Mobility Assistance Design of the Intelligent Robotic Wheelchair

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Po Er Hsu¹, Yeh Liang Hsu¹,*, Kai Wei Chang¹ and Claudius Geiser²

1 Gerontechnology Research Center, Mechanical Engineering Dept., Yuan Ze University, Taiwan
2 Hochschule Augsburg, University of Applied Sciences, Germany
* Corresponding author E-mail: mehsu@saturn.yzu.edu.tw

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Abstract This paper presents the development of the “intelligent Robotic Wheelchair” (iRW), emphasizing its mobility assistance design. The vehicle uses four Mecanum wheels to facilitate movement in all directions, including sideways, and zero radius of rotation. The iRW requires much less space than ordinary electric wheelchairs in turning and sideways manoeuvres. Based on this moving vehicle, mobility assistance functions are designed for three different operators: the wheelchair user, caregivers, and the iRW itself in autonomous behaviours. Five operation modes, all mutually exclusive, are developed: obstacle avoidance, joystick mode, handlebar mode, teleoperation, and indoor navigation. Man-machine collaborative control is reflected in the assignment of priorities to the three operators. The functional test performed in this research compared the operational efficiency of the five operation modes.

Keywords Robotic Wheelchair, Mobility Assistance, Manoeuvrability

1. Introduction

Over recent decades, a rapidly aging society has meant increasing demand for living support and healthcare. The ageing process in older adults results in a decline in functional status and decreased mobility, which affects individuals’ level of self-care and independence. Mobility is a crucial aspect in independence. It is sensitive to changes in health and psychological status and is one of the most crucial factors determining one’s functional capacity [1, 2].

For older adults with mobility impairment, a wheelchair is the most common and important aid. An electric wheelchair is an option for older adults who cannot propel themselves on an ordinary wheelchair. However, operating an electric wheelchair is often difficult for them. Fehr et al. [3] surveyed 200 practising clinicians in a variety of clinics, residential treatment facilities, and rehabilitation hospitals. 40% of the patients who received electrical-wheelchair training thought that the electric wheelchair was difficult or impossible to manoeuvre. Nearly half of the patients unable to control a power wheelchair by conventional methods would benefit from an automated navigation system, according to their clinicians. The usability of electric wheelchairs can therefore be a major problem for older adults.

Miller and Slack [4] first used the term “robotic wheelchair”. They applied various sensing and navigation
technologies that are often used in robotics and built two prototypes of robotic wheelchairs, which were able to assist users to pass through narrow paths and avoid obstacles. Simpson [5] reviewed many recent studies on the development of “smart wheelchairs” that can perform some autonomous behaviours for mobility assistance, such as obstacle avoidance and navigation.

Automatic navigation is a major research area in robotic wheelchairs, since mobility assistance is the fundamental function of a wheelchair. Prassler et al. [6] developed the robotic wheelchair MAiD (Mobility Aid for Elderly and Disabled People) to support and transport users with limited motor skills. The system provides functions ranging from fully autonomous navigation in an unknown crowded environment such as a railway station, to partially autonomous local manoeuvres such as passing through narrow doorways. Cruz et al. [7] proposed a landmark-based navigation system and an obstacle avoidance strategy for robotic wheelchairs. In their system, every landmark was composed of a segment of a metallic path and an RFID tag. All landmarks were detected by inductive sensors and identified by an RFID reader.

Man-machine collaborative control, which addresses how a human and a robot collaborate to perform tasks and achieve goals [8], is another important research area in robotic wheelchairs [9-13]. There is no supervisor in the collaborative control scheme: the robotic wheelchair is more like a partner to help the user find good solutions when there are problems [8]. Galindo et al. [14] developed the robotic wheelchair SENA to facilitate the mobility of disabled people and older adults. SENA implemented human-robot integration, which permits a person to extend/improve the autonomy of the whole system by participating at all levels of the robot operation, from deliberating a plan to executing and controlling it.

This paper presents the development of the “intelligent Robotic Wheelchair” (iRW), which intends to redefine the wheelchair as the most important aid to the mobility, everyday living, and healthcare of older adults. Figure 1 illustrates the overall design concept of the iRW. The core of the iRW is a user interface designed specifically for older adults’ declining abilities in perception, motor control, and cognition. Technically, the iRW is composed of a moving vehicle, a multiple degree-of-freedom (DOF) seat adjustment mechanism, and an information/communication module.

