Design and Evaluation of a Seat Orientation Controller during Uneven Terrain Driving

Jorge Candiotti¹; Hongwu Wang¹; Cheng-Shiu Chung¹; Deepan C Kamaraj¹; Garrett G Grindle¹;
Motoki Shino²; Rory A Cooper¹

¹*Department of Rehabilitation Sciences and Technology, School of Health and Rehabilitation
Sciences, University of Pittsburgh*

²*Department of Mechanical Engineering, University of Tokyo, Japan*

Corresponding Author:

Rory A. Cooper, PhD

Telephone number: 412-822-3700

Fax: 412-822-3699

Email: rcooper@pitt.edu

Abstract:

Electric Powered wheelchairs (EPWs) are essential devices for people with disabilities as aids for mobility and quality of life improvement. However, the design of currently available common EPWs is still limited and makes it challenging for the users to drive in both indoor and outdoor environments such as uneven surfaces, steep hills, or cross slopes; making EPWs susceptible to loss of stability and at risk for falls. An alternative wheel-legged robotic wheelchair, “MEBot”, was designed to improve the safety and mobility of EPW users in both indoor and outdoor environments. MEBot is able to elevate its six wheels using pneumatic actuators, as well to detect changes in the seat angle using a gyroscope and accelerometer. This capability enables MEBot to provide sensing for a dynamic self-leveling seat

1 application that can maintain the center of mass within the boundaries of the wheelchair, thereby,
2 improving EPW safety. To verify the effectiveness of the application, MEBot was tested on a motion
3 platform with six degrees of freedom to simulate different slopes that could be experienced by the EPW
4 in outdoor environments. The results demonstrate the robustness of the application to maintain the
5 wheelchair seat in a horizontal reference against changes in the ground angle.

6 **Keywords:** posture, wheelchair control, wheeled-legged robots, assistive technology

7 **Abbreviations:**

8 CAREN: Computer Assisted Rehabilitation ENvironment

9 CoP: Center of Pressure

10 EPW: Electric Powered Wheelchair

11 MEBot: Mobility Enhancement RoBotic Wheelchair

12 IMU: Inertial Measurement Unit

13 P-D: Proportional - Derivative Controller

14 PWM: Pulse Width Modulation

15

Introduction:

An electric powered wheelchair (EPW) is a key mobility device for people with disabilities, providing independence, mobility, and a higher quality of life [1]. Currently, over 400,000 Americans benefit from using an EPW [2], and this number continues to increase over the years [3]. However, there have been limited improvements in EPW design to meet the increasing needs of users for both indoor and outdoor mobility over the past 20 years [4]. Few notable improvements have been the inclusion of passive suspension [5] to decrease vibration, power seat functions, and expanded intuitive user interfaces [4]. Despite these improvements, current designs limit most users to drive in indoor environments with firm and reasonably flat surfaces. Further, may have difficulties, and thus must avoid, driving their EPW over uneven terrain (non-compliant terrains with ADA standards in cross slopes (2° max) and ramps(5° max) [6]). Driving in these uneven environments have been shown to cause shift in the center of mass that leads to lack of stability control of the EPW [4], thereby increasing the risk of tips and falls [7-9]. These significant challenges have increased the need to design an EPW that is not only suitable for indoor environments, but will allow the user to be safe and highly functional in structured and unstructured outdoor environments (e.g., parks, trails, lawns).

Recent work in assistive mobility devices using wheeled-legged robots has led to the research and development of EPWs that can maintain seat orientation when traversing over uneven terrains. An advanced prototype EPW design was the iBot [10] which incorporated indoor and outdoor mobility applications, including two wheel self-balancing in the fore-aft directions. The PMR wheelchair, a two wheeled-legged EPW uses a balance platform and a linkage system within the wheelchair to self-balance in the face of small ground angle changes [11]. The RT-Mover robot [12] is another EPW that uses two arm actuators to control the elevation of the rear/front caster wheels. The large dimension of the RT-Mover allows the robot to overcome obstacles as well as to pivot the wheel linkage to preserve seat orientation up to 30 degrees. These recent improvements in mobility applications among robotic wheelchairs have provided possible solutions for better maneuverability in uneven terrains. However,

these EPWs have limited capability in accommodating the physical impairments and mobility goals of EPW users for everyday use, such as powered seating functions and alternative controls.

