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Autonomous / Semi-autonomous Navigation System of a Wheelchair by Active Ultrasonic Beacons

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Abstract

This paper describes the autonomous and semi- autonomous navigation system of a powered wheelchair for disabled people and nursing staffs. In order to detect its position reliably, this system utilizes active ultrasonic beacons on ceiling. 2 receivers on a wheelchair measures the time-of-flight of the ultrasonic pulses from 2 beacons. Since the distances from only 1 beacon can be obtained at once, the position should be dynamically estimated with its movement in a measurement interval during navigation. Three types of navigation mode by this positioning system are also proposed to assist users. "Automatic transfer mode" guides a wheelchair to a target position autonomously. "Operation assistance mode" helps a user's operation by moving a wheelchair straight toward a commanded direction. "Selective semi-automatic mode" runs path networks selecting a desired direction at each branch point. These navigations were practically succeeded.

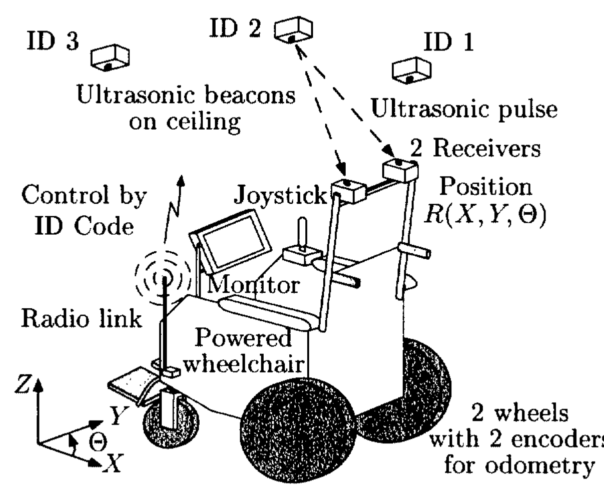


Figure 1: Navigation system using ultrasonic beacons

1 Introduction

Elderly population is increasing rapidly today and it has been a critical problem in our society. Since nursing staffs for elderly or disabled people are not enough and their work is very hard, assistance by effective technologies is strongly requested. Considering the mobility assistance for disabled people with motor problems, the autonomous transfer system by a powered wheelchair is needed in hospitals or nursing homes instead of a nursing staff to navigate a wheelchair. The assistant system to reduce the operation effort of a wheelchair is also required for disabled users to move independently, especially when they have disability to operate a normal joystick well or they use some interfaces by chin, electromyogram, voice, etc. Several autonomous navigation systems of a wheelchair [1]-[4] or a mobile robot have been proposed. Though the highest way is the *"intelligent"* control to recognize environment by vision, sonar, and so on, it doesn't have sufficient reliability and robustness now. Therefore, the methods using artificial landmarks have been developed to navigate them easily and reliably [5][6]. In the human-machine coexisting environment, landmarks and navigation system should be harmless and not be obstructive to human [7]. We have been developing a reliable, safe and inexpensive positioning system using active ultrasonic beacons mounted on a ceiling for an indoor mobile robot [8].

In this paper, we apply this system to a powered wheelchair and propose the autonomous navigation to transfer it and semi-autonomous navigation to assist a user to operate it easily by utilizing active ultrasonic beacons in house. Of course, the function of obstacle avoidance is necessary for safety, however, we do not deal with it and we focus on basic system of navigation in this paper.