The iRW is intended to facilitate physical interaction with and control of the environment, as well as information exchange and interpersonal communication with the outside world.

Souza et al. [15] examined 50 journal articles on mobility assistive technology (MAT) and concluded that electric wheelchairs should be considered not only as providing mobility for advanced stages but as mobility assistive technology that can be integrated with an adjustable seating system to reduce fatigue. The multiple DOF seat adjustment of the iRW is achieved by a four-axis Stewart Platform, which is capable of adjustments in height, pitch, and sway to provide transfer assistance, sit-stand assistance, and comfortable sitting. Equipped with soft pressure-sensing pads, the seat also provides automatic pressure relief by adjusting the seat mechanism when continuous, concentrated pressure is detected.

Figure 1. Design concept of the iRW

The information/communication module is in the form of an App running on a tablet PC mounted on the armrest of the iRW. Connected to blood pressure and blood glucose meters, the tablet serves as the platform for tele-healthcare management. Able to display caring messages, timely reminders, and photos sent by remote family members and caregivers, the tablet is also the communication channel for the wheelchair user [16].

This paper will emphasize the mobility assistance design of the iRW. Maneuuvrability is of the highest concern when designing the iRW vehicle. The vehicle uses four Mecanum wheels to facilitate movement in all directions, in particular, the sideways movement which cannot be achieved by ordinary electric wheelchairs. The efficiency of space utilization for the iRW is discussed in this paper, in terms of its ability to move sideways and show zero radius of rotation.

Based on this moving vehicle, three “operators”, the wheelchair user, caregivers, and the iRW itself, are considered in the mobility assistance design for the iRW. Five operation modes, all mutually exclusive, are developed. “Joystick mode” is the main operation mode used by the wheelchair user. “Handlebar mode” and “teleoperation mode” are designed for caregivers who intend to push the iRW or to operate the iRW from a remote site. “Obstacle avoidance” and “indoor navigation mode” are the two semi-autonomous modes of the iRW, aiming to reduce the operation load of the wheelchair user.
user or caregivers. Man-machine collaborative control is reflected in the assignment of three “operator priorities” (in descending sequence): the wheelchair user, caregivers, and finally the iRW itself. The functional test performed in this research compared the operational efficiency of the five operation modes.

The rest of the paper is organized as follows. Section 2 presents the design of the moving vehicle equipped with Mecanum wheels. Section 3 describes the five operation modes of the iRW and the assignment of control priority. Section 4 describes the space utilization assessment. Section 5 presents the functional test of the operation modes of the iRW. Finally, Section 6 presents a conclusion.

2. Moving vehicle of the iRW

The iRW is designed for home or nursing home use, mostly indoor or short-distance outdoor (such as taking a walk in the garden). Manoeuvrability is of the highest importance when designing the moving vehicle, so that the iRW can be used in crowded indoor environments. Most electric wheelchairs are two-wheel drive and cannot move sideways, which was the main reason that Mecanum wheels were chosen for the moving vehicle of the iRW.

Figure 2 shows the Mecanum wheels, which were invented by Swedish engineer Ilon in 1973 [17]. Around the wheel’s tread are several barrel-shaped free rollers arranged at an angle of 45 degrees to the main axis, which enable omnidirectional movement without using a classic steering mechanism. Mecanum wheels are commonly used where manoeuvrability is necessary in tight spaces, as with autonomous forklifts. Mecanum wheels also see applications in robots [18, 19] and electric wheelchairs [20]. One disadvantage of the Mecanum wheel is its energy consumption. Due to the rotation of the exterior rollers, only a component of the force at the perimeter of the wheel is applied to the ground [21]. The other shortcoming is that Mecanum wheels are susceptible to slippage. As a result, with the same amount of wheel rotation, lateral travelling distance may differ from longitudinal travelling distance, according to the ground condition [22].

The moving vehicle of the iRW uses four Mecanum wheels, one on each corner of the chassis, driven by four DC motors. Figure 3 shows how the components of the force vectors at every wheel sum up or eliminate each other by rotating either clockwise or anticlockwise to obtain the desired moving direction.