The Mobility Enhancement RoBot (MEBot), was designed to address the limitations in wheelchair design and provide better maneuverability in outdoor terrains. MEBot is a novel EPW that utilizes a dual system of electric and pneumatic actuators to maintain the seat orientation, aimed to reduce the risk of tips and falls. A simulation based testing of the seat orientation controller showed MEBot maintained its orientation when driving up-down hills (pitch angle) or cross-slopes (roll angle) independently without a payload [13]. In this paper we describe the implementation and experimental assessment of the controller that addresses simple as well as compound angles and compensate for user's center of mass. A general account of the components and kinematics of the MEBot wheelchair is provided in Section A, followed by the description of the orientation stabilization divided into lower and higher level control in Section B. Section C presents the test methods and Section D presents the results of the controller at different ground angles.

Methods:

A. Description of the MEBot wheelchair

MEBot is a novel robotic EPW comprised of a six-wheel design and an EPW seating system with powered seat functions. The characteristics of MEBot are shown in Table I. The front and rear wheel casters are controlled via four independent pneumatic actuators, mounted to the main frame using a four-bar linkage to follow vertical movement. Hub-motor powered wheels are mounted to the frame via a vertical-horizontal sliding platform, which allows the drive wheels to be moved fore/aft the frame and up/down independently with air spring actuators [13]. Pneumatic actuators are supplied by an air source through an air manifold. The electronic design of the MEBot wheelchair includes an EBX-COBRA embedded computer (Versalogic Co, USA); two 50A20DD motor drivers (Advanced Motion Controls, USA); a PC/104 PWM board to control the speed and direction of the pneumatic actuators; and position

sensors in each pneumatic actuator, including a gyroscope and accelerometer combined to detect the pitch, roll, and yaw angle change in the seat (Figure 1).

Table I: Characteristics of MEBot

Fig. 1: Electronics diagram of the MEBot wheelchair

B. Seat orientation controller design:

The active seat orientation control is divided into two components. The higher level control uses an Inertial Measurement Unit (IMU) to determine the pitch/roll angles of the MEBot's seat. These data are used with an internal mathematical model to determine the desired instantaneous position of each pneumatic actuator to maintain 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 then updates based upon the IMU data. Both levels of the seat orientation controller are sampled every 1.0 milliseconds.

B.1. Higher Level Control:

The IMU detects the angle change in the seat while position sensors detect the actual position of each pneumatic actuator. This section describes the use of the IMU sensor to obtain the desired position of the frame height to compare it with the actual position of the frame height calculated by the position sensors.

B.1.1. Frame height calculation using IMU (desired position):

The IMU sensor ONI-23503 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 are filtered through a complementary filter (Figure 2a). 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 in the high pass filter for the gyroscope [14]. The sampling frequency for the model is 1000Hz, therefore the filter coefficient is set at 0.91 to filter data slower than 1ms of sample time; this allows the gyroscope to take over and filter out the noise from the accelerometer. For time periods faster than 1ms, the accelerometer takes over the drift of the gyroscope. The complementary filter provides the pitch and roll angles with a sensitivity of $\pm 0.25^\circ$. The minimum sensitivity of $\pm 0.25^\circ$ was obtained due to the limitations of the complementary filter to obtain a higher angle resolution. Also, the sensitivity was sufficient to perform the seat orientation because the angle threshold to activate the controller was $\pm 0.5^\circ$.

