Development of an advanced mobile base for personal mobility and manipulation appliance generation II robotic wheelchair

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Background: This paper describes the development of a mobile base for the Personal Mobility and Manipulation Appliance Generation II (PerMMA Gen II robotic wheelchair), an obstacle-climbing wheelchair able to move in structured and unstructured environments, and to climb over curbs as high as 8 inches. The mechanical, electrical, and software systems of the mobile base are presented in detail, and similar devices such as the iBOT mobility system, TopChair, and 6X6 Explorer are described.

Findings: The mobile base of PerMMA Gen II has two operating modes: “advanced driving mode” on flat and uneven terrain, and “automatic climbing mode” during stair climbing. The different operating modes are triggered either by local and dynamic conditions or by external commands from users. A step-climbing sequence, up to 0.2 m, is under development and to be evaluated via simulation. The mathematical model of the mobile base is introduced. A feedback and a feed-forward controller have been developed to maintain the posture of the passenger when driving over uneven surfaces or slopes. The effectiveness of the controller has been evaluated by simulation using the open dynamics engine tool.

Conclusion: Future work for PerMMA Gen II mobile base is implementation of the simulation and control on a real system and evaluation of the system via further experimental tests.

Keywords: Spinal cord injuries, Mobile base, PerMMA Gen II, Obstacle-climbing, Simulation

Introduction

As of 2002, ~200 000 individuals in the United States were electrical-powered wheelchair (EPW) users, of which ~55 000 were older adults age >65 years.¹ The number of EPW users grew to 400 000 by 2010 in the United States.² Previous research has shown that by using power wheelchairs, users had enhanced activity and participation,^{3–5} satisfaction⁶, and quality of life.⁷ These wheelchairs have also given the users independence.^{4,6} The EPW user population is growing, and manufacturers are offering an expanding range of wheelchair options.^{8–10} Nevertheless, architectural barriers still exist in many cities and buildings, and it is expensive and time consuming to eliminate all of them. Thus, there are physical environmental barriers preventing EPW users from visiting friends and

family⁴ and carrying out more activities^{11,12} – especially with regards to stairs, doorsteps, uneven surfaces, etc. Studies show users adapt their behavior^{13,14} by choosing routes without physical barriers or by going to accessible places rather than to places they may really want to go.¹⁵ In addition, research shows that EPW users are inadequately prepared for outdoor driving situations since new EPW users normally receive little to no outdoor driving training.^{16,17} Focus group studies also found that EPW users either have to bring someone with them or avoid certain surfaces such as ramps, cross slopes, or snow during their daily activities.¹⁸

A few systems for climbing stairs or negotiating obstacles have been developed over the last 15 years, such as the TopChair,¹⁹ the Explorer,²⁰ and the iBOT.^{21,22} With these new devices, half of the users were able to climb stairs independently and felt that this capability was helpful. The remaining users were able to climb stairs with some assistance. All users

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agreed that such devices should be made available to veterans who use wheelchairs.^{21, 22}

The TopChair combines wheels and a caterpillar track. The TopChair was tested in France among 25 persons with spinal cord injuries, and the results showed that all participants were able to successfully operate the power wheelchair indoors and outdoors. One drawback of the TopChair is that due to its electro-mechanical properties and caterpillar tracks, it is a little bulkier and heavier than other power wheelchairs with similar functions. In addition, the mechanism of TopChair may not provide assistance when users drive on cross slopes or become stuck on a gravel surface. Like the TopChair, the Explorer is a stair-climbing wheelchair with wheels for level surfaces and tracks for climbing. The seat automatically tilts when moving up stairs. This wheelchair has two rear wheels but a single front wheel, limiting outdoor use.

The iBOT Mobility System also can travel over uneven terrain and climb curbs and stairs. It contains gyroscopes to maintain balance automatically. The gyroscopes respond to motion by sending signals to built-in computers, which use the information to control the motors in order to maintain stability. This system continuously realigns and adjusts the wheel position and seat orientation to keep the user upright and stable at all times, even when driving up and down steps. Stair climbing is performed by rotating the two sets of powered wheels about a cluster axle; however, the user must either hold a handrail or receive help from an assistant to stabilize the wheelchair. The iBOT was developed in the 1990s, but US Food and Drug Administration approval was not obtained until 2003 because of safety considerations. It was put on the market in 2005 in the United States and the United Kingdom. Even though the iBOT is a good mobility option for persons with ambulatory impairments, Medicare reimbursement was too low for profitable sales.

