

The Development of the Automatic Lane Following Navigation System for the Intelligent Robotic Wheelchair

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Abstract—In this paper, we constructed an intelligent robotic wheelchair equipped with automatic tracking function in barrier-free environment of campus; the system used video paint line detection as the basis of automatic tracking navigation; since the barrier-free environment of campus includes indoor and outdoor environment and the outdoor environment includes gentle slopes, sidewalk and etc, we proposed a paint line detection method, which showed color distribution and judgment of paint line using Gaussian mixture models; the input image completed paint line detection and parameters calculation with this method and then input them into the fuzzy logic controller of wheelchair and in this way, the tracking navigation control of wheelchair was performed; the system was actually tested on barrier-free paths in campus, including straight and curve barrier-free paths; the result showed that the system could make the wheelchair keep moving on the paint line correctly and the mean deviation was kept within ± 10 cm, which proved the navigation of intelligent robotic wheelchair could be realized automatically and successfully on barrier-free paths in campus.

Keywords—*path lane following; gaussian mixture models; color space conversion; color segmentation; fuzzy control.*

I. INTRODUCTION

In Taiwan, the percentage of population of the old aged above 65 to the total population increased from 10.4% in 2008 to 10.6% in 2009; it is estimated that the aging population will account for 20.04% of the total population in 2070[1, 2]; these figures show Taiwan has entered the aging society, therefore, there is an urgent need of the care for the aged. As more and more people are using wheel chairs in aging society, barrier-free space is built out in succession in many places; Chaoyang University of Technology has been always paying much attention to this issue, so a barrier-free space has been built in the campus; to apply the technology to the concept of holistic care [3], we introduced the intelligent robotic wheelchair in barrier-free environment in campus and created a intelligent robotic wheelchair equipped with automatic tracking navigation based on computer vision; the system captures images of barrier-free environment with a camera installed on the wheelchair and controls the automatic tracking navigation of robotic wheelchair in barrier-free environment in

campus through real time detection of paint line and fuzzy control.

The automatic tracking navigation technology based on paint line detection of computer vision has been mentioned in many related researches [4-13]; generally, the common detection methods include comparison based on characteristics, colors, models, etc; to highlight positions, the distinct paint line was used as path guide in barrier-free environment, so we used color detection method in this paper. The simplest method for color detection is critical value method; range of critical value was set according to the distribution of color to be detected; when color fell into the range, it was deemed to be the color detected, otherwise it was not; furthermore, some scholars proposed the method using the single Gaussian function to show the distribution of specific color in space [14]; since the barrier-free environment of campus includes indoor and outdoor environment and there is shadow, tree shade and stain, etc in outdoors, which can not be shown by the single Gaussian function, we proposed to express the probability distribution of color of paint line with Gaussian mixture models which are composed of several Gaussian functions according to different weight values, thus it can show the probability distribution of color of paint line more correctly; the input image could complete the detection of color of paint line through Gaussian mixture models more accurately; moreover, color of paint line changed at any time with environment and external light source, so we updated Gaussian mixture models at real time with the updating algorithm of dynamic Gaussian mixture models to make the paint line detection of the system more stable and more suitable for various environments. After paint line detection, calculate the position and angle of paint line with Hough transform, input the result into the entry of fuzzy controller of wheelchair and control the difference between velocity of the right wheel and left wheel through fuzzy logic to control wheel chair direction and then complete the tracking navigation function of robotic wheelchair.

The other structures of the paper are described as below; Section II proposes system architecture; Section III introduces methods to detect paint line; Section IV introduces fuzzy system control of automatic lane following of robotic

wheelchair; the simulated experiment and the actual experimental results are shown in Section V; the last section is conclusion and discussion.

II. SYSTEM ARCHITECTURE

Fig.1 shows the system architecture of intelligent robotic wheelchair proposed by us, which includes image capture and correction, paint line detection, parameter calculation, graphical operation interface, fuzzy controller, etc. Image capture and correction read images into the system through camera and capture card and converting camera into space coordinates; as camera coordinates are different from space coordinates, the input images should be converted to aerial view through coordinate conversion; paint line detection and parameter calculation detect color of paint line through images and calculate angular separation between paint line position and wheelchair direction through Hough transform.

