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Intelligent Wheelchair Robot “TAO Aicle”

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1. Introduction

Non-motorized manually operated wheelchairs are widely utilized in hospitals, welfare facilities, etc., to transport physically handicapped and elderly patients. Typically, these wheelchairs require the presence of healthcare staff who are burdened with actually moving the wheelchairs. To reduce the burden on staff in such facilities, we have developed a motorized wheelchair with autonomous traveling capability by applying robotics and mechatronics technologies. We believe that our research results will be useful for reducing the physical labor of the care workers and also promote the independence of the wheelchair users.

In previous research, intelligent wheelchairs with autonomous traveling capability guided by a vision system, laser range finder, etc. have been developed and demonstrated to a limited extent (Mori, 2005) (Adachi, 2003). However, such wheelchairs are not practical due to problems of safety, reliability, high cost, etc.

In this chapter we introduce an intelligent wheelchair with autonomous traveling capability called the “TAO Aicle”. This wheelchair can accurately determine its position and direction using internal sensors and assistance from the surrounding environment including the Global Positioning System (GPS) and Radio Frequency Identification (RFID). To assure safe travel, we utilize assistance from environment, especially RFID, which is a distinctive characteristic in this research. Regarding autonomous navigation of mobile robots using RFID information in the environment, some research studies have been reported (Hahnel, 2004) (Tsukiyama, 2003) (Yamano, 2004). In those studies RFIDs were attached to walls at specific points such as destinations. When the mobile robot approaches the RFIDs, it detects them and knows that it has reached its destination. This use seems to focus on identifying a place of arrival. In our system the position information is provided by RFID and the wheelchair uses it directly for its trajectory control. As the similar research, in indoor environment, the mobile robot can travel using the position information from passive RFID tags in the floor and active RFID tags on the ceiling (Kim, 2006). In this research the robot needs RFID tags arranged in the high density for precise positioning.

On the other hand, in our research, we propose a position compensation method using the position information including the RFID tags which are locally arranged in the surface of a road. We also confirm the effectiveness of this compensation method by the high performance of the trajectory following (Matsumoto, 2006).

To confirm the effectiveness of our research results, we demonstrated "TAO Aicle" by offering trial rides to visitors at the Aichi Expo 2005 for six months (from 25th Mar. to 25th Sep. in 2005) (Hatase, 2006).
In this chapter the total system of "TAO Aicle" and the positioning method using GPS and RFID are introduced. An autonomous traveling control method based on the estimation of position and direction using a Kalman filter is proposed. The characteristics of trajectory following are discussed and the demonstration experimental results at the Aichi Expo are reported.

2. Total system of autonomous travelling service using intelligent wheelchair

Figure 1 shows the system configuration of the experiment system that was constructed at the EXPO site. Wheelchairs and servers are continuously connected via wireless LAN. Positioning data and wheelchair status data are sent from TAO Aicle to servers, and map data, route data, and position-related information data are sent from the server to each TAO Aicle. On the server display the position of each wheelchair can be monitored and important status information, such as battery power remaining, can also be monitored. The intelligent functions of TAO Aicle are thus realized not by the robot itself but through interaction with the infrastructure and servers. Figure 2 shows a part of outdoor traveling course of TAO Aicle constructed beside the building at the EXPO site.

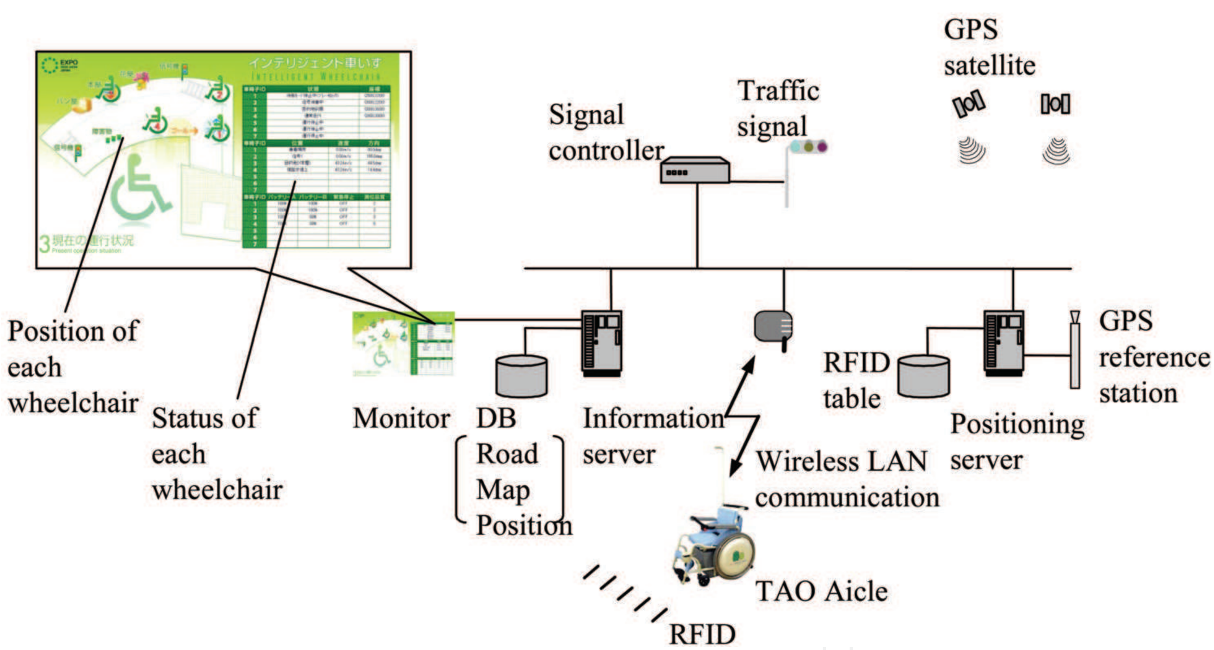

Fig. 1. Total System of autonomous traveling service using intelligent wheelchair