![Figure 2. Free rollers in a Mecanum wheel at 45 degrees to the main axis](image)

![Figure 3. Combined force vectors in a set of Mecanum wheels](image)
iRW can also manoeuvre sideways to the left/right or rotate clockwise/anticlockwise. When older adults use manual or power wheelchairs indoors, there is an inverse relationship between age and preferred movement speed [23, 24]. Tolerico et al. [23] found that the speed of manual wheelchair users is 0.79 ± 0.19 m/s, and Karmarkar et al. [24] indicated further that the speeds of manual and electric wheelchair users are 0.64 ± 0.13 m/s and 0.7 ± 0.3 m/s. Based on these results, the maximum forward speed of the joystick mode of the iRW is set at 50 m/min, which is close to the walking speed of older adults, and the maximum backward speed and sideways speed are set at 40 m/min and 25 m/min, respectively. To foster operating safety and promote user comfort, teleoperation and indoor navigation modes are set at a constant speed of 15 m/min, which is below the lowest manual operation speed suggested by Karmarkar et al. [24].

| Item                              | Specification |
|-----------------------------------|---------------|
| L×W×H                             | 800×610×300 mm |
| Forward speed                     | 50 m/min (Max) |
| Backward speed                    | 40 m/min (Max) |
| Sideways movement, clockwise/anticlockwise speed | 25 m/min |
| Speed of the teleoperation and indoor navigation | 15 m/min |
| Mecanum wheel diameter            | 25.4 mm (10 inches) |
| Voltage/Current of the motor      | 24V/3A (Max) |
| C-LiFePO4 Battery                 | 24 V, 9.6 Ah, 400×133×72 L×W×H (mm), 3.4 kg |

Table 1. Specifications of the moving vehicle of the iRW

3. Mobility assistance design for different operators of the iRW

Figure 4 shows a prototype of the iRW. Three "operators", the wheelchair user, caregivers, and the iRW itself, are considered in the mobility assistance design for the iRW. Five operation modes are developed:

1. Obstacle avoidance
   The obstacle avoidance uses the concept of the man-machine collaborative control to reduce the operation load and increase the safety for the iRW's users. When the iRW's ultrasonic sensors detect an obstacle within a specific distance (10 cm), the iRW stops all motion and alerts the user with a beeping sound. The user can override the stopping command using joystick mode or handlebar mode.

2. Joystick mode
   The joystick mounted on the right armrest of the iRW is the main operation mode used by the wheelchair user. The joystick includes three variable resistors that detect the movement of the joystick forward/backward to produce movement in that direction, left/right to produce sideways movement in that direction, or rotation clockwise/anticlockwise to produce rotation in that direction. Turning movement can be produced if the variable resistors detect forward and left/right movements of the joystick simultaneously. Releasing the joystick will cause the iRW to immediately stop.

3. Handlebar mode
   The handlebar mode is designed for a caregiver wishing to push the iRW. The diameter of the Mecanum wheels makes the iRW more difficult to push than a manual wheelchair. To enable the caregiver to push the iRW in an intuitive way, three soft pressure-sensing pads are implemented on the handlebar of the iRW, as shown in Figure 4. The caregiver can push the iRW to move forward, move backward, turn right, or turn left by applying pressure to the appropriate pressure pads. If equal pressure is applied on the right and left pads, the iRW will move forward; if greater pressure is applied on the right/left pads, the iRW will turn right/left. When pressure is applied on the middle pressure pad, the iRW will move backward. Pressing a button on either side of the handlebar will cause the iRW to move sideways in the direction of that button.

4. Teleoperation
   Teleoperation mode is designed for a caregiver to operate the iRW from a remote site. In teleoperation mode, the camera of the tablet PC mounted on the iRW's armrest captures its environment, and a remote-control interface enables a caregiver at a remote site to view it. The caregiver can then operate the iRW by sending commands via the Internet to the tablet PC, which relays the commands to the central microcontroller via Bluetooth to guide the iRW to move to the desired location.

5. Indoor navigation
   A semi-autonomous indoor navigation mode uses a concept similar to automated guided vehicles (AGVs) to reduce the operation load of the wheelchair user or care givers. QR code (Quick Response code) landmarks are deployed on the...
Man-machine collaborative control is reflected in the assignment of three “operator priorities” (in descending sequence): the wheelchair user, caregivers, and finally the iRW itself. The functional test performed in this research compared the operational efficiency of the five operation modes.

