Design of Visual Servo Controller using Color Coordinate System Transformation in Mobile Robot

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Abstract : *In this paper, color coordinate system transformation based visual servo controller has been considered. Mobile robot always has a position error and an orientation error resulted from wheel slipping etc.. Even more, the errors have accumulative properties. So feedback from environments is important. In this paper, by using <L, a, b> color model faster land mark extraction can be achieved. And the global position and the orientation of mobile robot can be known by only two land marks positions in image coordinate system. Finally, the adoption of visual information in path tracking problem makes visual servo control.*

1. Introduction

Recently by the aid of fast computer processing abilities, the study on mobile robots with colored CCD camera is briskly growing. The research area on mobile robot system is composed of 3 parts roughly. One is study on algorithm about path generation. Another is on path tracking algorithm, which path is given. And the algorithm for position estimation which can be known the position and the azimuth of mobile robot is the last subject.[1][2] This paper suggest the position estimation algorithm using colored CCD camera which realized the environment feedback and apply path tracking algorithm.

1.1. Previous Work

To find the junction point which meets horizontal line and vertical line in corridor environment one used edge detect algorithm such as Sobel operator etc. as pre-processing and performed Hough Transformation to extract straight lines.[4] But, the processing time in hough transformation is too long and this makes real time visual servo processing impossible Even more, it is not desirable to take such manner as converting color information to gray scale.

1.2. Suggest

The color coordinate system transformation method used in this paper is following such manner that one locates artificial land- marks distinguishable by color in the work space of robot movement and from these, the present position and azimuth information can be known.[5] In several color coordinate systems, <L,a,b> color model which can maximize color difference is used in this paper and this method makes the land marks position recognition faster. This paper composed of 3 parts. In chapter 2, color model, color coordinate system transformations, and the properties of each coordinate system were mentioned. And in chapter 3 extracting landmarks from single camera is mentioned and derives the equations finding the position and azimuth of mobile robot in world coordinates system. Finally in chapter 4, designing visual servo system which following given path is derived from the information of chapter 3.

2. Color Coordinate System Transformation

This chapter deals with the method of fast land-marks extraction by color coordinate system transformation.

2.1. Color Coordinate System

- C.I.E.X.Y.Z. system

In RGB color model as 3 primary sources of light, some frequencies make the tristimulus value negative. This means that the light of that frequency can not be reproduced. This has led to the development of C.I.E.X.Y.Z. system with hypothentical primary sources such that all the spectral tristimulus values are positive. This is a convenient coordinate system for color-metric calculations even the primary sources are physically unrealizable. Y represents the luminance of the color. The X,Y,Z coordinates are related to the R.G.B. system via the linear transformation. Transformation equation is as follows.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.490 & 0.310 & 0.200 \\ 0.177 & 0.813 & 0.011 \\ 0.000 & 0.010 & 0.990 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \qquad (1)$$

- L, a, b system

The X,Y,Z, values achived C.I.E.X.Y.Z model give a useful color difference formula. After applying X,Y,Z to the L,a,b transformation formula, new relations between brightness and color is achived.

$$L = 25\left(\frac{100Y}{Y_0}\right)^{1/3} - 16, \quad 1 \le 100Y \le 100 \qquad (2)$$

$$a = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{Y}{Y_0}\right)^{1/3}\right] \qquad (3)$$

$$b = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right] \qquad (4)$$

L : brightness, a : red-green component,

B : yellow-blue component $X_0 = Y_0 = Z_0 = 1$

3. Design of Position Estimation System

3.1. Structure of mobile robot system

The mobile robot used this paper is below PIONEER I robot which CCD camera is located front up side and has fixed tilt angle. Each coordinate system is configured as Fig.1

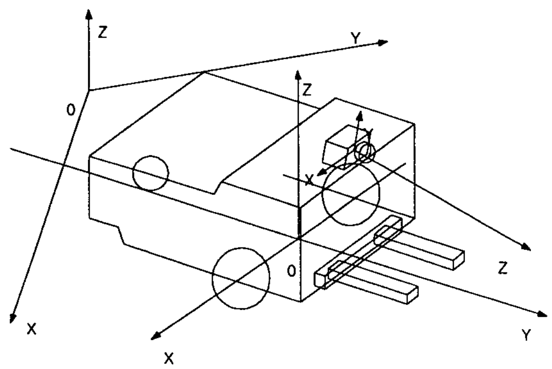

Fig. 1

3.2. The relation between image coordinate and robot coordinate system

A camera is device that maps 3-dimensional space to 2-dimensional plane surface, so a point shown in 2-d surface is corresponds to light in 3-d space. To overcome this, one can take multi camera configuration, or achieve several images from single camera, or use mark objects, singular point of environment to achieve geometric relation and the 3-d information can be achieved. In this paper once land-marks were extracted the constraint condition that make the value of Z-coordinate set to 0 is applied. Basic assumption is as follows.