Most current commercially available EPWs have significant shortcomings. The indoor EPWs have very limited outdoor performance. The TopChair is bulkier, heavier than most EPWs, and not able to provide assistance on cross slopes; the iBOT has inadequate tilt, no advanced control, does not recline, and has been discontinued due to unavailable funding from Medicare. Off-road power wheelchairs are unable to be used indoors because of the big wheels and dimensions.

A series of focus group studies were conducted to identify the problems of EPWs driving over different terrains, and to develop some driving rules based on different speeds, acceleration, and deceleration for different terrains.²³ However, during the user study, we found

out that under certain circumstances, rule-based driving failed due to the limitations of current EPWs. For example, when the driving wheel lost traction completely on a gravel surface or a slippery surface, it was impossible for the user to regain traction and drive through the challenge.²⁴ Therefore, there is a need for EPWs with comparable dimensions to current EPWs for indoor use, as well as with capabilities to drive through tough terrains like gravel and cross slopes, and the ability to climb curbs and steps.

The focus of this study was to develop a mobile base for the Personal Mobility and Manipulation Appliance Generation II (PerMMA Gen II). The design, development, and evaluation of PerMMA Gen I has been reported previously.²⁵ The emphasis of PerMMA Gen II is enhanced mobility. For PerMMA Gen I, a customized control was designed and developed to provide slip detection and control. The electronics were customized to put into a commercial power wheelchair base (PerMobile C500). For the Gen II, we built a power wheelchair base with position-adjustable casters and driving wheels. The design objective is to develop a PerMMA Gen II mobile base with

1. comparable dimensions to current EPWs – therefore no modification of users' homes will be needed;
2. a flexible base allowing for adjustments to the driving wheel and caster wheel that will
 - (a) allow a lap-to-floor distance less than 0.66 m, allowing users to access their office desks;
 - (b) safely go through both indoor and outdoor terrains such as carpet, floor mats, wet tile, gravel, cross slopes, curbs, and steps.

The same hardware platform used for previous research on smart controllers and PerMMA Gen I were adapted for the PerMMA Gen II mobile base, with the aim to propose a valid alternative to a wide range of existing solutions developed to improve wheeled mobility.

System description

PerMMA Gen II is a power wheelchair able to move in both structured and unstructured environments, to climb over obstacles, and to go up and down stairs (see Fig. 1). The PerMMA Gen II mobile base uses a six-wheel design, similar to many current power wheelchairs. The front- and rear-wheel casters are mounted to the main frame via four-bar linkages. The position of the front and rear casters is controlled via four independent pneumatic actuators.

The actuators permit leveling of the seat with roll and pitch of the driving surface, as well as curb/step climbing. The drive wheels use hub motors and are mounted to the frame via a sliding platform, which allows the

Figure 1 PerMMA Gen II system overview.

drive wheels to be moved up/down independently with pneumatic actuators, and fore/aft to alter the center of mass and driving dynamics with a carriage and an electric linear actuator. This helps in obstacle negotiation, allows for optimization of the drive dynamics for indoor and outdoor driving, and expands options for negotiating challenging terrain (e.g. gravel, grass, side-slopes, and ice). The seat, as shown in Fig. 1, is a standard EPW seating system with power seating functions of tilt, recline, seat elevation, and footrest angle.

The real-time EPW control platform developed²⁵ and evaluated in previous studies^{24,26,27} was used as a model to develop the PerMMA mobile controller because of its demonstrated capabilities of handling multiple tasks in real time while providing rich interfaces. Control algorithms were also developed to prevent people falling out of their chairs, such as real-time slip detection and prevention,²⁶ real-time tip-over detection and prevention,²⁷ and terrain-dependent driving to prevent slips and falls.²³

Figure 2 Electrical system diagram of PerMMA Gen II.