Man-machine collaborative control of the iRW is reflected in the assignment of three “operator priorities” (in descending sequence): the wheelchair user, caregivers, and finally the iRW itself, to avoid different modes’ disrupting each other and fosters safety. Following this principle, the five operation modes are assigned the following precedence (in descending order): obstacle avoidance, joystick mode, handlebar mode, teleoperation, and indoor navigation. Emergency modes such as obstacle avoidance might be needed at the shortest notice and therefore were assigned the highest priority. The manual control modes give the highest control priority to the wheelchair user (joystick mode), next highest to the caregiver at the local site (handlebar mode), then to the caregiver at the remote site (teleoperation mode). Indoor navigation mode receives the lowest priority. The higher-priority modes can interrupt the lower-priority ones. Figure 5 illustrates the control scheme of the five operation modes.

4. Space utilization assessment

According to the Wheelchair Skills Test (WST), “90° left/right turn”, “turns 180° in place”, and “manoeuvres sideways” are the skills directly related to changing directions of movement of the wheelchair for daily needs [25, 26]. The turning space is used here to assess and compare space utilization of the iRW with that of ordinary electric wheelchairs.

The specifications for 16 models of electric wheelchairs commercially available in Taiwan were examined. Their average size was 910×640 mm (L×W) and the turning radius ranged from 500 mm to 800 mm. The size of the iRW is 800×610 mm (L×W) and its turning radius is 0 mm. Additionally, the iRW can move sideways, unlike the 16 electric wheelchairs.

Figure 6 and Table 2 show the details of the calculation of the turning space required by the electric wheelchairs for “90° left/right turn” and “turns 180° in place”. For “turns 180° in place”, an electric wheelchair may need a space of up to 2m×2m. In contrast, the iRW can make a 180° turn within a 1 m×1 m space (i.e., a circle of diameter 1 m).

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**Figure 5.** Flow chart showing priority and processing of the operation modes

**Figure 6.** The turning space of commercial electric wheelchairs and the iRW

**Table 2.** The calculation of the turning space

“Transfer activities” involve moving to the transfer target and moving the user’s body from one surface to another,
such as from the wheelchair to a treatment table, a regular bed, a tub/shower bench, a toilet, or a car seat, and vice versa [26, 27]. The capability of the iRW to move sideways allows it to use much less space for transfer activities than ordinary electric wheelchairs.

Figure 7 shows the enlarged individual toilet room for a barrier-free lavatory recommended by the “Americans with Disabilities Act Accessibility Guidelines (ADAAG) for Buildings and Facilities” [28]. The turning space is defined as a circle of minimum diameter 60 in. (1,524 mm) for wheelchairs to turn 180°, designated by the outer dashed circle, which is smaller than the turning space required by electric wheelchairs in Table 2. Figure 7, the standard positions for toilet transfer are position 1 (the side approach) and position 2 (the reverse diagonal approach). Position 3 is for using the sink. The minimum clear floor space is 1,524×1,422 mm² for the toilet, and 762×1,219 mm² for the sink. As shown in Figure 7, the turning space of the iRW is a circle of diameter 1 m. It can be easily turned and moved from one position to the other, for example, sideways directly from position 2 to position 3.

![Figure 7. The recommended enlarged individual toilet room for a barrier-free lavatory](image)

5. Functional test of the operation modes by healthy young adults

A functional test was conducted to compare the operational efficiency of the five operation modes of the iRW.

Figure 8 shows the user interface of teleoperation mode. The caregiver at the remote site enters the IP address to connect to the tablet PC on the iRW. The user can then see the image captured by the camera of the tablet PC. The teleoperation user interface has seven operation commands to control the movement of the iRW: moving forward or backward, sideways to the right or left, rotating clockwise or anticlockwise, and stopping. Note that there is no command for turning in teleoperation mode. Turning right/left is achieved by the commands stop, rotate 90°, then move forward.

![Figure 8. The teleoperation user interface](image)

Figure 9 is the interface for setting up the virtual AGV track for the navigation mode. The navigation route map (Figure 9, left) is mapped to the virtual AGV track on the interface (Figure 9, right). The user can pick target stops (orange circles representing Stops 1, 2, 3, and 4) and the paths connecting the stops (orange lines) based on their relative positions, without considering real distances. Names of the stops (such as “Office”, “Laboratory”) can also be defined by the user. The intermediate stops (yellow circles) will be generated automatically, and a QR code is generated for each stop. The user can then print the QR codes and deploy virtual AGV tracks by simply sticking the QR code landmarks on the corresponding positions of the target stops and intermediate stops on the ceilings.