1) The straight line in 3-d space is projected on camera image as straight line.
2) Landmarks are locating on Z=0 surface of global coordinates system.

3.2.1. Correspondence of x coordinates

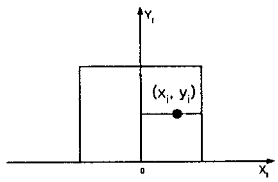

Fig.2 Image Coordinates System

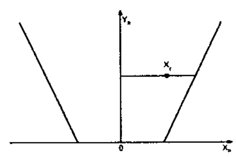

Fig 3. Robot Coordinates System

From the assumption that straight line corresponds to straight line, any point (x_i, y_i) in image coordinates system is corresponds to specified point of robot coordinates system. The value of x coordinates increases as y value of image coordinates system increases and has linear relations.

$$x_r = K * x_i + P \qquad (5)$$

x_r : x value in robot coordinates system

x_i : x value in image coordinates system

if $x_i = 0$, $x_r = 0$ so $P = 0$ and K varies with y_i linearly. Therefore,

$$x_r = (a * y_i + b) * x_i \qquad (6)$$

where, a, b : mapping parameters

3.2.2. Correspondence of y coordinates

Now the relation ship between y coordinates is derived.

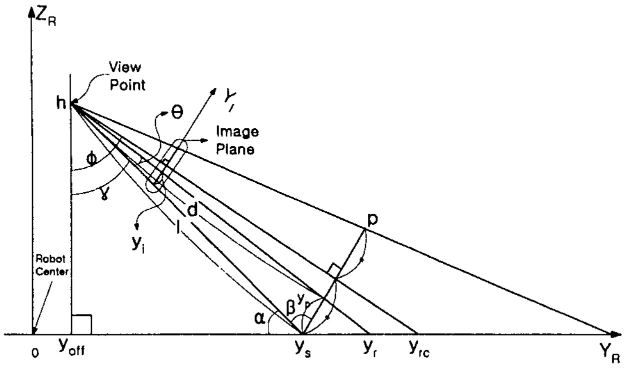

Fig 4

Fig.4 shows the slice surface of $X_R = 0$. Image plane is virtual plane captured by CCD camera. The points on the $Z_R = 0$ is projecting on image plane.

- Key variable definitions
- y_r : y value in robot coord. Sys.
- y_i : y value in image coord. Sys.
- y_{off} : distance from the center of robot to camera view point along y axis.
- y_{rc} : y value in robot coord. sys. projected center of camera
- β : a side angle of isosceles triangle hy_sp
- γ : $\angle y_{off} h y_s$
- θ : $\angle y_s h y_r$
- ϕ : the tilt angle of camera

y_r can be calculated as follows from the geometric relation of Fig. 4

$$y_r = h\tan(\gamma + \theta) + y_{off} \tag{7}$$

The triangle formed of view point and image plane and the triangle hy_sp has a relation of similar figure.

$$y_p = my_i \quad (m : \text{similarity}) \tag{8}$$

$$m = \frac{\overline{y_p}}{y_i} \tag{9}$$

m is calculated first one time from the ratio of real distance y_p that is known and y_i. From the geometric relations of Fig 4.

$$\gamma = 90° - \tan^{-1}\left(\frac{h}{y_s - y_{off}}\right) \tag{10}$$

$$\theta = \cos^{-1}\left(\frac{l - y_p\cos\beta}{\sqrt{l^2 + y_p^{\ 2} - 2ly_p\cos\beta}}\right) \tag{11}$$

Final formula to get y_r is as follows.

$$y_r = h\tan\left(90° - \alpha + \cos^{-1}\left(\frac{l - my_i\cos\beta}{\sqrt{l^2 + (my_i)^2 - 2lmy_i\cos\beta}}\right)\right) + y_{off} \tag{12}$$

where,

$$l = \sqrt{h^2 + (y_s - y_{off})^2} \tag{13}$$

$$\alpha = \tan^{-1}\left(\frac{h}{y_s - y_{off}}\right) \tag{14}$$

$$\beta = 180° - \tan^{-1}\left(\frac{h}{y_s - y_{off}}\right) - \tan^{-1}\left(\frac{y_{rc}}{h}\right) \tag{15}$$

h, y_s, y_{off}, m can be measured, therefore Fig.12 is non linear function of y_i and calculate y_r uniquely