3. Intelligent wheelchair robot "TAO Aicle"

TAO Aicle is an improved version of the currently commercially available "TAO Light II" electric motorized wheelchair manufactured by Aisin Seiki Co., Ltd. Figure 3 is an overview of TAO Aicle showing the wheelchair hardware, internal and external sensors, computers, etc. to allow autonomous traveling. TAO Aicle was designed and manufactured using lightweight frames and driving units (motors, encoders, magnetic brakes and batteries). The frames are reinforced versions of those used in "TAO Light II" to withstand the frequent use of the trial rides. Also the capacity of the batteries was increased by assigning one battery to computer power and the other one to motor driving power. The long stick-like object installed at the back of the wheelchair is a GPS antenna, with which the robot can accurately determine its position using GPS. A laser range sensor is installed at the front-right, with which the robot can detect obstacles in front of it. User interface equipment (Safety Information Provision Terminal) is installed at the front end of the right armrest. For the safety of users, emergency stop button, wheelcovers, anti-tipover and seatbelt are installed.

Fig. 2. Course panorama

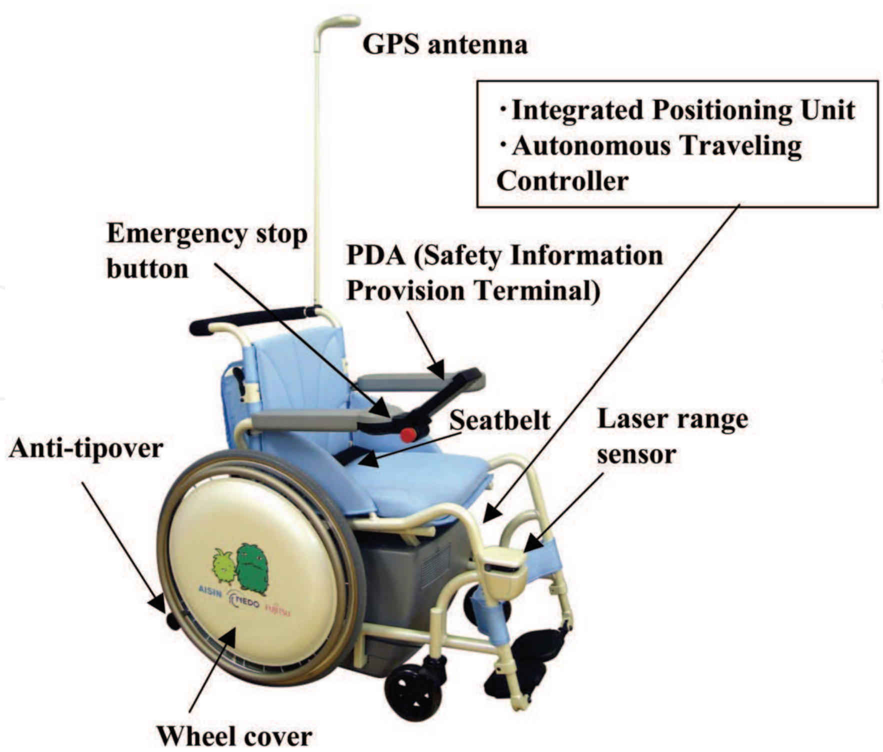

Fig. 3. Intelligent wheelchair robot TAO Aicle

Table 1 shows the specification of TAO Aicle. The right and left wheels are driven by DC servo motors with reduction gears, which is the same drive system as used in "TAO Light II". Each wheel is controlled independently so that the steering is controlled by the difference of the rotation angle between the right and left wheels. The overall wheelchair size is approximately the same as "TAO Light II" exclusive of the GPS antenna. The total weight is approximately 40 kg which is twice as heavy as "TAO Light II". The power source is a lithium-ion battery and the operating time with a full charge is approximately 3 hours. The traveling speed is potentially more than 6 km/h, however we limited the maximum speed to less than 2 km/h for safety demonstrations at the Aichi Expo site.
TAO Aicle consists of the following sub-systems. The assistance systems from the environment are shown in the next section.

Driving System	DC servo motors (90[W])x 2
Size (Length x Width x Height)	940 [mm] x 640 [mm] x 870[mm] (Height of GPS antenna: 1500 [mm])
Sensors	Rotary encoder x 2, GPS receiver, RFID reader, Directional compass, Laser range sensor
Total weight	40 [kg]
Battery	Lithium-ion Battery (24 [V], 6 [Ah]) x 2
Traveling speed	2 km/h (at Aichi Expo site)

Table 1. Specification of TAO Aicle

3.1 Autonomous traveling controller

The Autonomous Traveling Controller is a control unit driving the right and left wheel motors and includes a board computer (CPU, AD/DA converters and counter) and motor amplifiers. Using communication with the Integrated Positioning Unit, it recognizes the wheelchair's absolute position and direction based on GPS, RFID tags and a directional compass. Combining the above absolute information and the calculated position and direction using the integration of rotary encoder signals attached to the right and left wheels, the Autonomous Traveling Controller can estimate the accurate position and direction of TAO Aicle. The estimation method is described in section 5. The trajectory following control system and the speed control system to ensure safe stops and smooth starts are also installed. Moreover, various functions, such as obstacle detection using a laser range sensor, trajectory generation for obstacle avoidance, and the control algorithm for detecting and avoiding a fixed obstacle and stopping when confronted by moving obstacles, are also installed on the Autonomous Traveling Controller. With these features, TAO Aicle can follow the designed path accurately and achieve safe and comfortable traveling.