Fuzzy logic controller is responsible for controlling tracking navigation of wheelchair; it has two entries, which are angular separation between straight line of paint line and wheelchair direction; while the output controls the difference between velocities of two wheels directly, getting an angular velocity through changes of the difference between velocities of two wheels to make wheelchair be able to make a turn to proceed towards the correct direction; the last part is graphical operation interface; the system operation can be simplified through graphical operation interface to make the mobility-handicapped or senior citizen be able to operate the system by clicking.

We will elaborate on technologies of every part in Fig.1 in the following chapters.

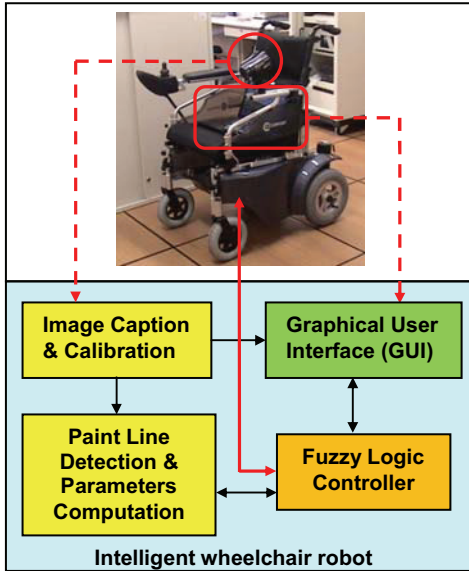


Figure 1. System architecture

III. PAINT LINE DETECTION

It was difficult to detect the position of paint line with color; since color of paint line was susceptible to light source, weather, stain, shadow and etc, we proposed a set of robust

paint line detection method in this paper; this method learned the probability distribution of color of paint line using a Gaussian mixture model and the input image detected position of paint line of image through a Gaussian mixture model it had learnt before. Below is detailed description.

A. Color space conversion

To reduce the effect of light source on color detection, we used a and b in CIE-Lab color space as the basis of paint line detection; in this paper, we used BT-709 format conversion of ITU-R and employed D65 as reference white point; since RGB color space could not correspond to Lab color space directly, it must be converted to XYZ color space first and then converted to Lab color space; the conversion of RGB color space to XYZ color space can be expressed by the matrix operation equation (1) below:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \quad (1)$$

while the conversion of XYZ color space to Lab color space can be defined as the equation (2):

$$\begin{aligned} L &= 116f\left(\frac{Y}{Y_n}\right) - 16, \\ a &= 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right], \\ b &= 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right], \\ f(t) &= \begin{cases} t^{\frac{1}{3}}, & t > 0.008856 \\ 7.787t + \frac{16}{116}, & t \leq 0.008856 \end{cases} \end{aligned} \quad (2)$$

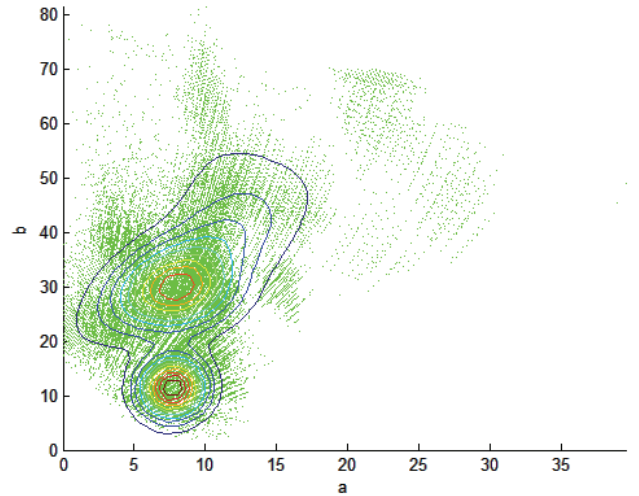


Figure 2. Distribution of a - b values of paint line color and the contour line of 5 Gaussian mixture models

where, $X_n=0.9504$, $Y_n=1$ and $Z_n=1.0883$ are D65 reference white points. Fig.2 shows the distribution map of a - b values of paint line color, where every blue point represents the sampling value of every paint line color a - b . We collected a - b values of 1,250,000 paint line colors under many circumstances (indoors and outdoors; the latter includes rainy

days, sunny days, at dusk, daytime, etc); we can find from the figure that the distribution of a - b values of paint line color is irregular, so it can not be expressed by setting range of critical values or by the single Gaussian function and we used mixed model of Gaussian function to learn the probability distribution of a - b values of paint line color.