3.3. Position Estimation in World Coordinates System

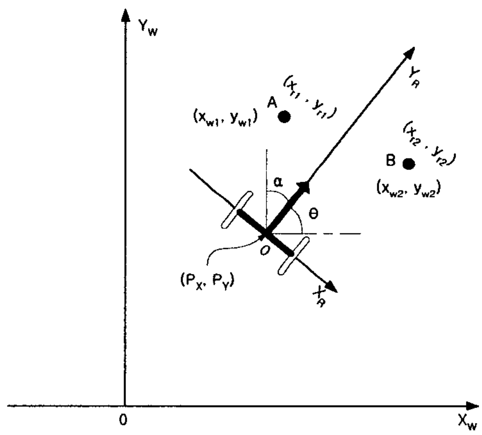

Fig. 5

Let (x_{r1}, y_{r1}), (x_{r2}, y_{r2}) be the coordinates value of landmarks A,B in robot coord. sys. And let the coordinates value of these points be (x_{w1}, y_{w1}), (x_{w2}, y_{w2}) which are known values. The points A,B on world coord. sys. can be thought as the result of rotating α following translating (P_X, P_Y). Let mapping matrix ${}_wT^R$ be matrix that maps one point in robot coord. sys. to the point in world coord. sys.

$$
{}_wT^R = \begin{pmatrix} 1 & 0 & P_X \\ 0 & 1 & P_Y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}
$$

$$
= \begin{pmatrix} \cos\alpha & \sin\alpha & P_X \\ -\sin\alpha & \cos\alpha & P_Y \\ 0 & 0 & 1 \end{pmatrix} \tag{16}
$$

as $\alpha + \theta = 90°$

$$
\begin{pmatrix} x_w \\ y_w \\ 1 \end{pmatrix} = \begin{pmatrix} \sin\theta & \cos\theta & P_X \\ -\cos\theta & \sin\theta & P_Y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_r \\ y_r \\ 1 \end{pmatrix} \tag{17}
$$

Applying the relation of (17) to A,B points

$$x_{w1} = x_{r1}\sin\theta + y_{r1}\cos\theta + P_X \tag{18}$$

$$y_{w1} = -x_{r1}\cos\theta + y_{r1}\sin\theta + P_Y \tag{19}$$

$$x_{w2} = x_{r2}\sin\theta + y_{r2}\cos\theta + P_X \tag{20}$$

$$y_{w2} = -x_{r2}\cos\theta + y_{r2}\sin\theta + P_Y \tag{21}$$

writing about $\sin\theta$,

$$\sin\theta = \frac{(x_{w1} - x_{w2})(x_{r1} - x_{r2}) + (y_{w1} - y_{w2})(y_{r1} - y_{r2})}{(x_{r1} - x_{r2})^2 + (y_{r1} - y_{r2})^2} \tag{22}$$

writing about $\cos\theta$,

$$\cos\theta = \frac{(y_{r1} - y_{r2})(x_{w1} - x_{r2}) + (x_{r1} - x_{r2})(y_{w1} - y_{w2})}{(x_{r1} - x_{r2})^2 + (y_{r1} - y_{r2})^2} \tag{23}$$

therefore,

$$\theta = \tan^{-1}\left(\frac{(x_{w1} - x_{w2})(x_{r1} - x_{r2}) + (y_{w1} - y_{w2})(y_{r1} - y_{r2})}{(y_{r1} - y_{r2})(x_{w1} - x_{r2}) + (x_{r1} - x_{r2})(y_{w1} - y_{w2})} \right) \tag{24}$$

$$P_X = \frac{1}{2}(x_{w1} + x_{w2} - x_{r1}\sin\theta - y_{r1}\cos\theta - x_{r2}\sin\theta - y_{r2}\cos\theta) \tag{25}$$

$$P_Y = \frac{1}{2}(y_{w1} + y_{w2} + x_{r1}\cos\theta - y_{r1}\sin\theta + x_{r2}\cos\theta - y_{r2}\sin\theta) \tag{26}$$

4. Design of visual servo controller

Generally, state vector representing position and azimuth of mobile robot is defined by $p = (x \quad y \quad \theta)^T$.

$$
\dot{p} = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v \\ w \end{pmatrix} = Jq \tag{27}
$$