3.2 Integrated positioning unit

The Integrated Positioning Unit integrates the positional information of GPS and an RFID reader, and the directional information of a directional compass. It provides the information to the Autonomous Traveling Controller. To function with other units, it includes interface software to the Autonomous Traveling Controller and Safety Information Provision Terminal, and wireless communication software to an access point as well as a coordinate function with a positioning server.

3.3 Safety information provision terminal

The Safety Information Provision Terminal is a user interface attached to an armrest on TAO Aicle. The basic hardware is Fujitsu's PDA (Pocket LOOX), but it has been customized to suit the operation of this wheelchair. Not only can the user select destinations with the PDA's touch panel, but also access a range of information provided in the form of images and spoken words. It also includes terminal software for the interface to the integrated positioning unit and wireless communication to an access point.

4. Assistance system for intelligent wheelchair robot

For the demonstration at the Aichi Expo site, we prepared assistance system to allow safety traveling of TAO Aicle. In this section, we introduce typical asistance systems, GPS, RFID and information provision server.

4.1 GPS

In order to travel accurately along the planned route, and in order to provide useful and timely information to users, accurate positioning is indispensable. TAO Aicle can determine its position and direction based upon the amount of wheel rotation. This is referred to as the "dead reckoning method." However, this method can lead to measurement errors accumulating in the integrated value. This means it is necessary to frequently receive absolute values (position and direction). One method is using GPS positioning. TAO Aicle has an accurate GPS receiver and can establish its own absolute position precisely. At the EXPO site, we installed a GPS reference station near the demonstration course in order to improve the positioning accuracy using the DGPS method.

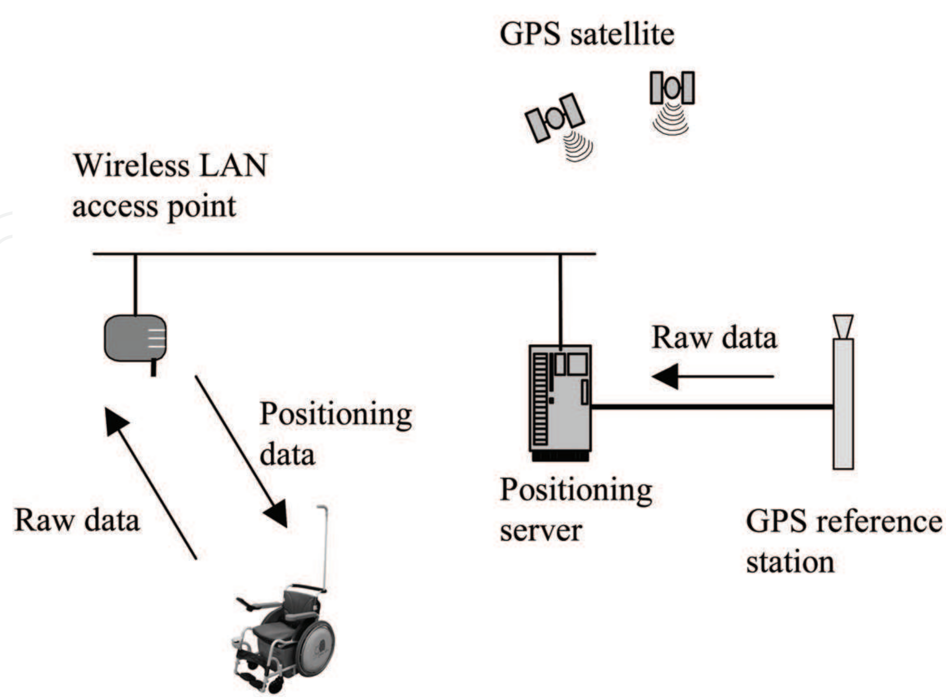

Fig. 4. Positioning mechanism using GPS

Figure 4 shows the system for accurate positioning using GPS. A rover receiver installed on TAO Aicle is connected to a positioning server via a wireless LAN access point. The rover receiver sends raw data to the positioning server every second. The positioning server receives the raw data from rover receivers and also receives data from a reference station which is installed nearby. The server calculates all receivers' accurate positions in real time and sends the positioning data to TAO Aicle. Accurate positioning is achieved by processing not only L1 code data but also carrier phase data. DGPS and RTK calculations are performed on the positioning server.

4.2 RFID

It is not possible to use GPS for indoor positioning. Even when outdoors, if the GPS sensor is too close to buildings, it is difficult to get accurate position information. For positioning, we propose the use of RFID (IC tags), which are being used recently to identify products in stores.

TAO Aicle has an RFID reader with an antenna installed under the seat. During operation it can read the RFIDs that are installed under the flooring panels. Each RFID has a unique code and the code can be converted into position data by referring to a database positioning table. Figure 5 shows the RFID that was actually used in the demonstration course at the EXPO site. The floor of the course was made of rubber blocks (Eco-rock) made from waste rubber material, each sized 10 x 20 x 5 cm. We installed a number of RFIDs under the rubber blocks along the course. An image of the actual landmark is shown in Fig. 5.