Electrical system

The PerMMA Gen II electrical design was expanded with more electrical components from the control platform as shown in Fig. 2: a relay board to control the seating functions, a relay board to control the pneumatic cylinders for moving the four casters and driving wheel up and down, an electrical motor for moving both driving wheels forward and backward (the driving wheels can translate), a relay board to control the caster brakes during curb and stair climbing, a pulse-width modulation (PWM) generation board to generate a PWM signal to control the pneumatic system, a circuit board to control the caster brakes, and a digital input/output (I/O) board for receiving feedback from the pneumatic cylinders. All the pneumatics, electrical motors, caster brakes, and power seating functions can be controlled either by the on-board single board computer through digital I/Os or by a keypad through relay boards.

Software system

PerMMA Gen II software inherited the multiple-layer software packages for the control platform. In order to improve wheelchair stability and at the same time to guarantee a comfortable seat angle for the passenger, a posture control module was added as shown in Fig. 3. This module keeps the passenger's posture in the preferred safety and comfort zone. The safety zone is determined to provide the maximum protection for each surface. From previous focus group studies,¹⁸ we found out that users reported different comfort levels when driving on different surfaces at various speeds, accelerations, and seating positions. Therefore, a comfort zone is defined based on user's height, weight, and surface. The system calibrates itself when the user is sitting in the chair and detects the user's center of gravity (CoG) similar to the iBOT system.²² The distribution of the user's CoG is monitored by pressure sensors in each pneumatic cylinder and the inertia sensor mounted on the frame. If the CoG is not in the predefined safety and comfort zone, the posture adjustment function adjusts the position of the casters and driving wheels to get the CoG inside the safety and comfort zone.

Description of driving modalities

As will be explained in the next section, the system provides two options for users to change between "advanced driving mode (ADM)" and "automatic climbing mode (ACM)": these modes can be switched by a user's manual input or triggered automatically.

1. ADM: When the wheelchair moves on flat or uneven terrain, the two motorized driving wheels are always in contact with the terrain. The caster wheels can be configured for front-wheel drive (rear caster wheels in contact with the terrain), rear-wheel drive (front caster wheels in contact with the terrain), or middle-wheel drive (both front and rear caster wheels in contact with terrain). While the wheelchair would be stable with all the six wheels in contact with the ground (especially during off-road travel), this configuration is not optimized for traversing obstacles such as curbs, grass, gravel, uneven terrain, and snow compared with a front-wheel drive configuration.
2. ACM: During curb-climbing operations, more importance is given to wheelchair stability and so all the four caster wheels are in contact with the ground when the driving wheels are lifting up for curb climbing (as shown in Fig. 4).

The wheelchair is controlled by a joystick for the motion of the whole wheelchair. The movement of the casters and driving wheels are controlled by the automatic controller and a keypad is also provided for the user to manually control the movement of casters and driving wheels.

Climbing strategies

The goal of PerMMA Gen II is to traverse challenge terrains such as slippery surfaces, gravel, and curbs. The curb-climbing strategy is the correct sequence of actions to allow the wheelchair to surmount a single curb of height of 20.32 cm (8 inches) or less. To confirm the effectiveness of the strategy, a simulation (Fig. 5) in the open dynamics engine (ODE) was conducted.²⁸ The wheelchair is driven in ADM when the system is in front of a curb, and then the user either switches to ACM or the system itself switches the mode when both casters are in contact with the step. When ACM is triggered, the system starts the sequence by aligning the wheelchair perpendicular to the curb using the pressure sensors in the front casters (Fig. 5A). The driving wheels are moved forward to be in front-wheel drive. Next, the wheelchair moves at a slow constant speed (1 m/s). This action, in combination with the elevation of the caster wheels, is used to measure the curb height. Then, the front casters elevate (Fig. 5B). If the height is not reached, the rear casters rise as well to tilt the frame to move to the desired height. Then, the front casters move down once placed on the curb (Fig 5C). This action suspends the driving wheels in the air. Next, the driving wheels move back until they make contact with the ground and then drive forward. The purpose of this action is