![Figure 9. The interface for defining the virtual AGV track](image)
in Figures 9 and 10), and start indoor navigation by pressing the “Start” button.

![Figure 10](image.png)

**Figure 10.** The user interface for indoor navigation

To compare the operation efficiency of operation modes, the functional test measures the operation time from Position 1 to Position 4 as shown in Figure 9 using joystick mode, handlebar mode, teleoperation mode, and indoor navigation. The total distance of the testing route was 46.40 m. Five healthy adults (three male and two female) participated in the test. The average age of the testers was 23.0 years old, and none of them had previous experience operating an electric wheelchair. Referring to Figure 9, the steps of the test were as follows.

1. A tester spent five minutes familiarize himself/herself with the various operation modes.
2. With the iRW at Position 1, the tester used indoor navigation mode to transport himself/herself automatically from Position 1 to Position 4.
3. After the experimenter repositioned the iRW to Position 1, the tester used joystick mode to manoeuvre the iRW from Position 1 to Position 4.
4. After the experimenter repositioned the iRW to Position 1, the tester used handlebar mode to push the iRW from Position 1 to Position 4.
5. After the experimenter repositioned the iRW to Position 1, the tester used teleoperation mode to move the iRW from Position 1 to Position 4.
6. Steps 3 to 5 were repeated three times.

Each operation mode was set to the same speed as that of indoor navigation mode. The time required for each round was measured. The time required for indoor navigation mode was almost the same for all testers (an average of 194.2 seconds, with standard deviation of 1.3 seconds) and was used as the “standard operation time” in this test when estimating operation efficiency. The operation efficiency of a given operation mode was defined as the ratio of the “standard operation time” to the average operation time of the given operation mode. When the operation efficiency was less than 1, testers took longer to arrive at the desired location using the given operation mode than using indoor navigation mode.

Table 3 shows the operation efficiency of each mode in this test. As expected, teleoperation mode has the lowest efficiency. Although all of the testers were familiar with the environment, they paused frequently when operating the iRW from the limited view obtained from the camera of the tablet PC. The operation efficiency of teleoperation mode increased steadily from Round 1 to Round 3, showing a good learning effect of the operation modes. However, the learning effect from Round 1 to Round 3 was not significant statistically ($p=0.24 > \alpha=0.05$).

The operation efficiency of joystick mode was slightly higher than 1. The testers quickly became proficient with the joystick, even though none of them had any experience operating an electric wheelchair. The standard deviation is the largest among the operation modes. As in the teleoperation mode, the operation efficiency of the joystick mode increased steadily from Round 1 to Round 3, although the learning effect was not significant statistically ($p=0.44 > \alpha=0.05$). In this test, the motor control speed of all operation modes was set to be the same. In actual practice, the speed in joystick mode can be controlled by the wheelchair user, and the maximum speed could be set higher than that of indoor navigation mode, which would increase the operation efficiency of joystick mode.

The operation efficiency of handlebar mode was the highest among the operation modes. The learning effect of handlebar mode from Round 1 to Round 3 was statistically significant ($p=0.027 < \alpha=0.05$), indicating that caregivers should find it easiest to become accustomed to “pushing” the iRW using the handlebar mode. As with joystick mode, the efficiency of handlebar mode is expected to increase when the speed is set higher in practice.

|                  | Indoor navigation | Joystick mode | Handlebar mode | Teleoperation |
|------------------|-------------------|---------------|----------------|---------------|
| Round 1          | 1                 | 1.09          | 1.34           | 0.76          |
| Round 2          | 1                 | 1.11          | 1.37           | 0.80          |
| Round 3          | 1                 | 1.14          | 1.39           | 0.83          |
| Average efficiency | 1                 | 1.11          | 1.37           | 0.80          |
| Standard deviation | 0.16              | 0.13          | 0.06           |

Table 3. The operation efficiency of operation modes

6. Usability comparison between the iRW and manual wheelchair

Since manual wheelchairs are the most common mobility assistive device adopted by older adults with impaired mobility, it is necessary to compare the usability of the iRW against that of a manual wheelchair. Six healthy participants (four males and two females, with an average age of 22.8) were recruited to conduct the user evaluation. In order to simulate the reduced ability of
older adults, each participant was asked to wear a pair of thick gloves made of cotton to reduce touch, and a pair of knee pads and 1.5 kg sand bags to constrain mobility of the legs.