Fig. 5. Structure of RFID landmark

The antenna and RFIDs are shown in Fig. 6. This passive type RFID is a product of Fujitsu Limited, and it has a frequency of 13.56 MHz (ISO15693 Standard). The RFID antenna is also from Fujitsu Limited and it is a middle range type antenna. Figure 7 shows cross sections of the antenna's detection area in orthogonal vertical planes. These areas were experimentally measured by changing the relative position between the RFID and the antenna three dimensionally while keeping their faces parallel. There is a central detection space whose shape is an ellipsoid. The main detection space is surrounded by a sub-space as shown in the figure. When the distance between the RFID and the antenna is short, for example 5 cm, the detection area is relatively large. For the stable detection, the distance between the RFID and the antenna should be between 10 to 25 cm, and in this case the size of the detection area is about 20 x 30 cm. If one RFID is used, the positioning resolution is approximately the size of the antenna. When multiple RFIDs are detected simultaneously, the resolution of the positioning can be decreased by averaging the detected position data. As the maximum number of simultaneous RFID detections by the antenna is 16, it is possible to refine the resolution by arranging the RFIDs on the floor. In our localization experiment in which the antenna moves over arrayed RFIDs that are spaced at 90 mm intervals, the antenna detects one to three RFIDs by the antenna size (300 x 214mm) simultaneously and the deviation of the positioning is about 40 mm — less than half of the 90 mm spacing interval. This result indicates that the detection of multiple RFIDs helps to refine the positioning resolution. The RFID detection rate is about 5 Hz. While the antenna is moving attached to the wheelchair, it will not miss detecting an RFID inside the detection area.

We designed a RFID landmark for TAO Aicle to move over and get the positioning information, as well as to be able to change the course easily. The RFID landmark consisted of multiple RFIDs set perpendicular to the course at regularly spaced intervals. From a comparison of the antenna size and the size of the Eco-rock, the maximum number of simultaneous detections of RFIDs is about four and the positioning error is about 5 to 10 cm depending on the direction of measurement.

Fig. 6. RFIDs and antenna

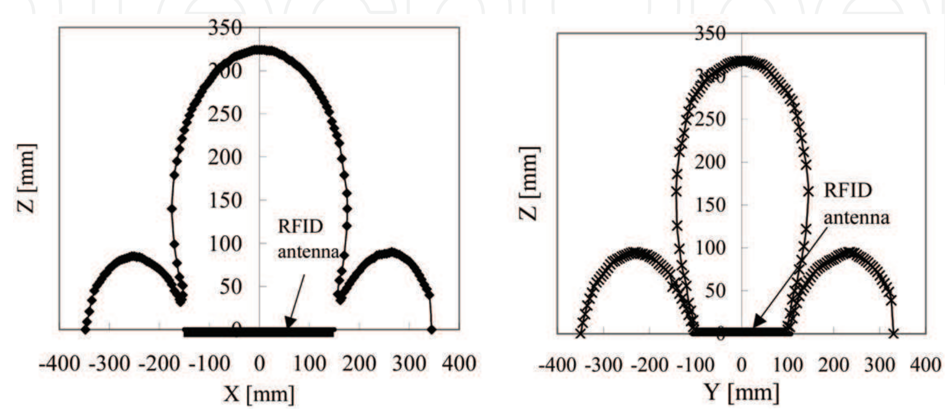

Fig. 7. Detection area of RFID antenna

4.3 Information provision server

For users of an intelligent wheelchair, information provision is indispensable. It starts, stops, and turns automatically according to various conditions. Other than in an emergency, users do not generally control the wheelchair, and if there is insufficient information, users may become uneasy. Examples of information that is currently provided is as follows:
- "The wheelchair is crossing a road."
- "The wheelchair will make a left turn soon."
- "You have arrived at the destination."

Each piece of information is provided at the moment the wheelchair reaches a specified position. LBS (Location-Based Service) technology can be used to achieve this. Fujitsu Limited had already developed a tourist information system and demonstrated this at a famous tourist resort in Kyoto in 2003 (Hatase, 2003). We applied the same technology used in the tourist information system to TAO Aicle.

Figure 8 shows a block diagram of the information provision system, and Figure 9 shows the terminal device screen. Information for users is provided by images and voice, displayed on the terminal device and transmitted by a speaker. When TAO Aicle is moving normally, the information on the screen shows mainly wheelchair conditions, such as speed, direction, and battery status (Figure 9(a)). On the other hand when it performs a particular action, the information on the screen shows the present situation or reason for the action (Figure 9(b)). The voice information tells users what the wheelchair is doing or what it will do next. The terminal device continuously receives accurate positioning data from the integrated positioning unit, enabling the terminal to play the appropriate voice data promptly when the wheelchair comes to a predetermined position.