Figure 3 PerMMA Gen posture control system diagram.

to place the wheelchair base on the curb in order to move the driving wheels onto the curb as well. When the front casters are positioned on the curb, caster brakes are applied to prevent the wheelchair from rolling backwards (Fig. 5D). Next, the rear casters are pushed down using the pneumatic system and the driving wheel are raised up, leaving the driving wheel suspended in the air (Fig. 5E). The driving wheel

slider moves forward until the driving wheels are on top of the curb (Fig. 5F). The driving wheels are then pushed down until contact is made with the curb. Then, the driving wheel carriage moves back until the wheelchair base is completely on the curb (Fig. 5G). Once the driving wheels and front casters are on the top of the curb, the driving wheels are lowered down to move the rear casters onto the curb (Fig. 5H).

Figure 4 PerMMA Gen II in automatic climbing mode. (A) The wheelchair in the middle of the curb climbing before driving wheels touching the curb. (B) The wheelchair in the middle of the curb climbing when driving wheels landing on the curb.

Figure 5 PerMMA Gen II step-climbing sequences. A, PerMMA Gen II detects the curb; B, Lift the front above the curb; C, Drive toward the curb; D, Move driving wheels backward; E, Lift driving wheels up; F, Move driving wheels forward; G, Drive the driving wheels up the curb; H, Lift rear casters up; I, Drive the wheelchair forward and rear casters on the curb.

Finally, the wheelchair drives automatically until all wheels make contact with the upper surface of the curb (Fig. 5I). After this, the wheelchair automatically switches back to ADM. There are force sensors in each caster wheel cylinder and driving wheel air springs for detecting when the caster will contact the curb, when the driving wheels leave the ground and reach the curb, and when the driving wheels land on the curb. There are also position sensors for measuring the length of each cylinder and air springs to know the position of the caster wheels and driving wheels.

Mobile base control system

Sensorial system

Operating the PerMMA Gen II requires a complex sensor system. There are six pressure sensors: four in the front and back caster-arm actuators to detect the instant at which the casters touch the step to either remind the user or to automatically switch the mode from ADM to ACM, and two in the pneumatic

dampens of the driving wheels to detect whether the driving wheels are touching the ground. To measure the positions of the different wheels, there are seven encoders – two in the front caster arms, two in the rear caster arms, two in the up-down racks of the driving wheels, and one in the fore-aft rack of the driving wheels. There is an inertia sensor on the frame to measure the level of the chair and to detect the instant when the chair is driving on a cross slope for implementation of the auto posture compensation control. Finally, there are four switches (two per side) to indicate the maximum and minimum positions for the driving wheels horizontally along the rack.

Actuator system

The movement of the PerMMA Gen II mobile base is powered by two driving wheels with built-in hub motors. The PW-12H wheelchair hub motor (brush/gear) is used for its low cost, compact size, linear power, and mechanical-electrical characteristics (24 V,

180–300 W, maximum torque 23.82 Nm, 7.2 kg). The fore-aft movement of the two driving wheels is powered by a liner actuator taken from a Permobil seat elevator (Part number: 308730). The liner actuator and the hub motor are powered by a 50A8DD Advance Motion Control PWM servo amplifier rated for 25 amp continuous and 50 amp for 2 seconds and accept a 20–28 V input. The up-down movement of two driving wheels is powered by two Thin-Sleeve Style adjustable air-powered springs (usable stroke: 4.4 inch, 8 inch extended height, 3.25 inch maximum outside diameter, maximum force when fully extended: 110 lb, maximum force when fully compressed: 360 lb). The movement of the four caster-arm cylinders is powered by pneumatic cylinders (Clippard miniature Stainless Steel Universal Double-Acting Rotating-Rod pneumatic cylinder with 2 inch bore, and 4 inch stroke). Finally, the five-port solenoid valve and a single-base manifold are used to pump the air for the cylinders and air springs.