In this utility evaluation, the participants are requested to do the same tasks by using both the iRW and a manual wheelchair. The tasks include basic movements that a wheelchair user performs in the home environment, such as making turns, crossing a narrow passage, and passing through a door with a threshold following a predefined route. The steps of the evaluation are described below:

1. Spending five minutes to become familiar with the operation of the iRW or the manual wheelchair
2. Steering the iRW or the manual wheelchair to turn right, turn left, and then pass through a narrow passage (120 cm wide and 300 cm long) on the predefined route
3. Steering the iRW or the manual wheelchair to cross the threshold (2.5 cm) and enter the restroom
4. Steering the iRW or the manual wheelchair to move as close as possible to the toilet
5. Steering the iRW or the manual wheelchair to leave the restroom and return to the initial position.

After finishing the tasks, the participant was asked to fill in a questionnaire to collect the subjective responses to the use of the iRW and the manual wheelchair. In this study, the 5-point scale is used for user satisfaction (1=very dissatisfied; 5=very satisfied) regarding the mobility functions of the iRW. The 10-point scale is adopted to measure subjective fatigue (1=no fatigue; 10=total fatigue) while using the iRW or the manual wheelchair.

The operation times required for the iRW and the manual wheelchair were measured and compared. Figure 11 shows the average operation time for each of the Steps 2-5. In Step 2, the participant took a significantly longer time to pass through the narrow passage in the iRW (p=0.0002 < α=0.05). For Steps 2 to 5, the operation times are not significantly different between the iRW and the manual wheelchair. (Step 2: p=0.06 > α=0.05; step 3: p=0.28 > α=0.05; step 4: p=0.38 > α=0.05).

Nevertheless, based on the subjective responses, the participants generally felt less fatigued while operating the iRW than the manual wheelchair. The participants reported very low fatigue (<3.0) for all body parts while operating the iRW. They felt most fatigue at the right wrist (2.7). For the manual wheelchair, the participants reported a higher fatigue (>3.0) for all body parts except the abdomen (1.2) and the calves (2.8). The most-fatigued body parts were shoulders, forearms, and wrists (5.8). In addition, while using the iRW, the participants were satisfied with the user interface by using the joystick (average score=4.5) and the sense of security during the forward/backward movements (average score=4.0).

Figure 11. The average operation time of each step

7. Conclusions

This paper presents the development of the “intelligent Robotic Wheelchair” (iRW). Mobility assistance functions of electric wheelchairs are usually designed for the wheelchair user alone. Most research in robotic wheelchairs has focused on developing autonomous behaviour to assist wheelchair users. In real application scenarios, caregivers also play an important role in assisting wheelchair users. In this research, three “operators”, the wheelchair user, caregivers, and the autonomous behaviour of the iRW, are considered in the mobility assistance design for the iRW.

The moving vehicle of the iRW is equipped with four Mecanum wheels to facilitate movement in all directions and zero radius of rotation. From the results of the space utilization assessment, the iRW requires much less space than general electric wheelchairs in manoeuvres such as “90° left/right turn”, “turns 180° in place”, and “manoeuvres sideways”.

Based on this moving vehicle, five operation modes are developed for the three operators: obstacle avoidance, joystick mode, handlebar mode, teleoperation, and indoor navigation. From the functional test results, the handlebar mode has the highest operation efficiency, followed by the joystick mode. The teleoperation mode has the lowest operation efficiency.

The priorities are assigned to the operation modes to avoid different modes disrupting each other and foster safety. Top priority is assigned to the emergency modes such as obstacle avoidance. Priorities are then assigned according to the operators of the modes (in descending sequence): wheelchair user, caregiver, and finally the iRW itself. In addition to the operation modes of the moving vehicle, the operation modes of the multiple DOF seat adjustment mechanism of the iRW, achieved by a four-axis Stewart Platform, also receive operation priorities following the same order. The same principle will be used
to assign operation priorities if new operation modes are added to the iRW in the future.

The iRW is intended to be an advanced technical solution for mobility assistance for older adults and their caregivers. A long-term field test of the iRW in a nursing home is taking place to obtain feedback on the functionality and usability of the iRW.

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