B. The expression of paint line color by Gaussian mixture models

Gaussian mixture model (GMM) refers to a mixed model composed of multiple Gaussian functions; because GMM can approach probability density distribution of any shape, it is very suitable for modeling the probability distribution of a - b values of paint line color; GMM can be represented by the weight sum of K Gaussian functions and the definition is shown as equation(3):

$$p(\mathbf{x}_i|\Theta) = \sum_{k=1}^K p_k p(\mathbf{x}_i|\mu_k, \Sigma_k), k=1, 2, \dots, K, \quad (3)$$

where $\mathbf{x}_i \in R^2$, $i = 1, 2, \dots, n$, is input vector; n refers to number of samples input; $\Theta = \{\mu_1, \mu_2, \dots, \mu_K | \Sigma_1, \Sigma_2, \dots, \Sigma_K\}$, where μ_k and Σ_k refer to the mean value and covariance matrix of the k th Gaussian function separately; p_k , $k = 1, 2, \dots, K$, represents the weight value of component of every Gaussian function in Gaussian mixture models and every Gaussian function can be expressed as equation (4):

$$p(\mathbf{x}_i|\mu_k, \Sigma_k) = \frac{1}{\sqrt{(2\pi)^d |\Sigma_k|}} \exp \left[-\frac{1}{2} (\mathbf{x}_i - \mu_k)^T \Sigma_k^{-1} (\mathbf{x}_i - \mu_k) \right], \quad k=1, 2, \dots, K, \quad (4)$$

where, μ_k and Σ_k refer to the mean value and covariance matrix of the k th Gaussian function separately, therefore, there are K mean values and K covariance matrices; $\Theta = \{\mu_1, \mu_2, \dots, \mu_K | \Sigma_1, \Sigma_2, \dots, \Sigma_K\}$; the method used to train Gaussian mixture models is called EM algorithm which is a recursive algorithm including two procedures, namely, estimation procedure(E -procedure) and update procedure(M -procedure) separately; E -procedure refers to estimating the probability that every input sample belongs to individual Gaussian function based on the current parameters of Gaussian mixture models and its calculation is defined as:

$$\hat{p}(k|i) = p(y_i = k | \mathbf{x}_i, \theta_k), \forall k, i, \quad (5)$$

where, $k = 1, 2, \dots, K$, K refers to the number of Gaussian functions used by GMM; $i = 1, 2, \dots, n$, n refers to the number of samples input, so $\hat{p}(k|i)$ stands for the probability that the input $\mathbf{x}_i$ the k th belongs to Gaussian function; $\theta_k = \{\mu_k, \Sigma_k\}$, μ_k and Σ_k refer to the mean value and covariance matrix of the k th Gaussian function separately; M -procedure updates all parameters with $\hat{p}(k|i)$ and its calculation is defined as below:

$$\hat{n}_k \leftarrow \sum_{i=1}^n \hat{p}(k|i), \forall k, \quad (6)$$

$$\hat{p}_k \leftarrow \frac{\hat{n}_k}{n}, \forall k, \quad (7)$$

$$\hat{\mu}_k \leftarrow \frac{1}{\hat{n}_k} \sum_{i=1}^n \hat{p}(k|i) \mathbf{x}_i, \forall k, \quad (8)$$

$$\hat{\Sigma}_k \leftarrow \frac{1}{\hat{n}_k} \sum_{i=1}^n \hat{p}(k|i) (\mathbf{x}_i - \hat{\mu}_k)(\mathbf{x}_i - \hat{\mu}_k)^T, \forall k, \quad (9)$$

Repeat E -procedure and M -procedure above until the convergence.