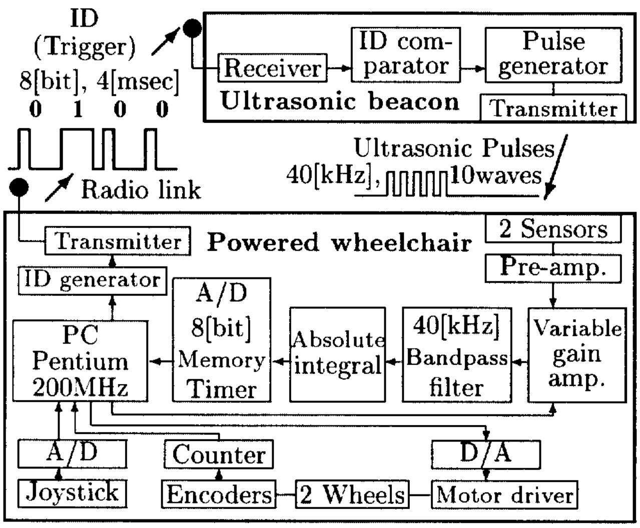


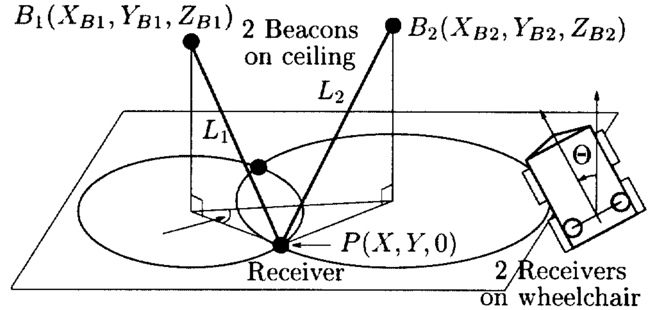
Figure 2: Block diagram of beacons and wheelchair

2 Positioning by Active Ultrasonic Beacons

2.1 Positioning System

Fig.1, 2 show the proposed navigation system and its block diagram. Ultrasonic beacons are mounted on the ceiling and two ultrasonic receivers are equipped on a wheelchair. It determines the wheelchair position by measuring the time-of-flight of the ultrasonic pulses from the beacons at known locations. At least two beacons and two receivers are necessary to calculate the 2D position and orientation. Each beacon has a unique ID code and ID comparator. The emission of the ultrasonic pulse of each beacon is controlled from a wheelchair by sending its ID code by radio link in order to prevent overlap of ultrasonic pulses, to synchronize beacons and a wheelchair and to identify a beacon. The positioning sequence is as follows.

1. A wheelchair sends an ID code (8bit, PWM) to beacons by radio and starts to measure the time-of-flight of an ultrasonic pulse.
2. Beacons receive and check ID code. The only beacon whose ID is same as the received ID emits an ultrasonic pulse and the others do not emit it.
3. 2 receivers on a wheelchair receive the ultrasonic pulse and measure its time-of-flight (distances).
4. After the steps 1~3 are repeated for 2 beacons, a wheelchair position/orientation is obtained from the distances between 2 beacons and 2 receivers.



2 distances between 2 beacons and 1 receiver give position $P(X,Y,0)$ of a static wheelchair (receiver).

Figure 3: Geometric solution of static receiver position

In order to measure the time-of-flight with high accuracy, the arrival time of ultrasonic pulse is assigned as the zero cross point of the tangential line at the half peak of the first leading wave after several signal processings (**Fig.2**). The amplifier gain is varied according to received amplitude to prevent saturation. Since reflected waves from walls etc. come after the first direct wave, their influences are relatively small. This system has following characters.

- It is simple and reliable without mechanical scanning. It is produced with lower cost than the system which uses laser beams etc.
- Ultrasonic wave is harmless and beacons on the ceiling is not obstructive to human.
- Ultrasonic sensors/transmitters of PZT type with small radius must be used for wide measurable range. Their directivities are much wider than condenser microphone type.
- The influence of tilt of a wheelchair is small because this system measures the distance directly.
- It essentially takes about 20~100[msec] to measure the distances from one beacon because of ID transmission time, time-of-flight of ultrasonic pulse and damping time of reflected waves.

Additionally, the odometry information from encoders of wheels and the operation output of a normal analog joystick are also obtained.

2.2 Position Estimation

The principle of the position estimation is described (**Fig.3**), assuming that a wheelchair moves flat floor. After measuring the time-of-flight of an ultrasonic pulse, the distance L between a beacon and a receiver

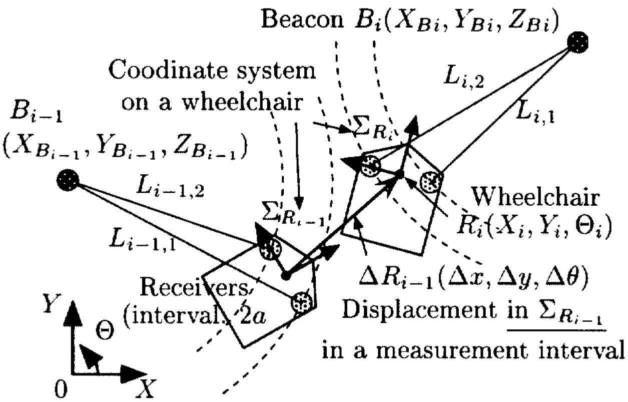


Figure 4: Relation between distances from beacons and wheelchair movement in a measurement interval

is obtained if the sound velocity is given. From the two measured distances between one receiver and two beacons, whose locations are known, the 2D position of a receiver (wheelchair) $P(X, Y)$ can be basically determined as a cross point of two circles. The orientation of a wheelchair Θ can be also obtained from the positions of two receivers by receiving a ultrasonic pulse simultaneously. However, there are two solutions which correspond to two cross points of two circles. In order to select the correct point, the distance to another beacon must be measured or the limitation of area must be added by placing beacons at the corner of ceiling (Ex. $\overline{B_1 B_2}$ is the wall of room).

