Self-Localization for an Electric Wheelchair*

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This paper presents an autonomous wheelchair system with the capability of self-localization. In our system, the ceiling lights are chosen as landmarks to realize the self-localization and auto-navigation of the wheelchair. An approach to landmark recognition is described, and a technique of self-localization for the wheelchair is proposed. Subsequently, the path planning for navigation is discussed. Finally, the total system for our wheelchair is introduced, and a navigation experiment is described. Experimental results indicate the effectiveness of our system.

***Key Words*:** Wheelchair, Landmark Recognition, Self-Localization, Path Planning, Navigation

1. Introduction

At present commercially available electric wheelchairs are widely used by physically handicapped people. The operation of an electric wheelchair generally requires some skill. It is not easy for physically handicapped people to drive a wheelchair skillfully. Recently, extensive research has been performed to develop an intelligent wheelchair[(1)-(3)]. In our laboratory, we have successfully developed an automatic wheelchair capable of self-localization and obstacle avoidance[(4)].

The ability to self-locate is critical for reliable performance of a wheelchair. Many methods realize self-localization of a wheelchair. One simple and reliable method provides landmark features in the workspace as external references. Several researchers have approached the self-localization problem of mobile robots by employing "standard marks"[(5)-(7)]. The key idea is to use special marks that include a wealth of geometric information in perspective projection so that the location of the camera can be easily computed from the image of the guide-marks. One reference[(8)] described how to use the visual surfaces of objects (e.g., a copying machine) as landmarks to guide the navigation of an office messenger robot. In our research, we have chosen ceiling lights as landmarks because they can be easily detected due to the high contrast between the light and the ceiling surface and do not require special installation. In a reference[(9)], the number of ceiling lights is counted during navigation to estimate the navigational distance. Another paper[(10)] uses ceiling lights under a special condition in which the navigational path is settled just below the ceiling lights. In our study, the ceiling lights are used to determine the two-dimensional position and posture of the wheelchair accurately. Due to this self-localization function, the wheelchair developed here is capable of moving along any path in the environment where ceiling lights are installed.

The aim of our research is to enable the wheelchair to navigate from one position to a desired

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position without any human assistance. It is assumed that this wheelchair will be used only in an indoor environment in which the geometrical layout is known in advance. To realize auto-navigation, one camera facing up is used to detect landmarks and navigate the wheelchair. When ceiling lights are not detected, the wheelchair navigates with information from a geomagnetic azimuth sensor and rotary encoders installed on both wheels.

In this paper, three kinds of ceiling lights are considered as landmarks: single fluorescent lights, double fluorescent lights and fluorescent lights with rectangular lampshades. An approach to landmark recognition is described in section 2. A technique of self-localization is proposed in section 3. Path planning for navigation is discussed in section 4. Finally, the total system for the wheelchair is introduced and experimental results are given.

2. Landmark Recognition

During navigation of the wheelchair, the landmark needs to be recognized. However, the camera may acquire some unnecessary images due to sunlight through windows or other light sources. These unnecessary images have to be eliminated. From all these images, the desired landmark image can be retrieved by checking the area, boundary, distance and position of every cluster. Considering the shape of fluorescent lights, the procedure is described as follows:

(1) Image signals from the TV camera are converted into binary image signals.

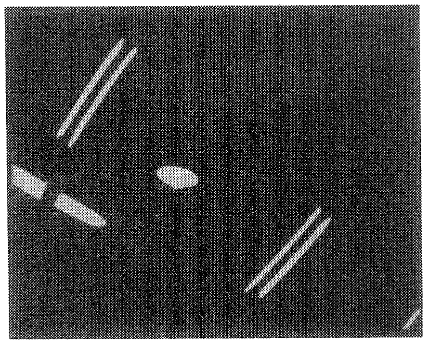
(2) Profiles of white clusters in the image (run-length data) are extracted from the binary signals by a logic circuit constructed by a FPGA (Field Programmable Gate Array: XC 4010).

(3) By the labeling program, we obtain geometrical data (area, length, width and position, minimum horizontal and vertical coordinates, maximum horizontal and vertical coordinates) of every white cluster in the images.