The contour line in Fig.2 shows Gaussian mixture model which uses 5 Gaussian functions to learn the result of probability distribution of a - b values of paint line color; it can be clearly seen from the figure that the probability distribution of two Gaussian functions is more distinct mainly because most a - b values of paint line color are converged in the range covered by the two Gaussian functions. After learning, Gaussian mixture models can be used to show the probability distribution of a - b values of paint line color, therefore, the a - b values of each pixel color of any input image can be substituted in Gaussian mixture models that has learnt in advance; after simple critical value judgment, the image result of paint line corresponding to input image can be obtained and its calculation definition is shown as below:

$$F(\mathbf{x}_i) = \begin{cases} 1, & p(\mathbf{x}_i|\Theta) \geq Th1 \\ 0, & otherwise \end{cases}, \quad (10)$$

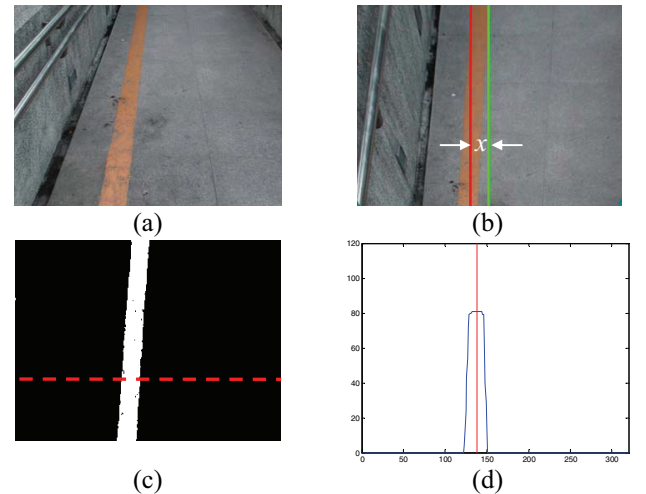


Figure 3. Example of paint line detection, (a) original input image, (b) aerial view of input image, (c) result of paint line detection, and (d) result of paint line position detection

where F represents the image result of paint line detection and $Th1$ is critical value 0.0005. Fig.3 is an example of paint line detection; Fig.3(a) is original input image; Fig.3(b) is the aerial view of input image after coordinate conversion; Fig.3(c) is result of paint line detection of the aerial view; the result shown in Fig.3(d) can be obtained by accumulating the 2/3

height of paint line image to its projection from the bottom to the horizontal axis; in Fig.3(d), we can find the mean value of the horizontal position corresponding to the maximum value, as shown by the red vertical full line in Fig.3(b) and (d), therefore, the width between the mean position to the imaging centre is defined as x (as pointed at by white arrow in Fig.3(b), where the green vertical line is the horizontal and center of image) and the variable quantity of x is defined as dx ; these two values are used as two input parameters of fuzzy control system, which will be introduced in the following chapter.

IV. FUZZY CONTROL OF WHEELCHAIR

In this paper, we used fuzzy logic to control wheelchair for tracking navigation because the advantage of fuzzy control is that it can express the expert knowledge as system easily to make the system closer to human thinking and comply with the nonlinear system in real world better. Fig.4 shows the fuzzy control system architecture proposed by us; the architecture includes two input parameters x and dx , and one output parameter is angular acceleration of wheelchair; a_1 and a_2 in the figure stand for normalized coefficients of input parameters and normalize input parameters to values within $[-1, 1]$; a_3 represents the output value, which was changed from output parameter by $[-1, 1]$ to corresponding motor control; Fig.5, 6 and 7 show triangular fuzzy membership function corresponding to input parameters x and dx , and angular acceleration of output, we use triangular membership functions, the main reason is simplify computation, and effective expression expert knowledge; each input parameter has 5 membership functions: $\{LE, LC, CE, RC, RI\}$ and $\{LE', LC', CE', RC', RI'\}$, where LE means Left, LC means Left Center, CE means Center, RC means Right Center, RI means Right, each output parameter has 5 membership functions: $\{NM, NS, ZE, PS, PM\}$, where NM means Negative Medium, NS means Negative Small, ZE means Zero, PS means Positive Small, PM means Positive Medium, so there are 25 fuzzy rules in the rule base; table 1 lists membership functions of output corresponding to fuzzy rules; Fig.8 is the output fuzzy graph of fuzzy control system.