Since distances from only one beacon can be measured at once, the static estimation generates errors when a wheelchair is moving. Therefore, the movement obtained from the odometry using rotary encoders of wheels must be added to the estimation by ultrasonic beacons. The position/orientation of a wheelchair is calculated from the detected displacement in a measurement interval of beacon and the measured distances between two beacons and two receivers. It must be noted that displacement of a wheelchair cannot be measured as the dimension in the base coordinate system but that in the coordinate system on its wheelchair. Let $R_i(X_i, Y_i, \Theta_i)$ be the wheelchair position at every measurement of two distances $L_{i,1}, L_{i,2}$ from one beacon $B_i(X_{Bi}, Y_{Bi}, Z_{Bi})$ to two receivers (interval: $2a$) and $\Delta R_{i-1}(\Delta x, \Delta y, \Delta\theta)$ be the relative displacement from R_{i-1} to R_i in the coordinate system located on the wheelchair at R_{i-1} (**Fig.4**). The four distances $L_{i-1,1}, L_{i-1,2}, L_{i,1}, L_{i,2}$ from two beacon to two receivers (before and after a measurement interval) are expressed by the function of a wheelchair position $R_i(X_i, Y_i, \Theta_i)$.

$$\begin{aligned} L_{i,1}, L_{i,2} \; &= \; \sqrt{(}X_i \pm a\sin\Theta_i - X_{Bi})^2 \\ &\quad +(Y_i \mp a\cos\Theta_i - Y_{Bi})^2 + Z_{Bi}^2 \quad (1) \end{aligned}$$

$$\begin{bmatrix} X_i \\ Y_i \\ \Theta_i \end{bmatrix} = \begin{bmatrix} X_{i-1} \\ Y_{i-1} \\ \Theta_{i-1} \end{bmatrix} + \begin{bmatrix} \cos\Theta_{i-1} & -\sin\Theta_{i-1} & 0 \\ \sin\Theta_{i-1} & \cos\Theta_{i-1} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta\theta \end{bmatrix} \quad (2)$$

Since these equations cannot be solved analytically, the steepest descent method is applied. The position R_i (X_i, Y_i, Θ_i) is numerically converged by minimizing the sum of square root error between the measured L' and estimated distances $L(X_i, Y_i, \Theta_i)$.

$$\begin{aligned} f(X_i, Y_i, \Theta_i) &= (L_{i,1} - L'_{i,1})^2 + (L_{i,2} - L'_{i,2})^2 \\ &\quad +(L_{i-1,1} - L'_{i-1,1})^2 + (L_{i-1,2} - L'_{i-1,2})^2 \quad (3) \end{aligned}$$

Since the position obtained by previous measurement is used as the initial value, the solution converges with less repetition and the position near the previous one is obtained automatically even if there are two solutions.

3 Navigation with Beacons and Joystick Operation

Helpful navigation methods using detected absolute position by ultrasonic beacons are proposed to assist wheelchair users. Three types of navigation modes are prepared as follows and they are changed according to a wheelchair user and its situation.

3.1 Automatic Transfer Mode

"Automatic transfer mode" is the navigation to transfer a wheelchair to a target position autonomously. A user gives a target position or some sub-targets by pointing it on the room map in the monitor or selecting the menu of registered positions with using a joystick. A wheelchair is guided to the target once it is commanded, however, such input is a little difficult for a disabled user. So, this mode is suitable for a nursing staff to transfer a wheelchair.