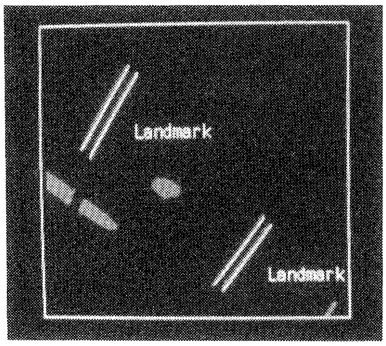
(4) Considering the area, length, width and the distance from the neighboring white cluster, we extract the desired images from other clusters.

An example of landmark recognition is shown in Fig. 1. Figure. 1 (a) is the binary image of all light sources including unnecessary images. From all images, two pairs of ceiling lights are selected as landmarks using the method shown in Fig. 1 (b).

For a single fluorescent light, the contour of the light extracted using this method is shown in Fig. 2. Our self-localization technique requires determining the end coordinates of the fluorescent light. Using the contour points of the light, the central line of the light can be calculated. From the crossing points of the central line and the image contour, the raster coordinates of the ends of the light, i.e., the coordinates of projection points $P_i (i=1, 2)$ of the ends of the light in the image plane, can be obtained[11].



(a) Binary image of all light sources



(b) Landmarks selected from all images

Fig. 1 Example of landmark recognition

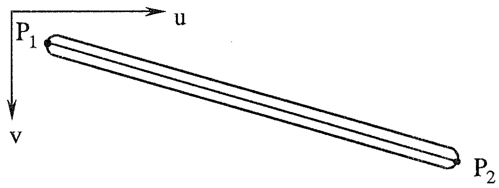


Fig. 2 Contour of single light

3. Self-Localization

The self-localization of a wheelchair determines the position and orientation of the wheelchair relative to the landmarks and the world coordinate system. In this section, we discuss the case of a single fluorescent light.

From the image of a single fluorescent light, we have a position vector $\boldsymbol{p}_i=(u_i\ v_i\ f)^T$ of projection points P_i of the ends of the light Q_i in the camera coordinate system $o_c-x_c y_c z_c$ (refer to Fig. 3). From perspective transformation, the relation between $\boldsymbol{q}_i$ and $\boldsymbol{p}_i$ can be expressed as

$$\boldsymbol{q}_i=k_i \boldsymbol{p}_i \quad (i=1, 2), \qquad (1)$$

where $\boldsymbol{q}_i$ indicates the position vector of the end of the light Q_i in the camera coordinate system, and k_i is the

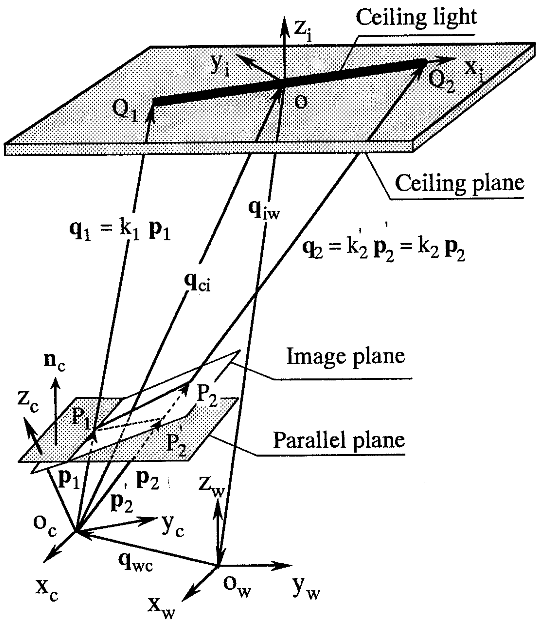


Fig. 3 Relation between camera and single light coordinate systems

proportionality coefficient between the two vectors. If the image plane and ceiling plane are parallel, the proportionality coefficient k_i is easily obtained as follows:

$$k=k_1=k_2=\frac{|k_1\boldsymbol{p}_1|}{|\boldsymbol{p}_1|}=\frac{|k_2\boldsymbol{p}_2|}{|\boldsymbol{p}_2|}=\frac{|\boldsymbol{q}_2-\boldsymbol{q}_1|}{|\boldsymbol{p}_2-\boldsymbol{p}_1|}. \tag{2}$$

Once k is known, the vector $\boldsymbol{q}_i$ can be obtained using Eq. (1).