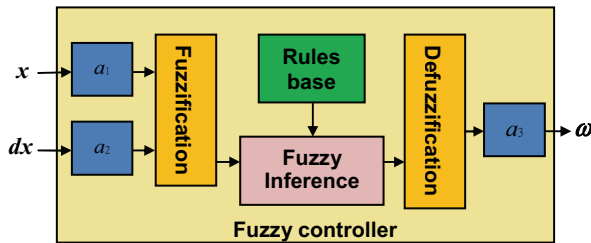


Figure 4. Fuzzy control system of wheelchair

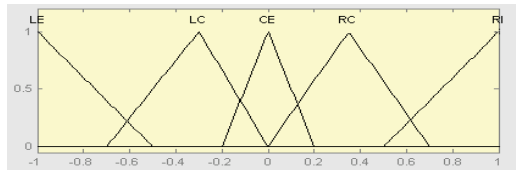


Figure 5. Membership function of input x

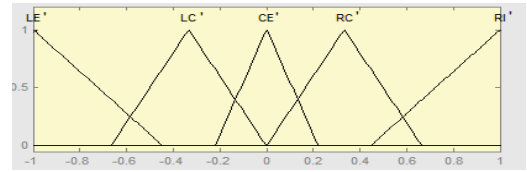


Figure 6. Membership function of input dx

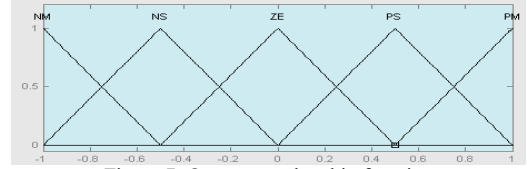


Figure 7. Output membership function

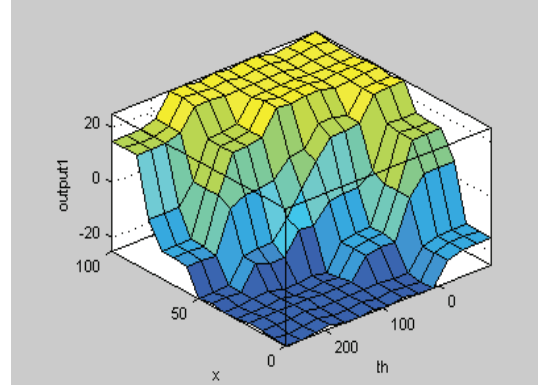


Figure 8. Output figure of fuzzy control system

TABLE 1. RULE BASE OF FUZZY CONTROL SYSTEM

$x \backslash dx$	LE	LC	CE	RC	RI
LE'	NS	PS	PM	PM	PM
LC'	NM	NS	PS	PM	PM
CE'	NM	NM	ZE	PM	PM
RC'	NM	NM	NS	PS	PM
RI'	NM	NM	NM	NS	PS

V. EXPERIMENTAL RESULT

In this paper, to verify the method proposed by us can complete paint line detection and automatic tracking navigation effectively, we conducted a simulated experiment and an actual test, which will be described below respectively.

A. Simulation test of wheelchair motion equation

To verify that the fuzzy control system can be applied to wheelchair control, we first use the equation of wheelchair motion to simulate the tracking control performance of wheelchair; Fig.9 is a schematic diagram of a robotic wheelchair which is driven mainly by two rear wheels; the two front wheels are steering auxiliary wheels which can support 360-degree steering and are used to stabilize wheelchair besides direction control; v stands for velocity of wheelchair and ϕ for the included angle between wheelchair and paint line; assume the right and left wheel velocities are defined as ω_r and ω_l and tyre radius of driving wheel of wheelchair is r , and then the velocity of the right and left wheels can be defined as:

$$v_l = r\omega_l \quad \text{and} \quad v_r = r\omega_r. \quad (11)$$

Since wheelchair velocity can be expressed as $v = (v_r + v_l)/2$, substitute the equation (11) into it and we can get:

$$v = \frac{r}{2}(\omega_r + \omega_l). \quad (12)$$

Finally, we can get the equation of wheelchair motion:

$$\dot{y} = v \cos(\phi), \dot{x} = v \sin(\phi), \text{ and } \dot{\phi} = \omega, \quad (13)$$