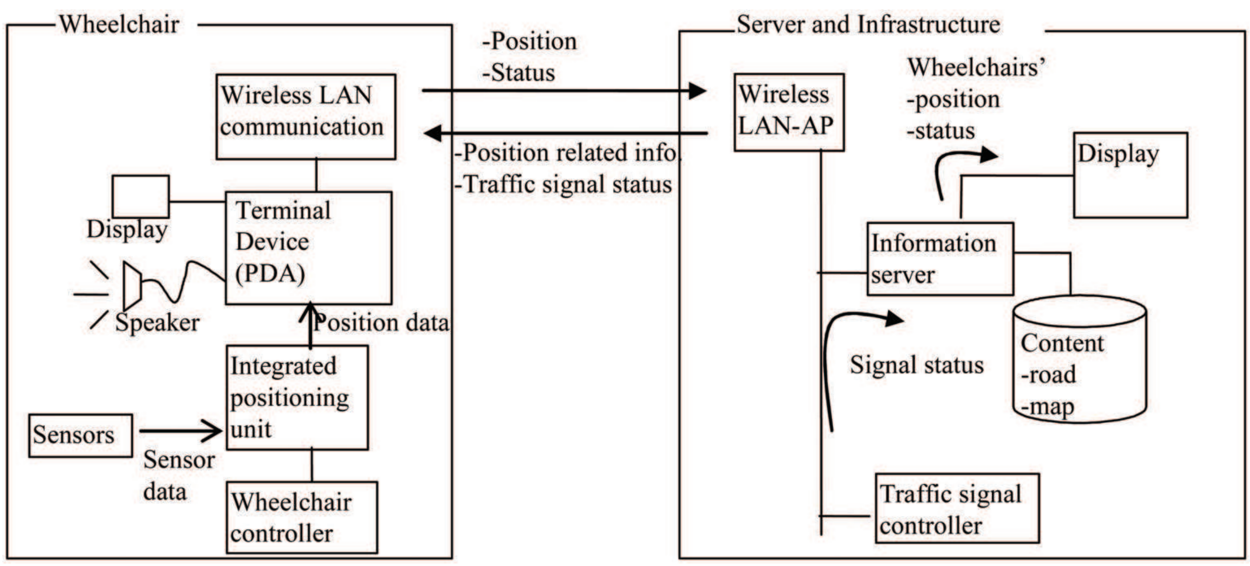

Fig. 8. Block diagram of information provision

The primary role of the information server is to store as much information as is necessary for controlling the wheelchair and to provide information to the user. The server retains information on the condition of relevant roads and shows each road's availability. At the request of the wheelchair controller, the server transmits this availability information to the wheelchair controller via the terminal device. The controller determines the route taking each road's availability into account. The server also returns the position-related information that is necessary for each wheelchair. The wheelchair terminal provides this information to the user according to the wheelchair's position. The traffic signal status is sent from the signal controller to the server and is then immediately sent to the wheelchair controller. Using the signal status data, the wheelchair can stop when the signal is red. The secondary role of the server is to monitor each wheelchair's position and status. It receives each wheelchair's status data continuously and displays this on an area map. Monitoring personnel can easily ascertain each wheelchair's situation and are immediately made aware of any emergency, should one occur.

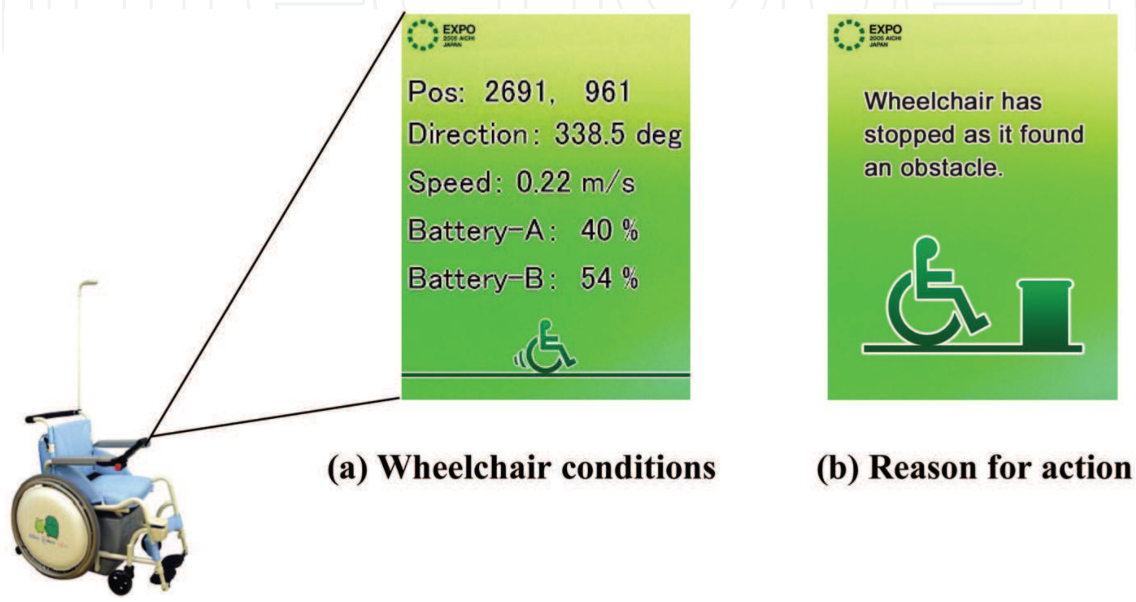

Fig. 9. Example of safety information provision terminal screen

5. Positioning method using GPS, RFID and directional compass

To achieve accurate trajectory following, the accurate present position and direction of TAO Aicle wheelchair are necessary. In our experimental setup, the position information from GPS was sent to the controller every second, while the position information from the RFIDs was sent to the controller when TAO Aicle passed over the RFIDs. To integrate the position (x, y) and the direction θ by dead reckoning using the rotary encoders of the right and left wheels, the direction θ from the directional compass and the position (x, y) information from GPS and the RFIDs, we constructed an estimating system for (x, y, θ) using a Kalman filter. Equation (1) shows the calculation of (x, y, θ).

$$\boldsymbol{x}_{fk} = \tilde{\boldsymbol{x}}_k + \left(\boldsymbol{X}_k^{-1} + \boldsymbol{Q}'^{-1}_s\right)\boldsymbol{Q}'^{-1}_s \hat{\boldsymbol{x}}_s \quad (1)$$

$\boldsymbol{x}_{fk}$: Calculated state vector (x, y, θ) using a Kalman filter

$\tilde{\boldsymbol{x}}_k$: State vector calculated from dead reckoning

$\boldsymbol{X}_k$: Error variance matrix of dead reckoning

$\boldsymbol{Q}'_s$: Error variance matrix of external sensors (RFID, GPS and directional compass)

$\hat{\boldsymbol{x}}_s$: State vector of the difference of (x, y, θ) between dead reckoning and external sensors

6. Autonomous travelling control

Our trajectory following control includes a Kalman filtering method for compensating position and direction using position information from GPS and RFIDs as described in the previous section. We adopted the conventional trajectory following method which is shown in Fig. 10 using eqs. (2)(3)(4). If the closest point on the planned path to the wheelchair is determined considering the present position and direction of the wheelchair, the reference velocities of the right and left wheels are calculated using eqs. (2)(3)(4). A velocity feedback control system is installed in the low-level controller to achieve the trajectory following control.