Dynamic model of PerMMA Gen II

PerMMA Gen II is designed to face different situations within both structured and unstructured environments: driving on flat, inclined or undulating ground, driving on uneven terrain, climbing stairs, or driving over obstacles. The kinematic relations are necessary to identify each kind of motion. These equations take place from the description of the mechanical system and as shown in Fig. 6, where

Driving wheel position:

$$x_d = \begin{Bmatrix} x_d \\ y_d \end{Bmatrix}$$

Front caster position:

$$x_f = \begin{Bmatrix} l_1 + l_f \cos \theta_f \\ l_f \sin \theta_f \end{Bmatrix}.$$

Rear caster position:

$$x_r = \begin{Bmatrix} -(l_2 + l_r \cos \theta_r) \\ l_r \sin \theta_r \end{Bmatrix}$$

CoG position:

$$x_{cg} = \begin{Bmatrix} x_{cg} \\ y_{cg} \end{Bmatrix}.$$

Wheelchair base tilt angle: θ_0

Total force:

$$R_d + R_r + R_f - \frac{W}{2} = 0$$

Reaction forces:

$$R_d = \begin{Bmatrix} R_d \sin \theta_0 \\ R_d \cos \theta_0 \end{Bmatrix}, \quad R_r = \begin{Bmatrix} R_r \sin \theta_0 \\ R_r \cos \theta_0 \end{Bmatrix},$$

$$R_f = \begin{Bmatrix} R_f \sin \theta_0 \\ R_f \cos \theta_0 \end{Bmatrix}$$

Total torque:

$$R_d \cdot x_d + R_r \cdot x_r + R_f \cdot x_f - \frac{W}{2} \cdot x_{cg} + \tau_d + \tau_r + \tau_f = 0$$

where τ_d , τ_f , and τ_r are the torques applied on the slider actuators and front and rear pneumatic actuators.

Based on the mathematical model, Euler method is applied for dynamic of the system. Two assumptions are made before the dynamic function: first, assume relative low speed of the system, the centrifugal force, and Coriolis force are ignored. Therefore the inverse dynamics model can be expressed as

$$\begin{bmatrix} \tau_{dl} \\ \tau_{dr} \\ \tau_{fl} \\ \tau_{fr} \\ \tau_{rl} \\ \tau_{rr} \\ F_{ph} \\ F_{pvl} \\ F_{pvr} \\ \tau_0 \end{bmatrix} = \begin{bmatrix} f_{11} & f_{12} & f_{13} & . & . & . & . & . & . & f_{110} \\ f_{21} & f_{22} & f_{23} & . & . & . & . & . & . & . \\ f_{31} & f_{32} & f_{33} & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & . \\ f_{101} & f_{102} & f_{103} & . & . & . & . & . & . & f_{1010} \end{bmatrix} \times \begin{bmatrix} \ddot{\theta}_{dl} \\ \ddot{\theta}_{dr} \\ \ddot{\theta}_{fl} \\ \ddot{\theta}_{fr} \\ \ddot{\theta}_{rl} \\ \ddot{\theta}_{rr} \\ \ddot{P}_h \\ \ddot{P}_{vl} \\ \ddot{P}_{vr} \\ \ddot{\theta}_0 \end{bmatrix} + \begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ . \\ . \\ . \\ . \\ . \\ . \\ g_{10} \end{bmatrix}$$

where τ_{dl} , τ_{dr} are the torques applied on the left and right driving wheels; τ_{fl} , τ_{fr} , τ_{rl} , τ_{rr} are the torques on the left and right side of the front and rear caster arms. F_{ph} is the horizontal force applied on the horizontal movement of driving wheel axis. F_{pvl} , F_{pvr} are the vertical forces applied on driving wheel's axis. τ_0 is the torque acting on the passenger body posture. Moreover, f and g are the

Figure 6 Mathematical model of PerMMA Gen II mobile base.

functions of all the variables as follows:

$$\begin{aligned} f_{ij} &= f_{ij}(\theta_{\text{dl}}, \theta_{\text{dr}}, \theta_{\text{fl}}, \theta_{\text{fr}}, \theta_{\text{rl}}, \theta_{\text{rr}}, \theta_0, P_{\text{h}}, P_{\text{vl}}, P_{\text{vr}}) \\ g_{ij} &= g_{ij}(\theta_{\text{dl}}, \theta_{\text{dr}}, \theta_{\text{fl}}, \theta_{\text{fr}}, \theta_{\text{rl}}, \theta_{\text{rr}}, \theta_0, P_{\text{h}}, P_{\text{vl}}, P_{\text{vr}}) \end{aligned}$$