A stable controller proved by Lyapunov stability theorem has suggested by Y.Kanayama[6]

$$
q = \begin{pmatrix} v \\ w \end{pmatrix} = \begin{pmatrix} v(p_e, q_r) \\ w(p_e, q_r) \end{pmatrix} = \begin{pmatrix} v_r\cos\theta_e + K_x x_e \\ w_r + v_r(K_y y_e + K_\theta \sin\theta_e) \end{pmatrix} \tag{28}
$$

$$
p_e = \begin{pmatrix} x_e \\ y_e \\ \theta_e \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c & 0 \\ -\sin\theta_c & \cos\theta_c & 0 \\ 0 & 0 & 1 \end{pmatrix} (p_r - p_c) \tag{29}
$$

$p_r = (x_r \quad y_r \quad \theta_r)^T$ represents reference state that robot to keep and $p_c = (x_c \quad y_c \quad \theta_c)^T$ means present robot state. Now let's apply $p_c = (P_X \quad P_Y \quad P_\theta)^T$, then we can construct visual servo controller of mobile robot get feedback from environment

5. Results

Fig.6 shows experimental environment and mobile robot PIONEER I.

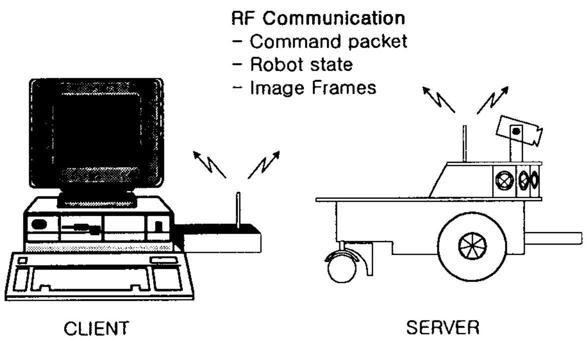

Fig. 6

Fig. 7 and Fig.8 show simulation results.

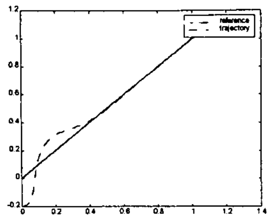

Fig. 7

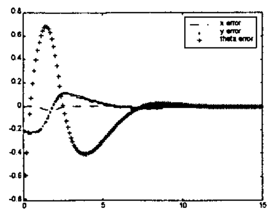

Fig.8

$(K_x = 10, K_y = 64, K_\theta = 12)$

Fig 7 is the result of tracking path that move from $(0 \quad 0 \quad \pi/4)^T$ at $v = 0.1, w = 0$ with mobile robot at initial state is $(0 \quad -0.2 \quad 0)^T$. Fig.8 shows the differences between reference states and present states.

0.009125	1.2625	465	315	1.333	990	630

Table 1. mapping parameters

Table 2. position of landmarks

x_{i1}	y_{i1}	x_{i2}	y_{i2}	P_X	P_Y	θ
-66	79	116	81	-2.049	10.019	90.197

Table 3. estimation position at practical $(0 \quad 0 \quad 90°)^T$

x_{i1}	y_{i1}	x_{i2}	y_{i2}	P_X	P_Y	θ
-86	64	62	97	-391.485	105.809	61.212

Table 4. estimation position at practical $(-400\ 100\ 60°)^T$

Fig. 9 shows actual tracking path applied to PIONEER I mobile robot.

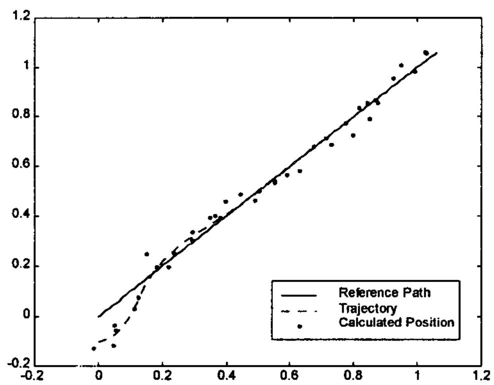

Fig. 9

- init position : $(0 \quad -0.1 \quad 0)^T$

- init path : $(0 \quad 0 \quad \pi/4)^T$, v=0.1 w=0

6. Conclusion

In this paper, by using artificial colored land marks and <L, a, b> color model faster land mark extraction can be achieved. And the robot states such as global position and the orientation can be estimated by only two land marks positions in image coordinate system. Finally, the adoption of visual information in path tracking problem makes visual servo control. To the previous robots which are tried visual feedback with environments, the processing time is too long because of complex pre-processings for visual process and algorithm for extracting land marks. So the visual process and the navigation process are separated and the mobile robots are operated in "Look and Move" type. By using suggested colored land marks and color coordinate system transformations, a fast land mark extraction is achieved and an efficient visual servo

a	b	y_s	h	m	y_{rc}	y_{off}

x_{w1}	y_{w1}	x_{w2}	y_{w2}
-133	915	224	904

system can be constructed.

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