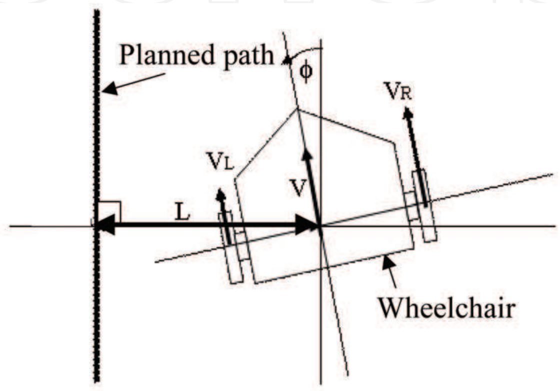

Fig.10. Trajectory following control method

Figure 11 shows a block diagram of this autonomous traveling control system including accurate positioning method using Kalman filter.

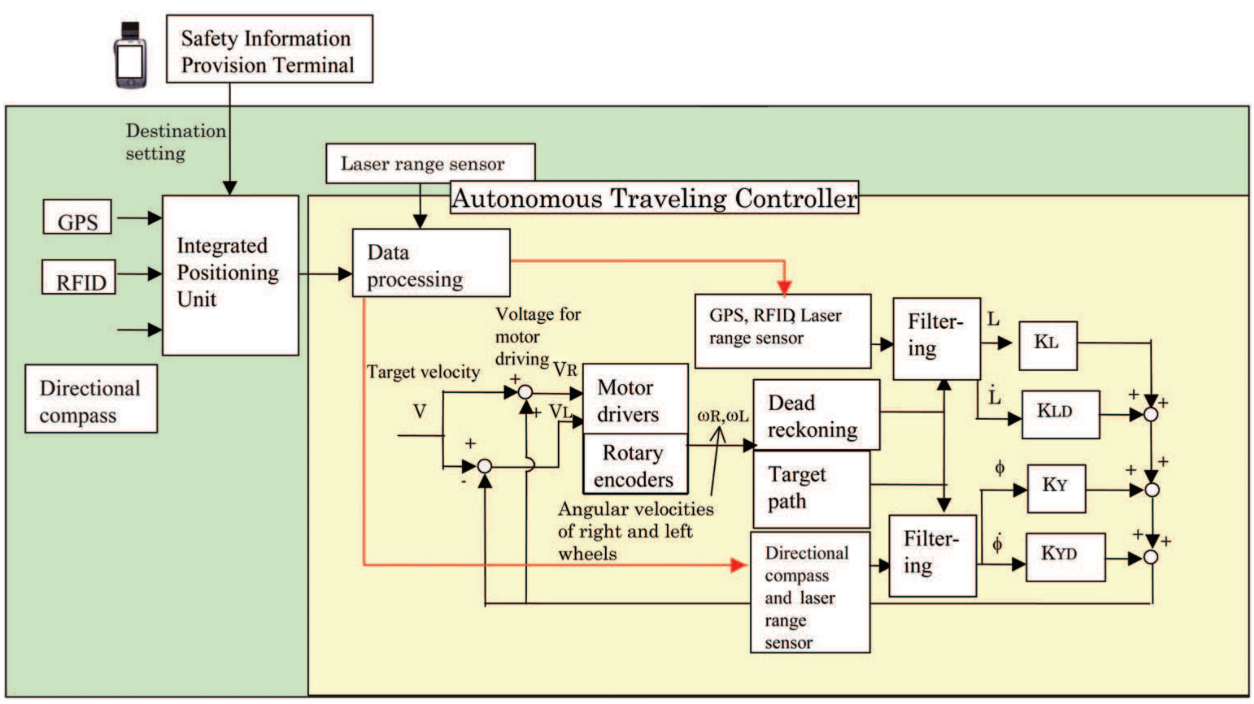

Fig.11. Block diagram of autonomous traveling control

$$V_R = V + \Delta V \tag{2}$$

$$V_L = V - \Delta V \quad (3)$$

$$\Delta V = K_L L + K_{LD} \dot{L} + K_Y \Phi + K_{YD} \dot{\Phi} \quad (4)$$

V: Target traveling velocity of wheelchair
V_R: Target velocity of right wheel
V_L: Target velocity of left wheel
L: Minimum distance between the wheelchair center and target path
Φ **:** Angle between the wheelchair yaw-direction and tangent direction of the closest point on the target path
K_L, K_{LD}: Feedback gains for position and velocity of minimum distance between the planned path and the wheelchair position
$K_Y K_{YD}$: Feedback gains for angle and angular velocity between the direction of planned path at the closest point to wheelchair and the wheelchair direction

7. Evaluation result of GPS positioning in Aichi Expo. Site

Figure 12 shows the GPS positioning result obtained during the test drive experiments. The solid line shows the position of TAO Aicle calculated in the controller and the dots show the calculated position based on GPS. In this test drive, the wheelchair left the starting point for the destination and after stopping at the destination it returned to the starting point. It crossed the crosswalk twice and avoided a fixed obstacle on the way. In Fig. 12 all dots appear to be plotted on the actual trajectory that the wheelchair passed, and the maximum deviation was approximately 40 cm. (This was better than average accuracy.) The effectiveness of the GPS positioning was confirmed through this experiment.

