Development of a Highly Maneuverable Walking Aid
- Design with Multi-functional Front Wheels and Direct Yaw-moment Control -

Masao Ishihama¹  Tatsuya Miyazaki²  Takashi Aritake³  Akira Homma⁴
1)-4) Kanagawa Institute of Technology
1020 Shimo-ogino, Atsugi, Kanagawa 243-0292, Japan (E-mail: ishihama@sd.kanagawa-it.ac.jp)

Received on June 7, 2011
presented at the JSAE Annual Congress on May 18, 2011

ABSTRACT: Walking aids are vehicles that need to carry a major part of the user’s weight and to run on roads. Therefore, automotive engineering was applied in this study to improve the walking aid design. The walking aid developed can turn in a small space such as in an elevator, ride over gaps such as curbs, and keep straight trajectories on rough and slanted surfaces with minimum user effort. The core part of this design lies in the adoption of a multi-functional swing-arm suspension for the front caster wheels and direct yaw-moment control by the rear-wheel motor drives.

KEY WORDS: (Standardized) ride comfort, suspension system, vehicle dynamics, (Free) walking aid, yaw control [B3]

1. INTRODUCTION
In this paper, the authors propose the design of a walking aid for outdoor use. The walking aid would enable elderly people to exercise and to have more social interactions. However, designing such a walking aid is not easy.¹ For example, walking aids for outdoor use must climb slopes. This requirement can be satisfied by using electric power. Similarly to motor vehicles, they also must run over rough surfaces while producing minimal vibration and providing reliable support to their users. The aids must turn in a small space and stop in the desired manner. Conventional walking aids cannot meet all these requirements. To satisfy these requirements with a simple, inexpensive, and compact design, caster type wheels can be installed. However, caster wheels are difficult to control while maintaining the desired trajectory. To maximize the advantages of caster wheels while minimizing the control problem, the authors propose a design that is a combination of a multi-functional swing-arm suspension for the front caster wheels and direct yaw-moment control by rear-wheel motor drives. The multi-functional swing-arm suspension has sensors that pick up the swing-arm sway angle and send signals representing the thrusts acting on the front wheels. The direct yaw-moment control system uses signals from the sway-angle sensors and a yaw-rate sensor to control the motors installed on the left and right rear wheels. A prototype based on this design principle was developed through the process described below and was proved effective by experiments.

2. DEVELOPMENT PROCESS
The first step of this study was exploring the needs of elderly users. The authors had discussions with doctors at the National Center for Geriatrics and Gerontology in Obu City, Japan and Prof. Hiroshi Okamura and professors at Shibaura Institute of Technology, Omiya City, Japan¹. These consultants have specialized knowledge useful in developing walking aids. Through the discussions and a literature survey, the authors identified the general requirements for walking aids.

The second step was identifying the assumed users. People who can stand on their feet but have to rely on some aid in walking were chosen. These users need to train their walking ability for walking outdoors to meet their daily needs, such as going to the post office and convenience stores. Fulfilling their daily needs reflects the intention of the Japanese government to reduce national medical expenditures while assuring the well-being of the elder generation.

The third step was to survey the barriers in a typical suburban residential area. By walking along pedestrian walkways and getting in and out of stores, statistical data such as curbstone height were obtained².

The fourth step was to identify the permissible vibration level at the handle grips. By simulating the grip vibration with an electro-magnetic shaker, desirable and permissible vibration amplitude thresholds were identified at each octave band center frequency from 4 Hz to 125 Hz².
The fifth step was to set the design specifications of the walking aid dynamics. The most critical performances selected were as follows: 1) stability to prevent falling over when the aid hits stones or when the user stands up from a sitting posture, 2) climbing ability on curbstones, and 3) riding on rough pavement. The design parameters corresponding to these performances were found to be 1) height of the center of gravity, 2) front-wheel suspension compliance in the longitudinal and vertical directions, and 3) stiffness of the space frame, especially in the torsion mode. The sixth step was to apply the ideas to design drawings to realize the required performances. The seventh step was to build a prototype and test it to evaluate the design. In this paper, the last three steps are described. The earlier steps were previously reported at FISITA2006(2).