where $\dot{y}$ and $\dot{x}$ refer to the variable quantity in the direction of x and y , and $\dot{\phi}$, the variable quantity of angle, is the angular velocity of wheelchair. Simulate the motion of wheelchair with the equation of wheelchair motion and fuzzy control and the result is shown in Fig.10, where the red block stands for wheelchair and the green arrow stands for the moving direction and the blue curve for the position of paint line; in this example, assume the initial position of wheelchair is 20 cm from the right of paint line and the wheelchair moves in parallel with the paint line; it is found after simulation of fuzzy control that the wheelchair approaches the paint line slowly and moves forward along the paint line indeed. Fig.11 shows x , the distance between wheelchair and paint line; Fig.12 shows the angle between wheelchair and paint line.

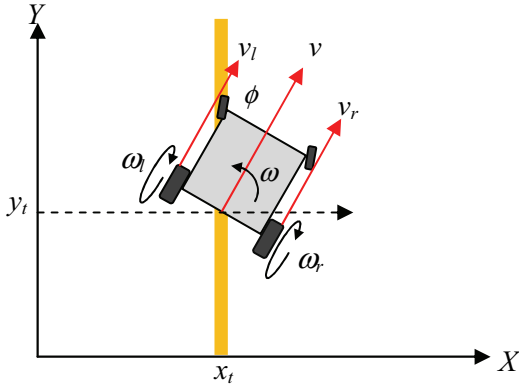


Figure 9. Motion model of wheelchair

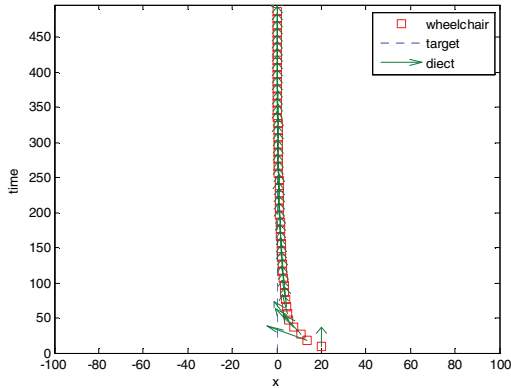


Figure 10. Lane following navigation simulation

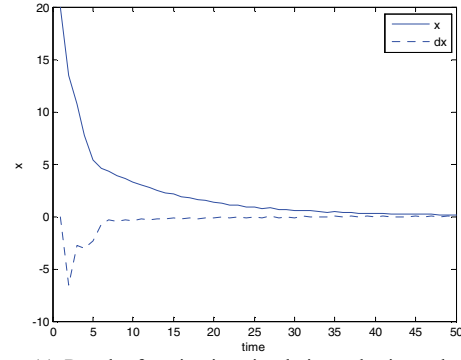


Figure 11. Result of navigation simulation at horizontal position

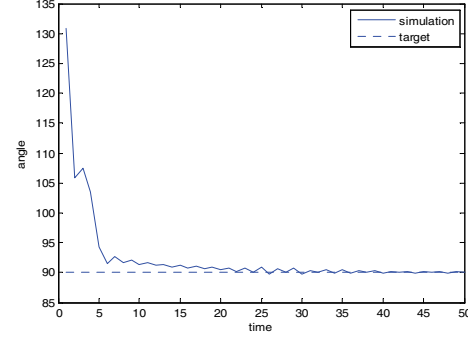


Figure 12. Result of navigation simulation at angle

B. Field testing

For this experiment, we divided it into two parts for description, namely, paint line detection and field test; for paint line detection, we performed it based on the effect of Gaussian functions of different numbers on Gaussian mixture models; we used GMM with best Gaussian function numbers to complete the field test. They will be discussed and described separately below:

First, perform test on paint line detection based on Gaussian functions of different numbers; we used images in different environment and under different light sources for tests; the results of paint line detection by GMMs with 1, 3, 5 and 10 Gaussian functions separately were used in the experiment (Fig. 15); it could be found from the experimental result that the result based on 1 Gaussian function was the worst; the result based on 3 Gaussian functions was much better than that of 1 Gaussian function; the result based on 5 and 10 Gaussian functions were improved, compared with that of 3 Gaussian functions under certain condition; there was little difference between detection results based on 5 and 10 Gaussian functions, therefore, we used GMM with 5 Gaussian functions for the subsequent tests.