Fig.5 shows the navigation procedure from an initial to a given target position. After a wheelchair turns toward a target, it moves straight based on the detected absolute position. There are some control strategies to maintain straight path. We choose the simple method that angular velocity is added in proportion to the error between the directions of a target and a wheelchair. When it arrives a target position, it turns again to adjust the orientation. If a target is behind and near

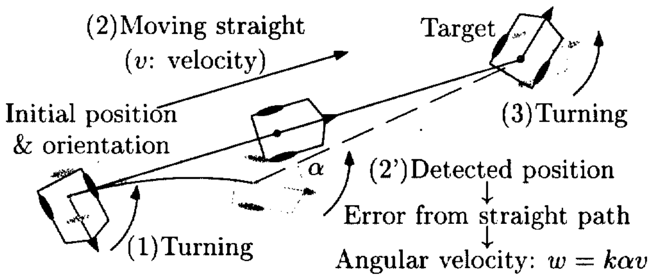


Figure 5: Automatic navigation to a target position

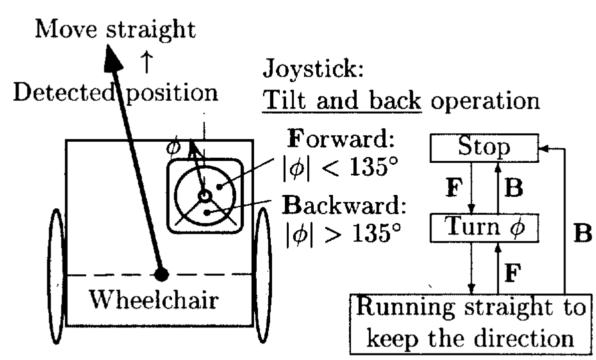


Figure 6: Operation assistance mode

(about 1[m]) the initial position, a wheelchair goes backward. Moreover, whenever a user tilts a joystick in any direction on running, a wheelchair is stopped. During the navigation, the position of a wheelchair is detected as follows. This procedure is also used in other two modes basically.

1. When the position is completely unknown, a wheelchair finds available beacons by requesting the emission of ultrasonic pulse for every beacon.
2. At least 2 beacons are necessary to estimate the position. The pair of beacons for estimation is changed according to the wheelchair position and they are given for each area previously. Then, a wheelchair requests ultrasonic pulses to 2 beacons one after the other to detect position dynamically with odometry information from wheels.
3. In real environment, the detection of wrong positions (far from previous position) and no ultrasonic pulse from beacons are sometimes occur by obstacles and humans. In such cases, the position is estimated by only odometry from wheels.

3.2 Operation Assistance Mode

"Operation assistance mode" assists a disabled person, who has disability to operate a normal joystick well, to navigate a wheelchair. Once a user tilts and back a joystick in a certain direction ϕ, a wheelchair is guided to run straight toward its commanded direction ϕ until the next joystick operation (**Fig.6**). Even if it is curved by the floor roughness and so on, this error can be correct by the measured position. When a user tilts the joystick forward ($|\phi| < 135$[deg]) on running, a wheelchair turns toward the joystick direction ϕ relatively and continues to run straight. When a user tilts it backward ($|\phi| > 135$[deg]) on running, a wheelchair stops. Since this mode does not need to keep a joystick tilting throughout running, the operation is easy and it has less fatigue.

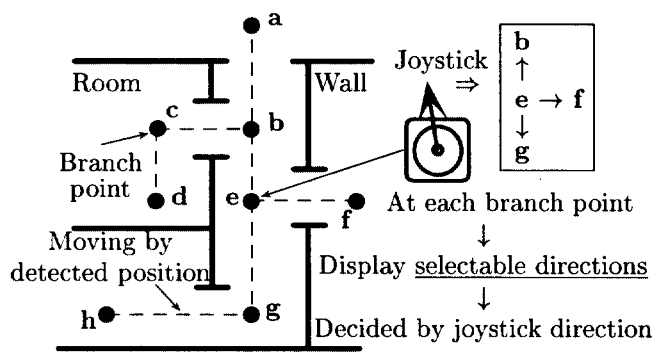


Figure 7: Selective semi-automatic mode

3.3 Selective Semi-automatic Mode

"Selective semi-automatic mode" is mainly for the transfer/mode between rooms and corridors. The network of paths and branch points is given previously as shown in **Fig.7**. A wheelchair is guided along the paths connecting branch points. When it arrives and stops at each branch point, the monitor displays the selectable directions to move as seen from a user. A user only decides a desired direction by tilting a joystick at each branch point. This operation is very easy for a wheelchair user. Though this mode cannot change paths on-line, it has flexibility to change paths off-line without any modification of constructions.