Control development

The posture control for PerMMA Gen II consists of a feed-forward compensator and a feedback compensator. The feedback controller is used for regulating the state deviation between the desired state X_{ref} and the actual state X of the wheelchair. The feedback gain K is determined by using the proportional-integral-derivative (PID) control theory.²⁹ The feed-forward controller is used for regulating the influence of gravity with respect

to the posture of PerMMA Gen II. The control system block diagram is shown in Fig. 7. The model and control structure are based on previous work,^{30,31} where

$$u_{\text{fb}} = K_{\text{P}}(X_{\text{ref}} - X) + K_{\text{I}} \int_0^t (X_{\text{ref}} - X) dt + K_{\text{d}} \frac{d(X_{\text{ref}} - X)}{dt}$$

$$u_{\text{ff}} = G_{\text{g}}(\varnothing, \theta)$$

If the body is kept nearly upright, $\sin \theta_0 \approx \theta_0$, $\cos \theta_0 \approx 1$. The dynamic model could be further linearized based on the assumptions described in the state equation

Figure 7 Block diagram of the state feedback feed-forward controller.

below:

$$\frac{d}{dt}X = AX + Bu$$

where

$$X = \left[\int \theta_0 dt \quad \theta_0 \quad \int P_{vl} dt \quad \int P_{vr} dt \quad P_{vl} \quad P_{vr} \quad \dot{P}_{vl} \quad \dot{P}_{vr} \quad \Delta P_h \quad \dot{\Delta P}_h \quad \theta_{fl} \quad \theta_{fr} \quad \theta_{rl} \quad \theta_{rr} \quad \dot{\theta}_{dl} \quad \dot{\theta}_{dr} \right]^T$$

Posture angle
Vertical move
Horizontal move
Caster arm angle
Driving wheel speed

$$u = [\tau_{dl} + g_1' \quad \tau_{dr} + g_2' \quad \tau_{fl} + g_3' \quad \tau_{fr} + g_4' \quad \tau_{rl} + g_5' \quad \tau_{rr} + g_6' \quad F_{ph} + g_7' \quad F_{pvl} + g_8' \quad F_{pvr} + g_9']^T$$

$g_1' \sim g_9'$ mainly consists of gravity which are not dependent on state variables. Detailed information about A , B , and $g_1' \sim g_9'$ are omitted due to space limitations.

Represented as a controllable system, because the system has observable state variables, this can be stabilized by state feedback. In this case, the control law is represented as follows:

$$u = K(X_{ref} - X)$$

where

$$X_{ref} = [0 \quad 0 \quad 0 \quad 0 \quad P_{vlref} \quad P_{vrref} \quad \dot{P}_{vlref} \quad \dot{P}_{vrref} \quad \Delta P_h \quad 0 \quad \theta_{flref} \quad \theta_{frref} \quad \theta_{rlref} \quad \theta_{rrref} \quad \dot{\theta}_{dlref} \quad \dot{\theta}_{drref}]^T$$

K is the state feedback gain matrix, derived from PID theory. When the PerMMA Gen II climbs the stairs, it uses the front and rear caster arm and the vertical and the horizontal movement of the driving wheels simultaneously (Fig. 8A). When the PerMMA Gen II drives on an up-down slope, caster-arm movement up and down can compensate for the passenger's posture (Fig. 8B). The passenger's posture remains horizontal with respect to inclination or cross slope by using the vertical movement of the driving wheel axis (Fig. 8C).

In addition, $\dot{\theta}_0$ is measured using the pitch-axis of the gyroscope of the attached inertia sensor. Thus θ_0 is estimated from the accelerometer and the integrated value of the pitch-axis gyroscope.