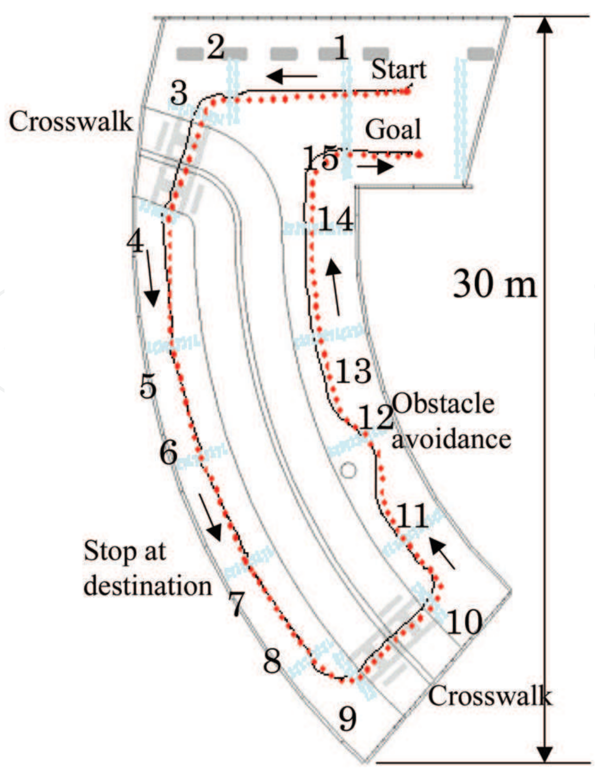

Fig.12. Evaluation result of GPS positioning

8. Experimental result of trajectory following in Aichi Expo. Site

The speed of the wheelchair was set relatively low at 1.4 km/h because various individuals were expected to try the demonstration. At this speed the number of RFIDs detected in the landmarks was measured along the demonstration course. The result is shown in Fig. 13. From this figure, the set of RFIDs in each landmark was measured at least twice.
The performance of the trajectory following control was tested by measuring the position of the wheelchair using surveying equipment (Total Station GTS-820A, Topcon Corp.). The resolution of the position measurement was 1 cm and the cycle time was 2Hz. For the measurement, an omnidirectional prism was set above the center of the wheel axis of the wheelchair.

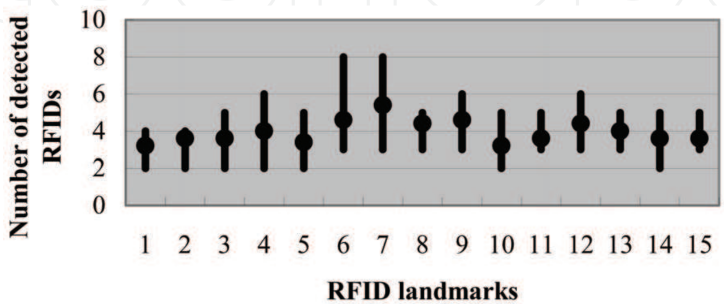

Fig.13. Number of detected RFIDs

The measured trajectory of the wheelchair was compared with the actual course as well as the course data calculated in the wheelchair controller. Figure 14 shows an example of autonomous traveling. After moving through one third of the total course, the wheelchair's deviation from the course was fairly large. The figure shows that at each landmark position the wheelchair recognized the deviation by detecting the RFIDs of the landmark and that it controlled its direction to follow the course. From these experimental results, the maximum deviation from the course was about 40 cm, and stable trajectory following control was achieved along the overall course. There was no dropout from the course during the total demonstration period of 6 months at the moving speed described above.

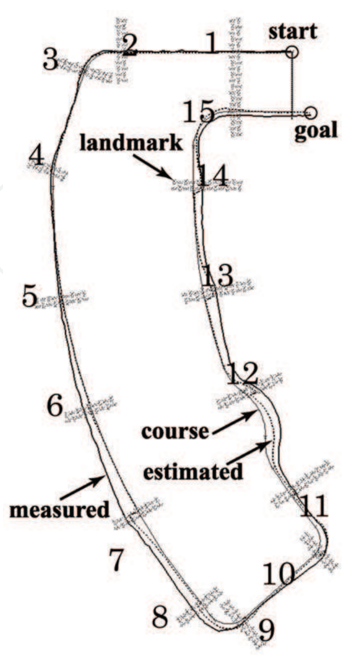

Fig.14. Results of trajectory following control

9. Evaluation result of information provision in Aichi Expo. Site

In the demonstration, the following information was provided as position-related information:
1. "You are coming to "Flower Shop" ("Bookshop", "Bakery") soon."
2. "The wheelchair is crossing the road."
3. "The wheelchair will make a left (right) turn soon."
4. "There is an upward (downward) slope ahead."
5. "You are coming to the terminal soon."
These informative statements should be provided at the optimal timing in order not to make users feel uneasy. They should neither be too early, nor too late. This was achieved without problem because TAO Aicle always knows its own position accurately in order to realize autonomous driving.
The following non-position-related information was also provided:
1. "The wheelchair will stop, as the next light is red."
2. "As the system found an obstacle ahead, the wheelchair will bypass it."
3. "Emergency! Push the emergency button!"
These voice statements were triggered by the wheelchair's action, however the timing was adjusted beforehand. Emergency information must be provided quickly after an emergency situation arises. Avoidance action should be announced not just before the actual action but sufficiently prior to the action because the user may feel uneasy when approaching an obstacle. This was possible as the laser range sensor can detect obstacles 4 m in front of the wheelchair. We evaluated that this information provision using voices and images performed optimally. Thanks to such information provision, visitors could enjoy autonomous traveling without worry.