Generally, we place the camera not in parallel with the plane of ceiling lights so that the view of the camera can be increased during the navigation of the wheelchair. In this case, Eq. (2) cannot be used. To calculate k_i, we consider a plane that passes through point P_1 and is parallel to the ceiling plane as shown in Fig. 3. If the rotation matrix to transform the camera coordinate system $o_c-x_cy_cz_c$ to the wheelchair coordinate system $o_w-x_wy_wz_w$ is represented by $\boldsymbol{A}$, then the equation of the parallel plane in the camera coordinate system is obtained as follows:

$$\boldsymbol{n}_c^T(\boldsymbol{p}-\boldsymbol{p}_1)=0, \tag{3}$$

$$\boldsymbol{n}_c=\boldsymbol{A}^T(0\ 0\ 1)^T, \tag{4}$$

where $\boldsymbol{p}$ indicates the arbitrary position vector on the parallel plane, and $\boldsymbol{n}_c$ is the normal unit vector of the plane in the camera coordinate system $o_c-x_cy_cz_c$. The equation of the line that passes through two points P_2 and o_c in the camera coordinate system can be expressed using the following equation

$$\boldsymbol{p}=t\boldsymbol{p}_2. \tag{5}$$

Substituting Eq. (5) into Eq. (3), the position vector $\boldsymbol{p}_2'$ of the crossing point P_2' of the parallel plane and the straight line can be obtained as

$$\boldsymbol{p}_2'=\left(\frac{\boldsymbol{n}_c^T\boldsymbol{p}_1}{\boldsymbol{n}_c^T\boldsymbol{p}_2}\right)\boldsymbol{p}_2 \tag{6}$$

Therefore, k_1 and k_2' can be determined by

$$k_1=k_2'=\frac{|\boldsymbol{q}_2-\boldsymbol{q}_1|}{|\boldsymbol{p}_2'-\boldsymbol{p}_1|}, \tag{7}$$

and $\boldsymbol{q}_i(i=1, 2)$ can be obtained using Eq. (1).

Once $\boldsymbol{q}_i(i=1, 2)$ is known, the relation between the light coordinate system and the camera coordinate system can be determined. The origin o of the light coordinate system is at the midpoint between points Q_1 and Q_2. The x-axis is set along the direction from Q_1 to Q_2. The unit vector of the z-axis of the light coordinate system is parallel to the z-axis of the coordinate system $o_w-x_wy_wz_w$ fixed on the wheelchair. The transformation matrix of the light coordinate system relative to camera coordinate system can be expressed as follows:

$$\boldsymbol{B}=[\boldsymbol{e}_x\quad \boldsymbol{e}_y\quad \boldsymbol{e}_z], \tag{8}$$

where

$$\boldsymbol{e}_x=\frac{\boldsymbol{q}_2-\boldsymbol{q}_1}{|\boldsymbol{q}_2-\boldsymbol{q}_1|},\quad \boldsymbol{e}_z=1,\quad \boldsymbol{e}_y=\boldsymbol{e}_z\times\boldsymbol{e}_x. \tag{9}$$

In the case of double fluorescent lights and fluorescent lights with rectangular lampshades, the methods to determine the light coordinate system are similar to those for a single fluorescent light.

After the transformation matrix $\boldsymbol{B}$ is obtained, the homogenous transformation matrix of the coordinate systems between the wheelchair and ceiling light can be expressed as

$$\boldsymbol{T}=\begin{bmatrix}\boldsymbol{A} & \boldsymbol{q}_{wc}\\ \boldsymbol{0} & 1\end{bmatrix}\begin{bmatrix}\boldsymbol{B} & \boldsymbol{q}_{ci}\\ \boldsymbol{0} & 1\end{bmatrix}, \tag{10}$$

where $\boldsymbol{q}_{wc}$ indicates the position vector of the camera coordinate system relative to the wheelchair. The inverse matrix of this matrix can be written in the following form

$$\boldsymbol{T}^{-1}=\begin{bmatrix}\boldsymbol{C} & \boldsymbol{q}_{iw}\\ \boldsymbol{0} & 1\end{bmatrix}, \tag{11}$$

where

$$\boldsymbol{C}=\boldsymbol{B}^T\boldsymbol{A}^T, \tag{12}$$

$$\boldsymbol{q}_{iw}=-\boldsymbol{B}^T\boldsymbol{q}_{ci}-\boldsymbol{B}^T\boldsymbol{A}^T\boldsymbol{q}_{wc}. \tag{13}$$