3. IDENTIFICATION OF DESIGN SPECIFICATIONS

3.1. Identification of potential users and environments

Because outdoor walking aids are to help people going outside their home, potential users were assumed to be able to stand on their feet but need some aid in walking. Based on the discussions mentioned above and the literature survey, we assumed that approximately 30% of their weight should be supported by walking aids. The authors surveyed barriers to walking aids in a typical suburban residential area(2). The major “bump” obstacles encountered were grids over underground sewage covers and grates, twigs, curbstones, etc. The frequency distribution of bump obstacles is shown in Fig. 1. Fifty millimeters, which is the standard curbstone height, corresponds to the accumulated frequency of 95%. The maximum slope was found to be 8% in this survey. Handling this height and slope were identified as the main requirements for our design.

![Fig. 1 Frequency distribution of bump height](image)

3.2. Specifications setting

By investigating the user needs and the Japanese legal requirements, the design specifications were set as shown in Table 1. Although not listed in Table 1, a very important requirement of the walking aid is that the center of turning must be located very close to the user. This condition excludes design options with a rear-wheel steering system.

### 4. CHASSIS AND FRAME DESIGN

4.1. Multi-functional swing-arm front suspension

To ride over bumps of 50 mm height, a multi-functional swing-arm suspension was adopted for the front wheels (Fig. 2). This suspension uses a small leading wheel and a main load-carrying wheel attached on two ends of a V-shaped link that can sway around a pivot at the center corner of the V link. When encountering a step, for example, the leading wheel rides on the step and supports part of the front load and helps the main wheel to climb up the step. The V-link rotation is suspended by a torsion spring and can absorb the shock when the main wheel hits the step.

![Fig. 2 Front-wheel suspension mechanism with a V-shaped arm](image)

Due to the sway motion, the effective slope of the main wheels during the climb over a bump is milder than the effective slope of a rigid axle type suspension, and so eventually the proposed wheel reduces the required thrust (Fig. 3). The torsion spring can store energy in the first step of riding over the bump.

| Table 1 Specifications of the prototype design |
|-----------------------------------------------|
| **Item**             | **Unit** | **Description**       |
| Dimension (LxWxH)    | mm       | 900 x 600 x 650*     |
| Weight               | kg       | <20 kg               |
| Wheelbase            | mm       | 500                  |
| Mass                 | ratio    | 50:50                |
| Maximum gap height to climb | mm | 50       |
| Grip height range    | mm       | 600–1000             |
| Vibration isolation from ground to grips      | dB       | 10                   |
| Turning radius       |          | On-spot turning      |
| Braking system       |          | Electric motor reverse torque |
| Human-machine interface|       | Push pressure sensors on L/R grips |

* Minimum grip height
Then, it releases the energy for climbing up the bump similarly to a pole vault action.

4.2. Topologically optimized lightweight frame

To be highly maneuverable, a walking aid frame must be light and stiff. To meet these conditions, the frame shape was designed through topological optimization and shape optimization by using the finite element analysis software Optishape®. The process began with a voxel model filling the space surrounding the user. Then, by applying suitable loads and boundary conditions, a topologically optimized voxel model was obtained (Fig. 4). With consideration of the most practical requirements, the final design was completed, and a prototype was built (Fig. 5). The frame itself weighed only 1 kg.

Fig. 3 Effective slope reduction by swaying motion of the front-wheel suspension with a torsion spring

Fig. 4 Topologically optimized voxel type finite element model

The shock from the front wheel to the frame can be reduced by the swaying motion mentioned above. To ease the vibration input from the rear wheels, this design adopted the swing-arm suspension, as shown in the figure 2. This system effectively reduces the vibration transmitted to the grips when the walking aid falls into a depression (Fig. 6). The threshold was identified using a shaker test of a grip model(2).

Fig. 5 Photo of the prototype

Fig. 6 Grip vibration reduction in falling into a gap of 50 mm

5. POWER TRAIN AND ITS CONTROL

5.1. In-wheel motor design

From the specifications and the authors’ experiences, the necessary assistance in power and thrust was estimated. Because of the necessary controllability and space constraint around the rear wheels, a DC brushless motor was selected as the power device. By following the guides written in a motor design manual(4), the specifications listed in Table 2 were set. Figures 7 and 8 show the inside arrangement of the motor and the motor performance curves, respectively. To save time and money in building the motor, off-the-shelf motors made by Mitsuba Corp. were adopted, as shown in Fig. 5.