10. Overall evaluation of demonstration experiment in Aichi Expo. Site

The feasibility of TAO Aicle was confirmed by the trial ride demonstrations at the Aichi Expo site. On a dedicated outdoor course, whose length was approximately 50 m with features similar to a downtown environment as shown in Fig. 15, TAO Aicle autonomously traveled along the course and stopped at the destination that the visitor selected then reached the goal position while detecting and avoiding obstacles on the way.
We developed seven TAO Aicles for the demonstration at Aichi Expo. site. Table 2 shows round (from start point to goal point) number of each TAO Aicle including test traveling before visitor's trial ride. Totally, TAO Aicles rounded the course at Aichi Expo. site 41,316 times. Table 3 shows travel distance of each TAO Aicle. Totally, TAO Aicles traveled approximately 2,107km. Figure 16 shows number of visitors at Aichi Expo. taking a test-ride on TAO Aicle. The total number of the visitors was 36,578 and the average number of visiters per a day is approximately 200. No severe accidents (e.g., collisions with the environment, the wheelchair tipping over) occurred during the period of the Aichi Expo (185 days).
Moreover, we received many positive comments from the visitors. Some typical comments were as follows:
- It is useful because we can go to a desired destination just by simple touch panel operations.
- Voice announcements help the user to feel comfortable.
- Early commercialization is desirable.

Fig. 15. Demonstration at Aichi Expo. Site

Through the experiment we were able to confirm the usability and reliability of this newlydeveloped intelligent wheelchair robot.

round

	Wheelchair (No.1)	Wheelchair (No.2)	Wheelchair (No.3)	Wheelchair (No.4)	Wheelchair (No.5)	Wheelchair (No.6)	Wheelchair (No.7)
March	311	228	251	344	161	0	85
April	671	1,400	1,533	807	1,565	320	1,090
May	776	1,400	545	668	1,150	1,511	766
June	1,014	514	0	864	1,626	905	825
July	878	554	586	1,204	1,199	899	493
August	550	1,082	1,042	1,869	1,121	1,196	995
September	649	835	969	986	885	495	1,499
Total	4,849	6,013	4,926	6,742	7,707	5,326	5,753
Total of all wheelchair	41,316						

Table 2. Round number of TAO Aicles

[m]

	Wheelchair (No.1)	Wheelchair (No.2)	Wheelchair (No.3)	Wheelchair (No.4)	Wheelchair (No.5)	Wheelchair (No.6)	Wheelchair (No.7)
March	15,824	11,721	12,852	17,497	8,201	0	4,350
April	33,888	71,571	78,259	40,744	80,338	16,389	55,480
May	39,595	71,526	27,719	34,054	58,653	77,403	39,045
June	51,653	26,253	0	43,965	83,135	46,297	42,066
July	44,580	27,837	29,976	61,248	61,326	45,621	24,944
August	27,844	55,505	53,234	94,781	57,022	60,456	50,889
September	33,155	42,756	49,695	50,353	45,283	25,265	76,799
Total	246,539	307,169	251,735	342,642	393,958	271,431	293,573
Total of all wheelchair	2,107,047						

Table 3. Travel Distance of TAO Aicles

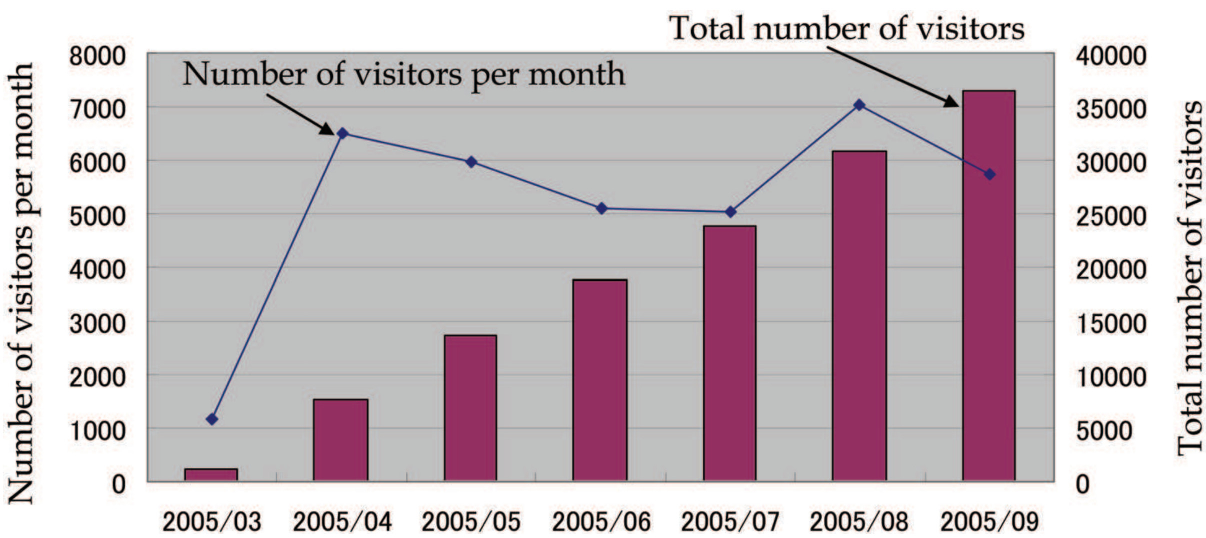

Fig. 16. Number of visitors taking a test-ride on TAO Aicle

11. Conclusion

In this chapter, we introduced an autonomous traveling control system for the "TAO Aicle" wheelchair with a view to increasing the quality of life of wheelchair users as well as their caregivers. Autonomous and safe traveling control was achieved by assistance from the infrastructure, such as GPS and RFID tags which provide accurate positioning. Our demonstration experiments at Aichi Expo confirmed the safety and reliability of the developed "TAO Aicle" system. By further analyzing minor problems that occurred (e.g., failure to avoid an obstacle, deviating from the desired path), we will seek to achieve improvements that enable the practical use of the "TAO Aicle" wheelchair.

12. Acknowledgement

The "TAO Aicle" wheelchair was developed as part of the "Project for the Practical Application of Next-Generation Robots (FY2004-2005)" of the New Energy and Industrial Technology Development Organization (NEDO) of Japan. We wish to express our gratitude to everyone supporting this project.

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