4 Experimental Results

Experiments were made by using the developed positioning system and a conventional powered wheelchair with two drive rear wheels (**Fig.8**). Two ultrasonic receivers are attached on the wheelchair as their

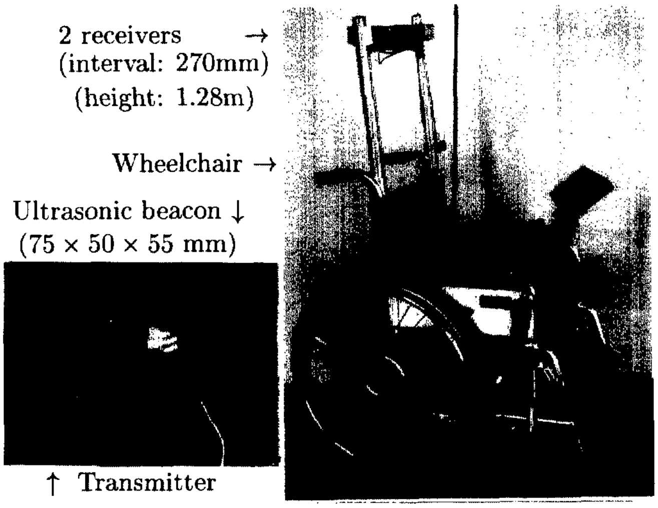
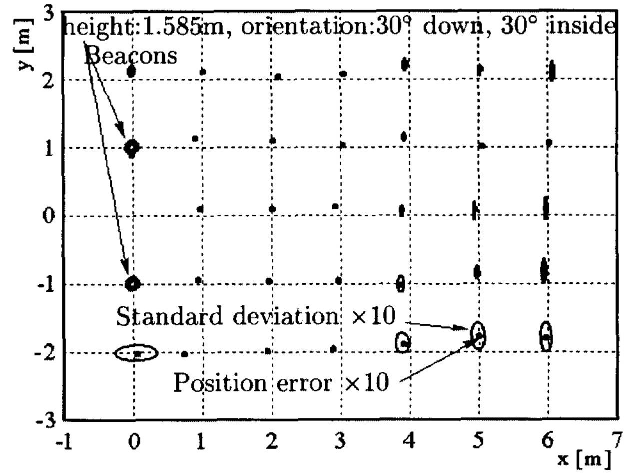


Figure 8: Developed beacons - wheelchair system



Positions at the cross points of 1m×1m were measured. (Sampling: 10Hz 100times)

Figure 9: Position detection by 2 beacons

orientations are fixed in vertical. The ultrasonic beacon is compact size to be mounted easily. The ultrasonic sensor has small radius and the directivity is wide enough ("MA40S3R/S" manufactured by Murata Co.,Ltd., PZT 40[kHz], ϕ9.9[mm], Half amplitude angle 100[deg]). First, position was measured by receiving ultrasonic pulses from two beacons. The orientation of the beacon transmitter was fixed in the direction of 30[deg] down from ceiling and 30[deg] inside. **Fig.9** shows the average point and standard deviation. The accuracy and scatter of measured positions is about ±25[mm] and ±20[mm](standard deviation) respectively. This result is enough for navigation.

Then, we arranged 8 ultrasonic beacons on the ceiling (Height of beacons: 2.035~2.860[m]) in rooms and corridors and the experiments of three types of navigation modes were made. **Fig.10** and **Fig.11** show the navigation examples in the operation assistance mode and the selective semi-automatic mode respectively. Maximum speed of a wheelchair was set at 0.5[m/sec]. **(a)** the detected positions of a wheelchair every 0.25[sec] and **(b)** the output of the joystick operation during navigation are indicated in these figures. Reliable navigation by utilizing ultrasonic beacons was succeeded. The method switching the position information by beacons and by only odometry properly was also effective for disturbances of obstacles and humans. In the case of **Fig.10**, a user operated the joystick at 6 points **(a-f)** to start, turn, and stop. It can be seen that the wheelchair was controlled to move almost straight between those joystick operations. A user could smoothly drive a wheelchair without keeping a joystick tilting throughout running. In the case of **Fig.11**, a user selected direction at 4 branch points **(a-d)**. A wheelchair was judged to arrive those branch points or a goal when it entered within 200[mm](position) and 10[deg](orientation) from there, and it stopped to wait user's input. After the selection, a wheelchair could move along network paths according to detected position. By the assistance of this navigation system, a user can move easier with less joystick operation than a user manually drives a powered wheelchair. Therefore, these navigation modes can be also applied the wheelchair with some other user interfaces such as voice, electromyogram, etc.