Fig. 2: Seat Orientation Controller Diagram: (a) Higher Level Control (b) Low Level P-D Control

Given the angle change in pitch and roll, the desired position of each pneumatic actuator i can be calculated to obtain the desired frame height. Figure 2a 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 $Rot(x, \theta)$, $Rot(y, \phi)$, $Trans(x_o)$, and $Trans(z_o)$ 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 .

Figure 3 shows the desired position of each pneumatic actuator (A_I , B_I , C_I , D_I). 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_o , B_o , C_o , D_o), and the rotational/translational transformation matrix $IMUangle$ (eq. 2) with respect to the pitch, roll, driving wheel position (x_o), and height of the top frame (z_o). This operation

allows the seat orientation controller to extend/compress the pneumatic actuators to reach the highest pitch and roll seat angles. The matrix Translate Z-axis, $\text{Trans}(z_0)$, shift the position reference to the mid-point from the lowest and highest ground clearance of the frame; matrix Translate X-axis, $\text{Trans}(x_0)$, is used to perform the self-leveling seat orientation at different wheel drive modes (rear-, mid-, or front-wheel drive). $\text{Trans}(x_0)$ measures the position of the driving wheel along the frame.

Fig. 3: Calculation of desired position for each corner (A_1, B_1, C_1, D_1) of the frame using the pitch (θ) and roll (ϕ) angle measured by the IMU

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

$$\mathbf{IMUangle} = \mathbf{Rot}(x, \theta) * \mathbf{Rot}(y, \Phi) * \mathbf{Trans}(x_0) * \mathbf{Trans}(z_0) \quad (2)$$

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

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.

$$\mathbf{newMEBot} = [\mathbf{A}_1 \quad \mathbf{B}_1 \quad \mathbf{C}_1 \quad \mathbf{D}_1] \quad (3)$$

B.1.2. 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 4, and compared with the desired position of the frame height obtain in Section B.1.1.

Fig. 4: 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:

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

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

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

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:

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

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 $u_{a,i}$ is used to obtain the actual pitch θ_a and roll angles ϕ_a and feedback into the higher level controller (Figure 2a). 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.

B.2 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 2b.

$u_{d,i}$ is the desired position for each pneumatic actuator ($i = 1..4$), $u_{a,i}$ is the actual position of the pneumatic actuator i , $\dot{u}_{d,i}$ 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 desired speed $\dot{u}_{d,i}$ of the pneumatic i is converted into a PWM signal which is fed into the air manifold that regulates the air volume going into each pneumatic actuator. $\dot{u}_{d,i}$ is set to a minimum and maximum speed threshold per pneumatic actuator i due to the non-linearity of the system. A linear response is obtained over a duty cycle of 35%; however, no response was shown at duty cycles lower than the minimum speed threshold.

C. Experimental Set-up:

Prior to testing the seat orientation controller, two low level controllers were compared to control the pneumatics for the casters and driving wheels: proportional control (P) and proportional-derivate control (P-D) in order to demonstrate the improvement in the controller with the addition of P and D gains. Following the comparative low-level controller's evaluation, MEBot was tested in both static and dynamic experimental set-ups to compare its behavior with and without the activation of the seat orientation controller. These tests were performed (Figure 5) within the Computer Assisted Rehabilitation ENvironment (CAREN, MOTEFORCELINK Medical, Amsterdam) [15], The CAREN is a simulation

environment that incorporates a 6 degree-of-freedom (pitch (y'), yaw (z'), roll (x'), surge (x), sway (y), and heave (z) axes) Stewart platform [16, 17], 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.

Fig. 5: Experiment Setup: MEBot on the CAREN system

The purpose of the static test was to quantify the system response, reliability, and practicability of the controller to maintain the seat orientation over nominal slopes as described by the ADA standards for accessible design in ramps and cross-slopes [18]. 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 $1^\circ/\text{s}$ 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 and without the seat orientation controller 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 $1.85^\circ/\text{s}$ 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 transitioning from horizontal ground to a 3 degrees slope. The equation shown below:

$$\text{Linear speed} = (\text{wheelbase length})/(\text{maximum angle/angular speed}) \quad (7)$$

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 controller. 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.

