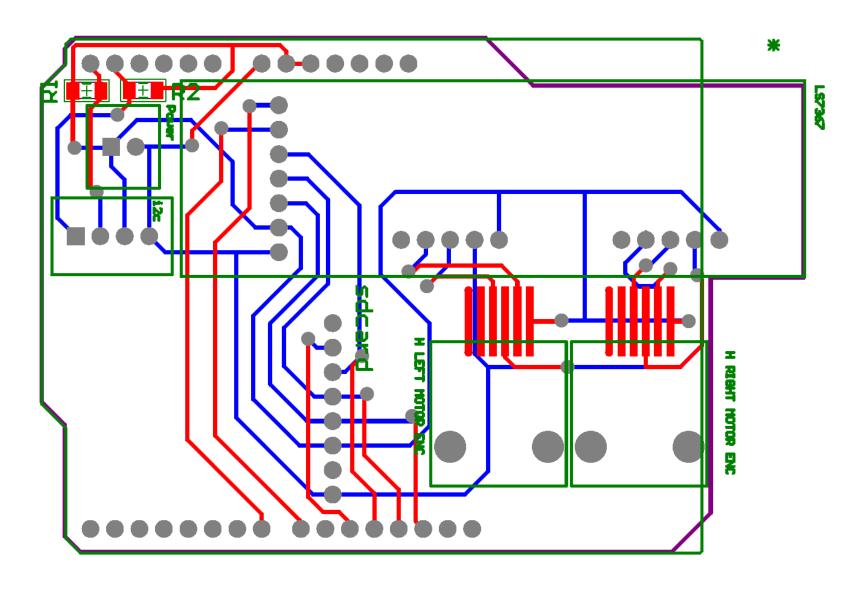
PWM PRINTED CIRCUIT BOARD

Generic Relay Board (White)

139
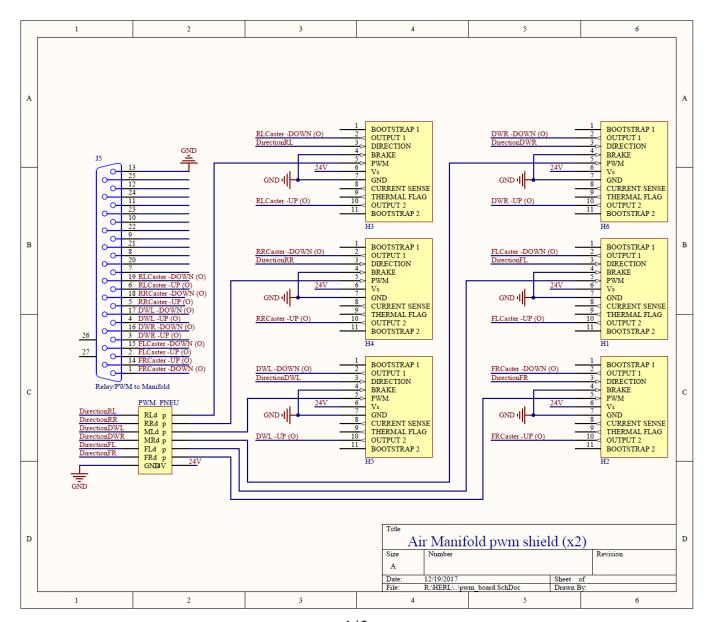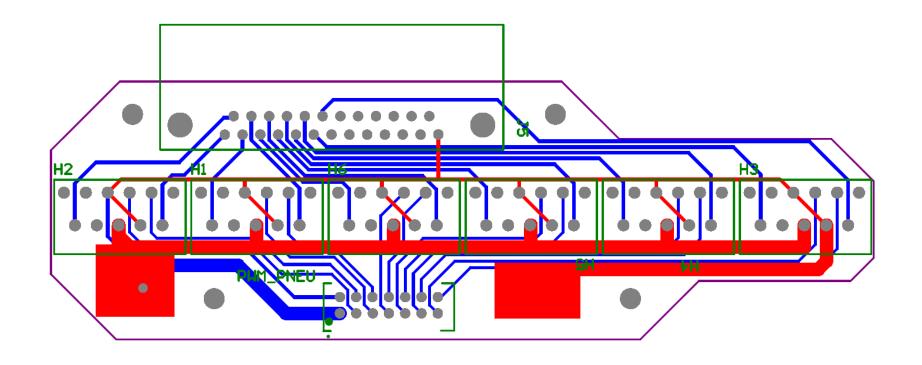
GENERIC RELAY BOARD (WHITE) PRINTED CIRCUIT BOARD

DATA ACQUISITION BOARD

Title		
	DATA ACQUISITION BOARD	
Size	Number	Revision
A		
Date:	12/19/2017	Sheet of
File:	R:\HERL\..\arduino_UNOleddar.SchDoc	Drawn By:

141
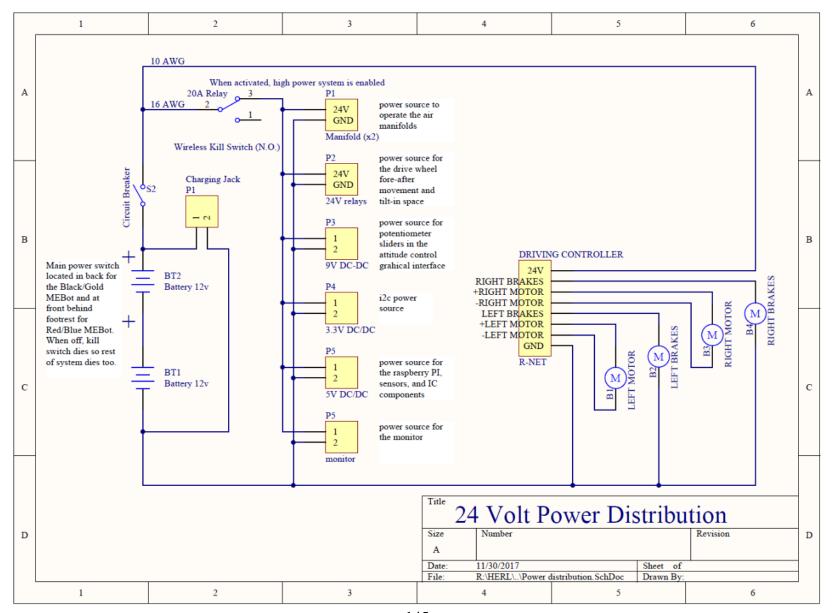
DATA ADQUISITION PRINTED CIRCUIT BOARD

142

Air Manifold pwm shield (x2)

143
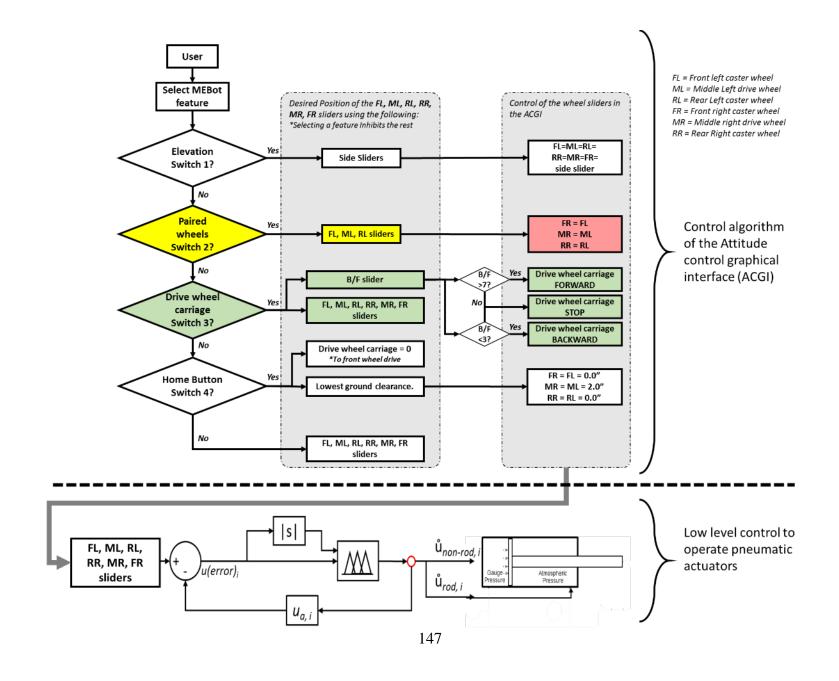
AIR MANIFOLD PWM SHIELD (X2) PRINTED CIRCUIT BOARD

24 Volt Power Distribution

APPENDIX G

CONTROL ALGORITHM OF THE SECOND ITERATION OF THE MEBOT CONTROLLER USING THE ATTITUDE

CONTROL GRAPHICAL INTERFACE (ACGI)

User

Select MEBot feature

Desired Position of the FL, ML, RL, RR, MR, FR sliders using the following:
Selecting a feature Inhibits the rest

Control of the wheel sliders in the ACGI

Elevation Switch 1? — Yes → Side Sliders → FL=ML=RL= RR=MR=FR= side slider

No

Paired wheels Switch 2? — Yes → FL, ML, RL sliders → FR = FL MR = ML RR = RL

No

Drive wheel carriage Switch 3? — Yes → B/F slider → B/F >7? — Yes → Drive wheel carriage FORWARD

No → Drive wheel carriage STOP

FL, ML, RL, RR, MR, FR sliders → B/F <3? — Yes → Drive wheel carriage BACKWARD

No

Home Button Switch 4? — Yes → Drive wheel carriage = 0 *To front wheel drive*

Lowest ground clearance. → FR = FL = 0.0" MR = ML = 2.0" RR = RL = 0.0"

No → FL, ML, RL, RR, MR, FR sliders

FL = Front left caster wheel
ML = Middle Left drive wheel
RL = Rear Left caster wheel
FR = Front right caster wheel
MR = Middle right drive wheel
RR = Rear Right caster wheel

Control algorithm of the Attitude control graphical interface (ACGI)

Low level control to operate pneumatic actuators

FL, ML, RL, RR, MR, FR sliders → + − $u(error)_i$ → $|s|$ → △ → $\mathring{u}_{non\text{-}rod, i}$

$\mathring{u}_{rod, i}$

Gauge Pressure / Atmospheric Pressure

$u_{a, i}$

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