Table 2 Parametric design of DC brushless driving motor

| Parameter                          | Symbol/Unit | Value |
|------------------------------------|-------------|-------|
| Number of poles                    | P           | 8     |
| Number of slots                    | nq          | 6     |
| Magnet inner diameter              | Di, mm      | 150   |
| Magnet length                      | Lh, mm      | 30    |
| Magnet thickness                   | Lm, mm      | 10    |
| Outer diameter of rotor yoke       | Da, mm      | 148   |
| Armature core outer diameter       | Db, mm      | 137   |
| Armature core inner diameter       | Dd, mm      | 45    |
| Armature core length               | La, mm      | 25    |
| Air gap                            | da, mm      | 1     |
5.2. Motor speed control for normal driving

To control the walking aid driving speed, a control system was designed, as shown in Fig. 9. Sensing the thrust applied by the user with pressure sensors on the right and left hand grips (Fig. 10), the controller supplies electric current separately to the motors installed on both the rear wheels. The summation of the two thrust signals constitutes the driving speed command. The difference between the right and left signals constitutes the turning command.

The yaw-rate sensor on the frame and the potentiometers to detect the front-suspension sway angle minimize the unwanted yaw and lateral movements caused by road surface disturbances.

5.3. Human interface design

To support the user firmly, the only human–machine interface is the hand grips, which are used instead of a movable steering device, such as a steering handle. The grip handle is fixed to the frame and holds membrane type pressure sensors on its side. The sensors detect the thrust placed by the user. However, when the user grips the handle more firmly than the average the electronic circuit receiving the sensor signals judges them as emergency signals and stops driving the motors. With the input circuits closed, the motors act as electric brakes.

Exploiting the control system combined with the multi-functional front suspension, the user effort to ride over a bump can be kept in a comfortable range, as shown in Fig. 11. This result shows that the power-assist system reduces the impulsive reaction force to the user’s hand, even while climbing a bump.

The function of the abovementioned control system was simulated using the software SIMULINK to obtain the suitable control gains empirically. The program results were converted to machine language, then operated on the interface “LabView Compact RIO” that connects the computer and the control hardware.
5.4. Yaw stabilization on laterally sloped sidewalks

Though the caster type front wheel provides on-spot turning and a fixed grip handle, it has one disadvantage: it changes its direction very easily by lateral disturbances. The gravitational force working laterally on a laterally sloped sidewalk tends to turn the walking aid head downward\(^5\), \(^6\). To lessen the user effort to maintain a straight course, direct yaw-moment control using the two motors was added. A multi-body dynamics model was created to simulate the control performances (Fig. 12).

![Fig. 12 Multi-body dynamics model for driving on lateral slope (8 degrees)](image)

The results indicate that direct yaw-moment control using the yaw sensor signal and generating different torques to the right and left wheel motors works well on a road with an 8° lateral slope, as shown by the “Xcontrol” curve in Fig. 13.

![Fig. 13 Effect of course-maintaining control on a lateral slope (simulation) “Xcontrol” and “Xfree” stand for conditions with and without control.](image)

5.5. Yaw stabilization on an uneven bump

The course-maintaining control using the yaw-rate sensor was set to respond relatively slowly to avoid unnecessary fluctuation. However, to avoid rapid unwanted lateral or yaw motion in such events as hitting a bump with only one front wheel, a quicker response was needed. Therefore, a type of feedforward control was tested as well as a feedback control by the motor control based on the yaw-rate signal. To conduct this test, an angular potentiometer was installed on each front wheel, as shown in Fig. 14, to sense the V-link sway angle, because it represents the disturbance force on the walking aid. By ignoring sway-angle signals below a suitable threshold, the controller can be free from unwanted self-induced vibration.

![Fig. 14 Detecting front-wheel rolling-resistance disturbance by the sway-angle sensor](image)

Figure 15 shows the yaw-rate change of the walking aid, when it hits a bump at an angle of approximately 45° from the original course. By detecting the sway angle of the left front wheel, the controller tries to raise the left rear-wheel motor speed instantaneously. Then, the controller adjusts the two motor speeds by receiving the yaw-rate sensor signal to maintain the original course. Because the aid cannot obtain information of its absolute location, the course traveled deviates from its original course. However, the deviation is small enough for practical use.