Results:

D.1 Low-Level PD control evaluation:

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 are 154.0ms and 283.0ms for a 10% steady-state error, respectively (Figure 6). The settling time difference between actuators is due to a combination of the hardware components, i.e., 1) the delay time in each valve is 20ms and 2) the drive wheels are attached to a one-way air spring actuator to extend it and requires 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. In order to provide an energy-efficient system, the seat orientation controller is activated only if the actual pitch/roll angles passes an angle change threshold of $\pm 0.5^\circ$. This way, the system does not consume air and battery power within the angle change threshold. The final constant K_D and K_P gains were applied in the self-leveling seat orientation controller.

Fig. 6: P (dash-dot line) and P-D (dotted line) controller comparison with a unit step response (solid line) for (a) Rear casters and (b) Driving wheels

D.2 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 are shown in Table II. The results demonstrate when the seat orientation controller is not activated, the seat angle tilts along with the angle of the platform. However, when the controller is activated the seat stays horizontal by maintaining its pitch and roll angles within an angle range of $\pm 0.5^\circ$ as designated by the limits designed within the controller. The experiment shows that MEBot is able to maintain the seat horizontally at roll angle between $+5.5^\circ$ & -4.3° (figure 7) and pitch angle between $+5.5^\circ$ & -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 7 shows the results of the static test in the pitch forward direction at 2° , 4° , 6° , 8° , and 10° , which simulates MEBot driving up slopes. As the CAREN platform moves in the pitch direction, the change in the seat roll angle is negligible; while the seat pitch angle changes within the $\pm 0.5^\circ$ as designed in the controller except when the CAREN platform goes back to horizontal (0°) and at angles higher than 6 degrees. The peak in the seat pitch angle (figure 8) is due to the limited speed of the controller to self-level the seat in comparison to the CAREN platform speed and time delay to detect the change in the seat angle.

1

2 Fig. 7: Experimental Results: Static test in the roll lateral right direction. Top figure shows the transition
3 from horizontal to 8° cross-slope with seat orientation controller activated. Bottom figure shows the
4 markers tracked for the MEBot and CAREN platform by the VICON camera system in the same
5 experimental test.

6 Fig. 8: Experimental Results: Static test with control activated in the pitch forward direction. Pitch (dotted
7 line) and Roll angle (dash-dot line) of the seat are compared with the angle of the platform (solid line)

8

9 The angle error between the pitch/roll seat angle and the horizontal plane (pitch $\theta_d=0.0$, roll $\phi_d=0.0$) were
10 partially due to the sensitivity of the IMU sensor in detecting an accurate slope angle and the
11 extension/compression limitation of the pneumatics to reach higher angles. Another type of filter such
12 as the Kalman filter showed similar reading reliability as the complementary filter; however, the
13 latter was used because of its simplicity, code-efficiency and ease of implementation [14].

14 Figure 9 show the results of the dynamic test for the pitch and roll seat angle. The results show that at
15 $0.37^\circ/\text{s}$, the seat maintains a pitch and roll angle of ± 0.8 degree at all times. However, at 0.61 and 1.85
16 degree/sec the controller maintains the seat angle at 1.2 degrees and 1.7 degrees, respectively, showing
17 that as the platform speed increases, the response of the controller begins to lag. This issue can be in
18 some measure due to the delayed response in the air manifold to move each pneumatic actuator and the
19 slow response of the air spring actuators in the drive wheels. Another issue that should be taken into
20 consideration might be the sensitivity of the IMU sensor as it showed a sensitivity of ± 0.25 degrees and
21 the angle threshold of ± 0.50 degrees in the controller. Finally, the results in Table II showed better
22 results in the lateral left than right at $6, 8$, and 10° in the roll angle; same as better results in the pitch
23 forward than pitch backward at 8 and 10° . These 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 calibrates the angles of the IMU sensor by setting them as zero degrees regardless the position of the pneumatic actuators and seat angle.