5 Conclusion

Autonomous and semi-autonomous navigation system by using the active ultrasonic beacons has been proposed. This system is helpful for disabled people and nursing staffs. It was implemented to a conventional powered wheelchair and three types of navigation modes (automatic transfer mode, operation assistance mode, and selective semi-automatic mode) were succeeded practically. This system and strategies are reliable and stable for wheelchair navigation. Optimal beacon arrangement, fusion of obstacle avoidance for safety, and navigation of multiple wheelchairs are remained for our further works.

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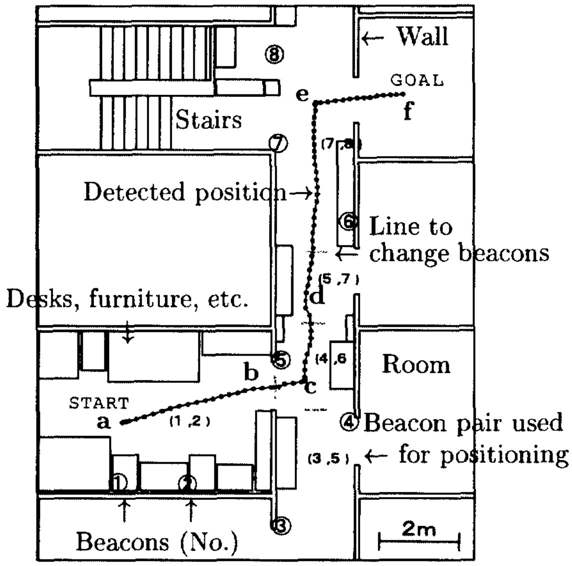
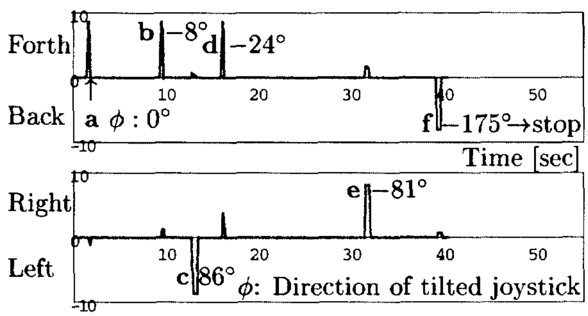
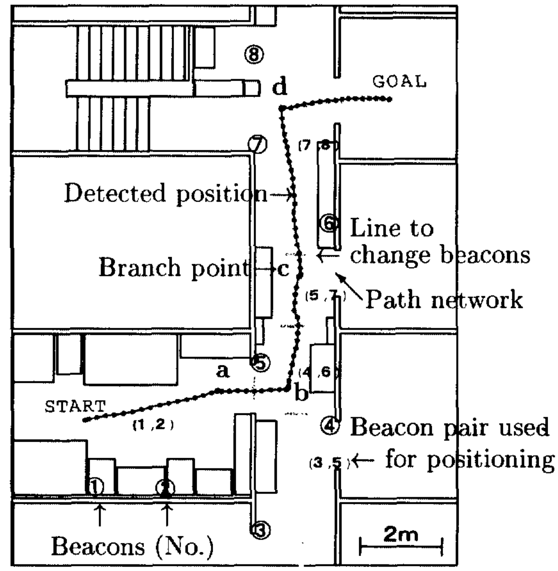


(a) Navigation trajectory (Detected position)

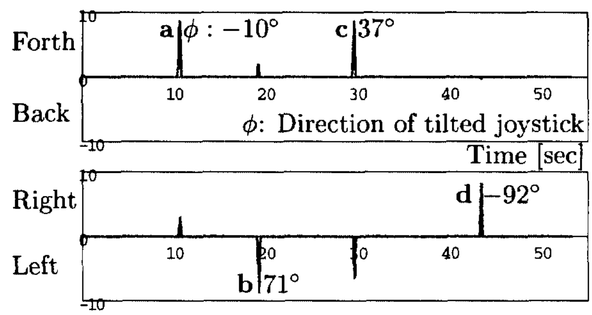


(b) Joystick operation (output [V])

Figure 10: Navigation in operation assistance mode



(a) Navigation trajectory (Detected position)



(b) Joystick operation (output [V])

Figure 11: Navigation in selective semi-automatic mode

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