![Fig. 15 Effect of yaw stability control in riding over a bump](image)

The results obtained for the outdoor walking design developed in this study were compared with one of the most advanced conventional power-assisted walking aids\(^7\). The results are shown in Table 3. Because almost all conventional power-assisted walking aids are for indoor use, they do not run well over rough terrain. Our design has advantages over conventional aids in terms of turning radius, running over rough terrain, and ride quality. The primary reason behind these advantages is the adoption of the multi-functional front
suspension system combined with the direct yaw-moment control using two motors on the rear wheels.

6. CONCLUSIONS

A walking aid for outdoor use was designed. The proposed aid can turn in a small space, ride over bumps such as curbstones, and keep straight trajectories with minimum user effort on rough and slanted surfaces. A prototype based on the design showed better performances over conventional designs. The effect of each design feature is stated below.

1) The combination of rear wheels with motor drives and front caster wheels enables the outdoor walking aid to successfully perform both on-spot turning and stable straight running, as shown in Figs. 10 and 13.

2) The combination of the swing-arm front suspension and the rear-wheel motor drive can easily climb up bumps as high as 50 mm with minimum shock to the user’s hand, as shown in Fig. 11.

3) The combination of the yaw-rate sensor and front suspension sway-angle sensors can minimize the lateral course deviation, as shown in Figs. 14 and 15.

ACKNOWLEDGEMENT

The authors would like to thank Prof. Hiroshi Okamura and Prof. Yukio Kawakami of Shibaura Institute of Technology for providing funding and equipment for this study. Ms. Shiowaki and Ms. Shiobara of National Instrument Japan gave helpful advice in using the control equipment and software. Dr. Keizo Ishii of Quint Corporation allowed the authors to use his structure optimization software at no cost.

REFERENCES

(1) Hiroshi Okamura, et.al.: Study and Control of Walking Assist Device, Proceedings of Dynamics and Design Conference of Japan Society of Mechanical Engineers, No.401 (2005)
(2) Masao Ishihama, Takashi Aritake: Dynamical Design of a Outdoor Walking Aid, FISITA2006 Transactions, F2006D112T (2007).
(3) Quint Corporation: Structural optimization software product explanation home page, http://www.quint.co.jp/eng/index.htm
(4) Practical Motor Design Manual, Toshiba Motor Research Group, Sohgoh Denshi Press (1992)
(5) Makoto Kamachi, et.al.: Improvement of Vehicle Dynamic Performance by Means of In-Wheel Electric Motors, Mitsubishi Motors Technical Review, Vol.18, p.107-113 (2006)
(6) Masato Abe: Vehicle Handling Dynamics: Theory and Application, Chapter 8, Butterworth-Heinemann (2009)
(7) Nemoto et al.: Power assist control for walking support system., Proceedings of the Ninth International Conference on Advanced Robotics, Tokyo, Japan, pp. 15–18 (1999)

Table 3 Performance comparison with conventional motorized walking aids

| Evaluation items | Design target | Conventional motorized walkers | Our design | Score | Features | Score |
|------------------|---------------|--------------------------------|------------|-------|----------|-------|
| **Driving on flat surfaces** | Easy speed control | Motor driven rear wheels | Good | Hub-motor rear wheels | Good |
| **Climbing** | Same performance as that on a flat surface | Motor driven rear wheels | Good | Hub-motor rear wheels | Good |
| **Braking** | Automatic speed limitation | Electric braking | Good | Electric braking using a slope sensor | Good |
| **Stability** | Easy line tracing on rough surfaces and gaps/holes/bumps | Front-wheel steering connected to handle grips with links. Needs maneuvering skill. | Fair | Automatic direct yaw moment control with hub-motor rear wheels | Good |
| **Turning radius** | Turnable in an elevator car of width=1 m | Front-wheel steering connected to handle grips with links | Poor | Free casters in front wheel | Good |
| **Running over rough terrain** | Climbable 50 mm gap height | No special device for riding over gaps | Poor | Special front suspension system | Good |
| **Ride** | Shock on handle grips should be less than 1 G | No special device for absorbing shocks in riding over gaps/bumps | Poor | Front & rear suspension system | Good |
| **Size** | Width< 0.6 m, Length< 1 m | Large | Fair | W x L = 0.6 m x 0.9 m | Fair |

Copyright © 2011 Society of Automotive Engineers of Japan, Inc. All rights reserved

142