Fig. 9: Dynamic test results at platform speed of $0.37^\circ/\text{s}$, $0.61^\circ/\text{s}$, and $1.85^\circ/\text{s}$. (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

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

D.3 Practical implications for wheelchair users and the wheelchair design and configuration:

Results of the CoP and tipping point estimation demonstrate that the CoP remains within the boundaries of the footprint without a controller activated in every direction except when the wheelchair is tilted over 6° in the forward direction, which is considered the tipping point of the wheelchair. Figure 10 demonstrates 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 is not activated.

Fig. 10: Location of Center of Pressure (CoP) during the static test without seat orientation controller (solid line) and with controller (dashed line).

Conclusions

This study describes an alternative solution to address key hurdles faced by EPW users when traversing uneven terrain as well as the limitations in the design of EPWs. The results demonstrate the ability of the

self-leveling application to maintain the wheelchair seat orientation during changes in the surface angle, which could improve the safety and effective mobility of the user by keeping the center of mass within the boundaries of the wheelchair and reduce the jostling of the user when traversing uneven terrain. As a prototype robotic wheelchair, MEBot shows limitations that need to be taken into consideration for future work. MEBot is limited to approximately ± 5 degrees in the roll direction and - 5 to +7 degrees 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) limits the MEBot from tilting forward further than 6 degrees (without a controller) before tipping, addressing the importance of a seat orientation dynamic control algorithm. During this experiment, the MEBot was connected to an air compressor with large source of air. In the future, 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. 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; future experiments will include driving under real-world scenarios to test the performance of the seat orientation controller. A second generation of MEBot is in development, addressing the key limitations by increasing the range of motion up to ± 15 degrees in each direction to reach over standard accessible ramp dimensions, using the same pneumatic actuators as in the rear casters in every wheel and implementing the controller for other outdoor applications such as curb climbing, obstacle negotiation, and different drive wheel configurations.

Acknowledgment

This work was funded by the VA Center for Excellence for Wheelchairs and Associates Rehabilitation Engineering (Grant #B9250-C) and National Science Foundation (Grant #EEC0540865 – Quality of Life Technology Engineering Research Center).

Conflict of Interest: None

1 Ethical Approval: None. The study did not require an IRB. The study did not involve human subjects

2

References

1. Evans, S., et al., *Young people's experiences using electric powered indoor - outdoor wheelchairs (EPIOCs): potential for enhancing users' development?* Disabil Rehabil, 2007. **29**(16): p. 1281-94.
2. US Access Board Washington, D., *Demographics of Wheeled Mobility Device Users*. 2003.
3. LaPlante, M.P. and H.S. Kaye, *Demographics and trends in wheeled mobility equipment use and accessibility in the community*. Assistive Technology®, 2010. **22**(1): p. 3-17.
4. Ding, D. and R.A. Cooper, *Electric powered wheelchairs*. Control Systems, IEEE, 2005. **25**(2): p. 22-34.
5. Finch, J.A. and T.E. Finch, *Suspension system for powered wheelchair*. 1998, Google Patents.
6. Board, U.A., *Americans with Disabilities Act accessibility guidelines for buildings and facilities*. Washington, DC: Federal Register, 2004: p. 35455-35541.
7. Chen, W.-Y., et al., *Wheelchair-related accidents: relationship with wheelchair-using behavior in active community wheelchair users*. Archives of physical medicine and rehabilitation, 2011. **92**(6): p. 892-898.
8. Gaal, R.P., et al., *Wheelchair rider injuries: causes and consequences for wheelchair design and selection*. Journal of rehabilitation research and development, 1997. **34**(1): p. 58-71.
9. Salatin, B., *Electrical powered wheelchair driving outdoors: user needs evaluation and the development of an advanced controller (Master Thesis)*. 2011.
10. Uustal, H. and J.L. Minkel, *Study of the Independence IBOT 3000 Mobility System: an innovative power mobility device, during use in community environments*. Archives of physical medicine and rehabilitation, 2004. **85**(12): p. 2002-2010.
11. Tomokuni, N. and M. Shino. *Wheeled inverted-pendulum-type personal mobility robot with collaborative control of seat slider and leg wheels*. in *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*. 2012. IEEE.
12. Nakajima, S. *Proposal for step-up gait of RT-Mover, a four-wheel-type mobile robot for rough terrain with simple leg mechanism*. in *Robotics and Biomimetics (ROBIO), 2010 IEEE International Conference on*. 2010. IEEE.
13. Wang, H., et al., *Development of an advanced mobile base for personal mobility and manipulation appliance generation II robotic wheelchair*. The journal of spinal cord medicine, 2013. **36**(4): p. 333-346.
14. Colton, S. and F. Mentor, *The balance filter*. Presentation, Massachusetts Institute of Technology, 2007.
15. Isaacson, B.M., T.M. Swanson, and P.F. Pasquina, *The use of a computer-assisted rehabilitation environment (CAREN) for enhancing wounded warrior rehabilitation regimens*. The journal of spinal cord medicine, 2013. **36**(4): p. 296-299.
16. Stewart, D., *A platform with six degrees of freedom*. Proceedings of the institution of mechanical engineers, 1965. **180**(1): p. 371-386.
17. van der Eerden, W., et al., *CAREN--Computer Assisted Rehabilitation Environment*. Studies in health technology and informatics, 1998. **62**: p. 373-378.
18. United States, D.o.J., *2010 ADA standards for accessible design*. 2010, [Washington, D.C.]: Dept. of Justice.