In Eq. (13), $\boldsymbol{q}_{iw}$ expresses the position vector of wheelchair in the light coordinate system. Considering that the z-axes of the light coordinate system and wheelchair coordinate system are always parallel, the rotation angle α of wheelchair relative to the light coordinate system can be calculated as follows:

$$\alpha=\tan^{-1}\left(\frac{\sin\alpha}{\cos\alpha}\right)=\tan^{-1}\left(\frac{c_{21}}{c_{11}}\right), \tag{14}$$

where c_{ij} is the element of i-th row and j-th column in matrix $\boldsymbol{C}$.

Because the position vector of the i-th ceiling light in the world system is known in advance as shown in Fig. 4, the position vector of the wheelchair in a two-dimensional coordinate system o-xy can be obtained as follows:

$$\boldsymbol{r}_{ow}=\boldsymbol{r}_{oi}+\boldsymbol{r}_{iw}, \tag{15}$$

where $\boldsymbol{r}$ is the two dimensional vector with x and y coordinates. The orientation angle of the wheelchair in the world coordinate system can be obtained using the following equation

$$\alpha_{ow}=\alpha_{oi}+\alpha_{iw}, \qquad (16)$$

where α_{ow} and α_{oi} indicate the orientation of the coordinate systems fixed on the wheelchair and the i-th light relative to the world coordinate system respectively, and α_{iw} is the orientation of the wheelchair relative to the coordinate system of the i-th light.

We consider a general case where m landmarks are in sight of the camera as shown in Fig. 4. It is readily understandable that the more landmarks in sight, the higher the accuracy of the self-localization attained using the method of least squares(12). Since the distance between the wheelchair and landmark has an effect on the accuracy of the measurement, the weighting factor for every landmark should be considered. From Eq. (15), the sum of the squares of the measurement error with a weighting factor can be written as

$$J(\boldsymbol{r}_{ow})=\sum_{i=1}^{m}\left(\frac{l}{l+|\boldsymbol{r}_{iw}|}[\boldsymbol{r}_{ow}-(\boldsymbol{r}_{oi}+\boldsymbol{r}_{iw})]^2\right), \qquad (17)$$

where $\frac{l}{l+|\boldsymbol{r}_{iw}|}$ is the weighting factor for every landmark, and l is the length of a ceiling light. Minimizing $J(\boldsymbol{r}_{ow})$, the position vector $\boldsymbol{r}_{ow}$ of the wheelchair relative to the world coordinate system can be expressed as follows:

$$\boldsymbol{r}_{ow}=\frac{\sum_{i=1}^{m}\left(\frac{l}{l+|\boldsymbol{r}_{iw}|}(\boldsymbol{r}_{oi}+\boldsymbol{r}_{iw})\right)}{\sum_{i=1}^{m}\frac{l}{l+|\boldsymbol{r}_{iw}|}}. \qquad (18)$$

Using a similar method, the orientation of the wheelchair relative to the world coordinate system can be obtained as

$$\alpha_{ow}=\frac{\sum_{i=1}^{m}\left(\frac{l}{l+|\boldsymbol{r}_{iw}|}(\alpha_{oi}+\alpha_{iw})\right)}{\sum_{i=1}^{m}\frac{l}{l+|\boldsymbol{r}_{iw}|}}. \qquad (19)$$