Results and simulation

A working prototype of PerMMA Gen II has been built as shown in Fig. 4. The characteristics of PerMMA Gen II are:

- PerMMA Gen II weighs 90.72 kg, has a 0.36 m driving wheel tire diameter, and has a maximum speed of 6 miles per hour. The dimensions are listed in Table 1.
- PerMMA Gen II has two driving wheels, two front caster arms, two rear caster arms, and four caster wheels. The degrees of freedom of the wheels are listed in Table 2.

- PerMMA Gen II has five degrees of freedom: the longitudinal, the vertical, the yaw, the pitch, and roll motion. Each caster and driving wheel has three degrees of freedom.
- To measure posture, PerMMA Gen II includes a three-axes gyro sensor and a three-axes accelerometer.

To confirm the effectiveness of the control law obtained in the previous section and the stability performance by using the proposed controller, a simulation in the ODE was conducted.²⁸ Fig. 9 shows a three-dimensional (3D) model-based simulation of the behavior of the PerMMA Gen II test unit.

In the simulation of stability performance with the developed control law, the wheelchair was driven with the maximum speed of 1.38 m/s. The wheelchair was driven straight. After reaching the maximum speed, the speed was changed to 0 m/s to simulate sudden braking. For the slope driving simulation, the slope angle was set to 10° with maximum speed of 1.38 m/s. Fig. 10 shows PerMMA Gen II performers during the simulations. Fig. 11 shows the change in the posture of the wheelchair and behavior of vertical slider as a control input.

Simulation results show that with the controller applied, there is less pitch and roll motion than by controlling the vertical driving wheel position and the caster arms simultaneously without automatic control (Fig. 11A and B). The dark line represents the result with the control law applied and the light line represents angles without automatic control. There is less deviation for the pitch angle with the control law applied than without the control algorithm. When the wheelchair is driven on a slope, the roll angle is within 3° with the control law applied, while without the control algorithm the roll angle is more than 8°. Different vertical forces are applied on the left (blue) and right (red) driving wheels (Fig. 11C), to change the vertical position of the left and right driving wheels (Fig. 11D) to react to the slope the wheelchair is driven on. From the simulation results, the controller successfully maintains its posture.

Discussion

The PerMMA Gen II mobile base prototype has dimensions comparable with current commercially available power wheelchairs, and is within the range of RESNA/ANSI wheelchair standard.^{32,33} RESNA/ANSI wheelchair standards are specific test procedures used to provide information about the performance, safety, and dimensions of wheelchairs. The use of a standardization process among wheelchair manufacturers

Figure 8 PerMMA Gen II control states. (A) Climbing the stairs. (B) The up-down slope. (C) The cross slope: inclination driving.

and designers greatly reduces inconsistencies between the previously different methods of measurements, testing procedures, and the reporting of results. For example, “seat width” could have meant the measurement between the inside of the seat rails to one manufacturer, or between the outside of the seat rails to another, or between the armrests to yet another manufacturer. ANSI/RESNA wheelchair standards were established to eliminate these inconsistencies and provide uniform methods for analyzing wheelchairs and prescribing the chair by therapists. After finishing the integration of caster wheel brakes, more tests will be performed on the PerMMA Gen II mobile base based on the standards such as turning radius and static and dynamic

stability (Section 8 of the durability test will not be performed). Owing to the adjustable caster and position of the driving wheels, the overall test results – especially stability – are expected to be better than most of the other power wheelchairs. Since PerMMA Gen II can fit underneath standard 0.66 m high office desks, this may lead to reduced costs for rebuilding the working environment. The new PerMMA Gen II robotic wheelchair has comparable weight with current commercial available power wheelchairs. The test of the battery life has not been conducted according to RESNA/ANSI standards, but with the wheelchair turned on and all the components powered up, the wheelchair battery could last more than 8 hours during the

Table 1 Wheelchair dimension comparison

Wheelchair model	Base length (m)	Overall width (m)
Permobil C500	1.26	0.65
PerMMA2	1.02	0.66
Invacare TDX	0.90	0.65
RESNA dimensions	1.20	0.70

Table 2 Wheel's degree of freedom

Wheels	No. of wheels	Degree of freedom (distance)
Driving wheels	2	Up/down (0.1 m) Rotation Horizontal position (0.2 m)
Rear casters	2	Up/down (0.1 m) Spinning rotation Swivel rotation
Front casters	2	Up/down (0.2 m) Spinning rotation Swivel rotation

experimental test. In the next study, more thorough tests according RESNA/ANSI standard will be conducted except those which would destroy the current prototype.