Figures Legend:

- Fig. 1: Electronics diagram of the MEBot wheelchair
- Fig. 2: Seat Orientation Controller Diagram: (a) Higher Level Control (b) Low Level P-D Control
- Fig. 3: Calculation of desired position for each corner (A_1 , B_1 , C_1 , D_1) of the frame using the pitch (θ) and roll (ϕ) angle measured by the IMU
- Fig. 4: Calculation of height of the Frame w.r.t rear casters and driving wheels
- Fig. 5: Experiment Setup: MEBot on the CAREN system
- Fig. 6: P (dash-dot line) and P-D (dotted line) controller comparison with a unit step response (solid line) for (a) Rear casters and (b) Driving wheels
- Fig. 7: Experimental Results: Static test in the roll lateral right direction. Top figure shows the transition from horizontal to 8° cross-slope with seat orientation controller activated. Bottom figure shows the markers tracked for the MEBot and CAREN platform by the VICON camera in the same experimental test.
- Fig. 8: 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)
- Fig. 9: Dynamic test results at platform speed of $0.37^\circ/\text{s}$, $0.61^\circ/\text{s}$, and $1.85^\circ/\text{s}$. (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
- Fig. 10: Location of Center of Pressure (CoP) during the static test without seat orientation controller (solid line) and with controller (dashed line).
- Table I: Characteristics of MEBot
- Table II: Experimental Results: Pitch and Roll results for static test in each direction

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6a

Figure 6b

Figure 7

Figure 8

Figure 9

Figure 10

Table I: Characteristics of MEBot

Parameters	Values
MEBot length	125.7 cm
Wheel-to-wheel width	66.0 cm
MEBot mass (without payload)	165.5 kg
Wheels Vertical movement	7.1 cm
Driving wheel horizontal movement	20.3 cm
Maximum velocity	7.2 km/h (2.0 m/s)
Maximum payload	113.0 kg

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

<i>Angles</i> (degrees °)	<i>Lateral Left</i>		<i>Lateral Right</i>		<i>Pitch Forward</i>		<i>Pitch Backward</i>	
	<i>Pitch</i> (°)	<i>Roll</i> (°)	<i>Pitch</i> (°)	<i>Roll</i> (°)	<i>Pitch</i> (°)	<i>Roll</i> (°)	<i>Pitch</i> (°)	<i>Roll</i> (°)
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