Next test on environment of barrier-free path was performed; we experimented with a barrier-free space in campus, which included two paths which were a straight path of paint line as shown in Fig.13(a) and a quarter-turn curve path as shown in Fig.13(b) with the overall length of 40m; upon the start of the experiment, we pointed the camera on wheelchair at the position 20cm from the right of paint line and made it parallel to the paint line; the wheelchair advanced at about 5 km/h; because the camera was not completely against the paint line direction at first, it was obvious that the

wheelchair moved to the left after program execution in an attempt to make the camera pointing at the paint line; Fig.14 shows x , the distance between paint line and the horizontal center of image during experiment; it can be seen clearly from Fig.14(a) that the distance between paint line in image and the horizontal center of image was -20cm at first and it approached zero slowly, which took about 1second (10~15 frames/sec), and then the wheelchair moved forward along the paint line; Fig.14(b) shows the result of experiment in the quarter-turn curve path, from which we can find that the wheelchair entered the turn in 380 frame, when the distance between paint line in image and the median of image was significantly negative (as pointed by the first arrow in Fig.14(a)) and the wheelchair turned left; immediately the wheelchair approached paint line slowly(as pointed by the second arrow in Fig.14(b)); at last, x , the distance between paint line and the center of image, approached zero again and the wheelchair moved forward along the paint line continuously. Table 2 shows the performance of paint line detection and the MSE defines as following:

$$MSE = \frac{1}{N} \sum_{i=1}^N x_i^2, \quad (14)$$

where N is the number of frames.



Figure 13. Actual testing environment (rainy day), (a) path of straight paint line, (b) path of curve paint line

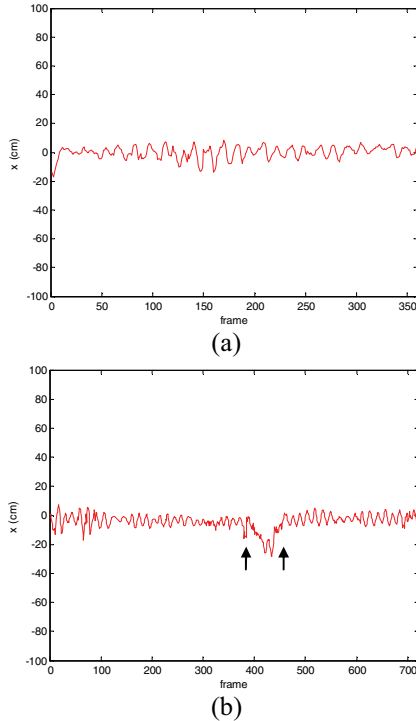


Figure 14. Result of navigation in real barrier-free route, (a) path of straight paint line, (b) path of curve paint line

TABLE 2. THE DETECTION ACCURACY AND THE CONTROLLER MSE

Scene	Frames	Hit	Miss	Accuracy (%)	MSE(cm ²)
1	6,420	6,420	0	100.00	9.05
2	3,615	3,609	6	99.83	25.05
3	7,111	7,111	0	100.00	23.01
Average	5715.33	5713.33	2	99.94	19.04

VI. CONCLUSION AND FUTURE RESEARCH

In this paper, we constructed an intelligent robotic wheelchair equipped with automatic tracking navigation, which used video paint line detection and fuzzy logic control for automatic tracking navigation of wheelchair; for paint line color detection, we proposed a robust method to detect color of paint line, which is suitable for indoor and outdoor barrier-free path; in addition, for wheelchair control, we used fuzzy logic to complete the control system of robotic wheelchair and the system is actually tested in experiment of barrier-free path in campus, including straight and curve barrier-free paths; the result shows the system could make the wheelchair move along the paint line correctly and the mean deviation was kept within ± 10 cm. In future research, the robotic wheelchair will be equipped with ultrasonic range sensors all around to avoid colliding pedestrians or obstacles on barrier-free paths and we will build an intelligent robotic wheelchair with automatic obstacle-avoidance navigation, drawing on the ultrasonic sensor, besides completing automatic paint line detection tracking navigation.