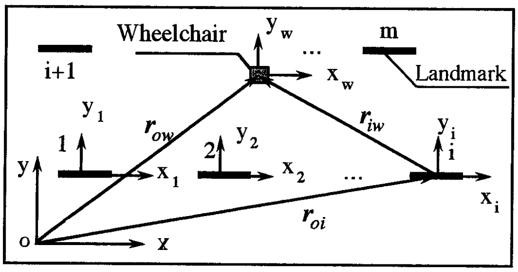


Fig. 4 Landmarks in sight of camera

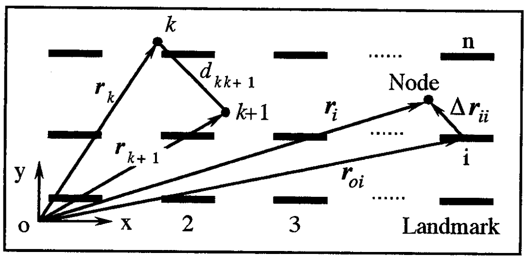


Fig. 5 Navigation map

4. Path Planning

The navigation of a wheelchair utilizing landmarks depends upon the navigation map shown in Fig. 5. The navigation map should contain information about the position of every landmark and possible path. The possible paths are determined as a series of lines which connect neighboring nodes settled near the landmarks. A navigation map with n landmarks can be expressed using the following matrices:

$$\boldsymbol{R}_{mark}=[\boldsymbol{r}_{o1}\ \boldsymbol{r}_{o2}\cdots \boldsymbol{r}_{on}],\quad \Delta\boldsymbol{R}=[\Delta\boldsymbol{r}_{11}\ \Delta\boldsymbol{r}_{22}\cdots\Delta\boldsymbol{r}_{nn}]. \qquad (20)$$

Matrix $\boldsymbol{R}_{mark}$ is composed of the position vectors of all landmarks (ceiling lights) in the world coordinate system. Matrix $\Delta\boldsymbol{R}$ indicates the position vector of every node relative to the corresponding landmark. This matrix determines the navigational course drift from the landmarks considering the obstacles on the path. The position vectors of all nodes can be expressed as

$$\boldsymbol{R}_{node}=[\boldsymbol{r}_1\ \boldsymbol{r}_2\cdots\boldsymbol{r}_n]=\boldsymbol{R}_{mark}+\Delta\boldsymbol{R}. \qquad (21)$$

To find the optimal path among all possible paths, we introduce the following network matrix

$$\boldsymbol{D}=\begin{bmatrix}0 & d_{12} & \cdots & d_{1n}\\ d_{21} & 0 & \cdots & d_{2n}\\ \cdots & \cdots & \cdots & \cdots\\ d_{n1} & d_{n2} & \cdots & 0\end{bmatrix}, \qquad (22)$$

where d_{ij} indicates the distance between node i and j, i.e., $d_{ij}=|\boldsymbol{r}_i-\boldsymbol{r}_j|$. If there is an obstacle between node i and j or node i and j are not neighboring, we set $d_{ij}=\infty$ to express that the path between node i and j is not feasible. Based on matrix $\boldsymbol{D}$, the shortest path from the starting position to the selected node (goal position) can be found using the method of shortest path analysis(13) in which we only specify a starting position and goal. The path vector (shortest path found) can be expressed using a vector as

$$\boldsymbol{c}=(c_1, c_2\cdots c_k)^T,$$

where c_i is the node number (landmark number) in the shortest path. Corresponding to the path vector $\boldsymbol{c}$, the position vector of every node in the shortest path can be obtained. A control scheme can be generated so that the wheelchair can automatically navigate from the starting position to the goal position.

5. Total System and Navigational Experiment

The control system for the wheelchair is shown in Fig. 6. Two high speed microprocessors (HITACHI:

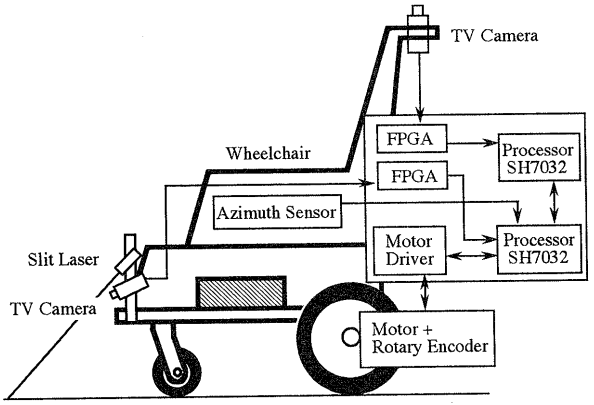


Fig. 6 Control system for wheelchair

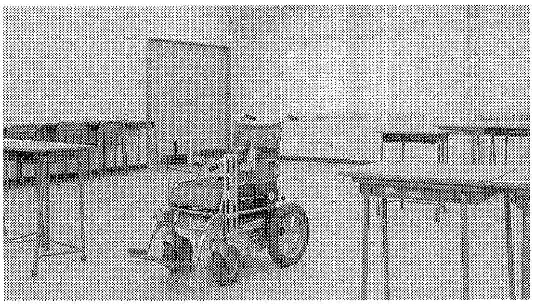


Fig. 7 Navigation scene for wheelchair

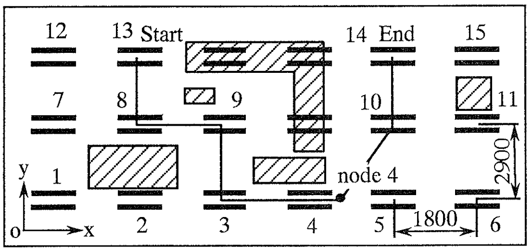


Fig. 8 Navigation map of experimental environment

SH 7032) are used for the self-localization and navigational control of the wheelchair. Two rotary encoders are installed at the two drive wheels to measure the distance over which the wheelchair has traveled. To know the direction of the wheelchair, a geomagnetic azimuth instrument is employed. One camera and a slit laser are employed to detect obstacles in the path-way. The other camera is used to recognize landmarks. Two image processing boards that consist of a FPGA are developed to realize high speed image processing.

We ran a navigational test in a room where eighteen ceiling lights were installed as shown in Fig. 7. The navigation map is shown in Fig. 8. Considering obstacles in the environment, fifteen landmarks are labeled. When we wanted to move the wheelchair from node 13 to 14, the shortest path was found as a path vector $\boldsymbol{c}=(13, 8, 9, 3, 4, 10, 14)^T$. Positions of

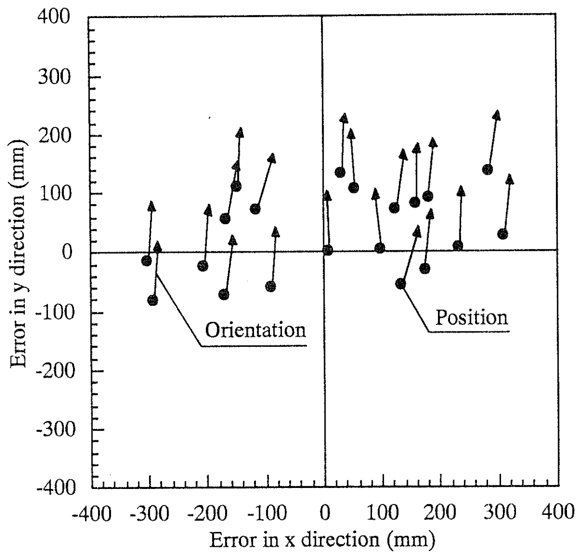


Fig. 9 Error in navigational experiment

nodes and landmarks are identical in this path except for node 4.

We have tested the navigation of the wheelchair along this navigation path twenty times. Our wheelchair was able to navigate with a maximum position error of 0.35 meters and a maximum orientation error of 17° at the final destination point as shown in Fig. 9. In this figure, the lines with arrows represent the orientation of the wheelchair at the final destination where the desired orientation was specified along y direction. The error in the x direction is bigger than the error in the y direction. Our electric wheelchair is a remodeled commercial wheelchair; therefore, the motion of the wheelchair meanders slightly during navigation due to the driving mechanism installed.

6. Conclusion

In this paper, we present an autonomous wheelchair system with the capability of self-localization. Three kinds of ceiling lights are considered as landmarks to navigate the wheelchair. The approaches to landmark recognition and self-localization of the wheelchair as well as path planning are described. In our system, the wheelchair needs not to be precisely under the ceiling lights and is capable of moving on any path specified.

Due to the use of FPGA and high speed microprocessors, fast image processing and computation can be realized and the total system can be constructed in a compact body. We ran experiments for the navigation for the wheel chair in a room. The experimental results indicate the effectiveness of the approach presented here.

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