PerMMA Gen II's climbing sequence models can be applied to any curb height of 0.2 m or less. The same concept will be used for stair-climbing simulation in the ongoing study. Multiple interfaces for users to switch between different driving modes will be used, since users may have different capabilities and preferences for changing the mode, either by themselves or by the controller.

The ODE simulation results demonstrate the effectiveness of the posture control algorithm. However, the control gain K is decided by iteration, which could be

improved by applying a linear quadratic regulator (LQR) method that has been used to improve the stability of a two-leg-wheeled inverted-pendulum-type vehicle equipped with a slider.³⁰ Since PerMMA Gen II was built from scratch, a very good model of the system is available, and because of PerMMA Gen II's advanced sensory system, all of the states are available for feedback and stability may be guaranteed when using LQR. In addition, the controller is automatically generated by simply selecting control parameters (no need to do loop-shaping).

The ODE software and the Single Board Computer of the PerMMA Gen II wheelchair use the same programming language, C/C++, which makes the algorithm

Figure 9 3D simulation environment of PerMMA Gen II on a slope using ODE.

Figure 10 Simulation setup for PerMMA Gen II posture control.

transition to the wheelchair controller simpler. However, the ODE algorithm needs to be calibrated based on the sensor outputs to provide accurate control of the pneumatic actuators. The pneumatic actuators on the PerMMA Gen II system may require some modification of the control algorithm. The pneumatic system is a non-linear system as it depends on air valve pressure. This might limit the control when applying pressure to raise the wheels. An alternative system would be to use electric actuators instead of pneumatics since it is a linear system; however, electric actuators consume more battery power, are more expensive, and have a slow response.

In addition, with independently controlled casters and driving wheels for PerMMA Gen II, the left- and right-side height of the wheelchair can be adjusted independently; therefore, lateral pressure relief could be performed to prevent pressure ulcers and increase the comfort of the wheelchair users. Seeking lateral

support is one of the many strategies in normal sitting behavior that users may develop to cope with long-term sitting. The efficiency of lateral support is closely related to the (lateral) support surface built in the backrest. Even minor lateral adjustments can have positive effects on function, weight distribution, mealtime management,³⁴ and raising comfort level.³⁵ There are also examples of case studies showing that lateral tilt-in-space has applications in difficult seating problems in the areas of gastric emptying, pressure relief, hip pain relief, head and trunk balance, oral secretion control, progression of scoliosis, need for repositioning, posture induced tone, and sitting tolerance.³⁶ However, active lateral tilt in wheelchairs is seldom used. One possible reason for the rare usage of lateral tilt in wheelchairs is the paucity of available lateral tilt capabilities for wheelchairs or seating systems currently on the market. PerMMA Gen II could provide up to 10° of dual lateral tilt. More evaluations of the lateral tilt

Figure 11 Simulation results for PerMMA Gen II posture control. (A) Pitch angle [rad]. (B) Roll angle [rad]. (C) Vertical slider force [N]. (D) Vertical slider position [m].

function of PerMMA Gen II regarding to pressure relief will be conducted.

Conclusion

A future goal is to evaluate the control simulation of the step-climbing sequence by applying it to PerMMA Gen II. Experimental tests will be setup to evaluate the posture control when the wheelchair driving over obstacles and on slopes. A secondary goal is to be able to climb up to three steps; however, this will require some modification to the current wheelchair. The ability of lifting up/down each wheel independently allows PerMMA Gen II to perform other applications such as lateral pressure relief and automatic seat leveling while driving over uneven surfaces. These applications

can be performed manually with the use of switches; however, more work is in progress to perform these applications automatically. The features of PerMMA Gen II will be used in combination with another project that recognizes different terrains and change acceleration and velocity according to these terrains.³⁷ The safety of the user is the highest priority during the development and simulation of the step climbing.

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