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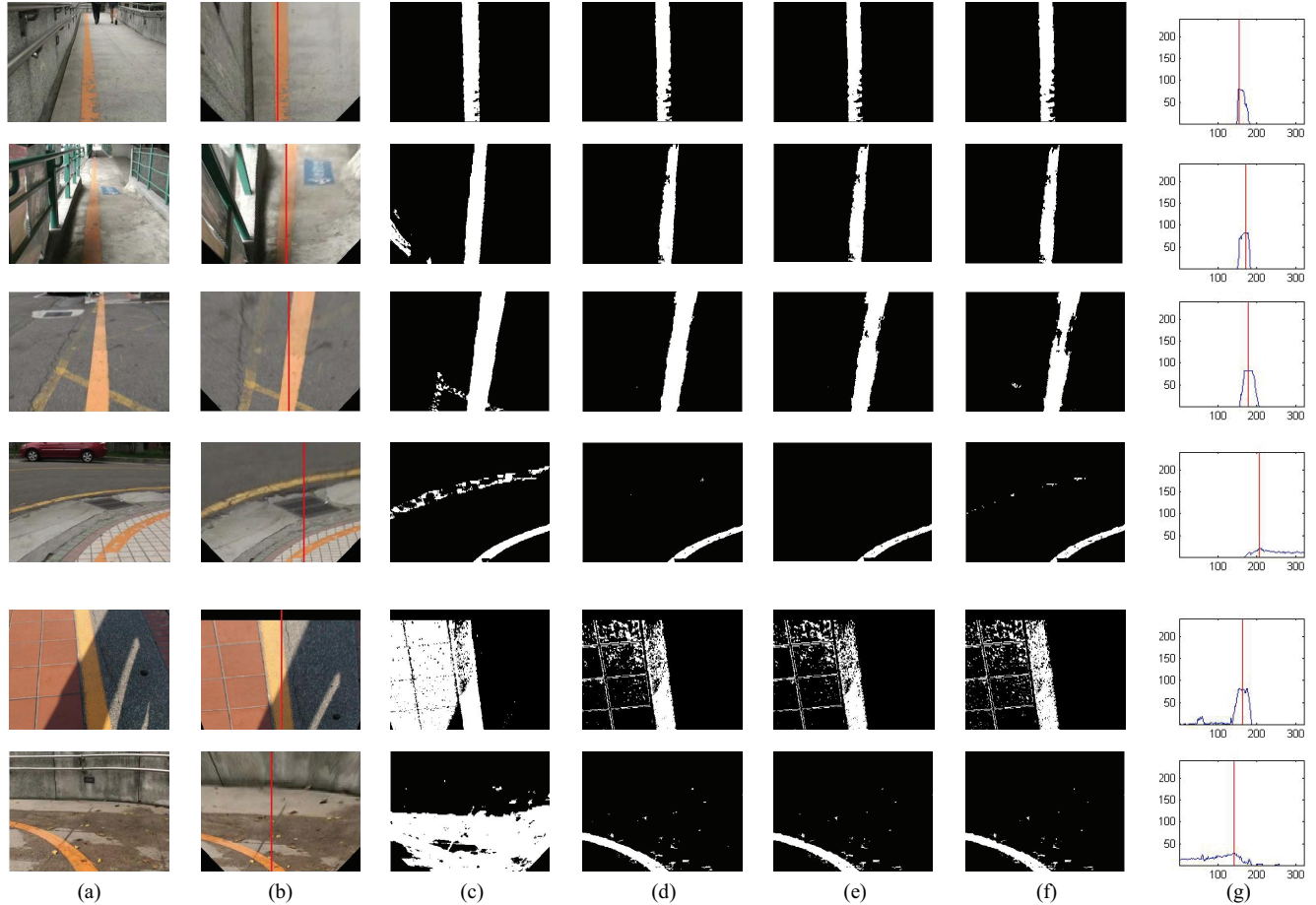


Figure 15. The some results of paint line detection, (a) input images, (b) aerial view of input images(c)-(f) K = 1, 3, 5, and 10 Gaussian mixture models, (g) paint line vertical accumulation values(K = 5).