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Human-following robot using infrared camera

Quoc Khanh Dang [1] and Young Soo Suh[2]

[1] Department of Electrical Engineering, University of Ulsan, Ulsan, Korea
(Tel : +82-52-524-1524; E-mail: khanhdq86@yahoo.com)
[2] Department of Electrical Engineering, University of Ulsan, Ulsan, Korea
(Tel : +82-52-259-2169; E-mail: yssuh@ulsan.ac.kr)

Abstract: Human-following robots have been researched and developed actively these decades due to its plentiful applications in daily life and manufacturing. A human-following robot requires several techniques such as human's target detection, robot control algorithm and obstacles avoidance. Various approaches of following robots have been proposed such as using ultrasonic sensors, voice recognition sensors, laser range sensors, charge-coupled device (CCD) camera and so on. These technologies detect the relative position between a mobile robot and a human. In this paper, we present a new approach in detecting position of a mobile robot using an infrared camera which is the basic technique in human following robot. In our experiment, a Wii camera, which captures four groups of IR-LEDs installed on the robot, is attached on a human. A simple application implemented in real time using a PI controller shows some advantages of the proposed method.

Keywords: human-following robot, mobile robot, infrared camera

1. INTRODUCTION

Together with the explosion of improving daily life services and manufacturing demands, human-following robots are used in numerous fields such as taking care of human in hospitals [1], carrying loads in industrial zones, airport, helping people during shopping. The most important thing in a human following robot is to estimate the relative position between the human and the robot. The robot in [1] uses CCD cameras for getting high resolution pictures of target person and the accurate recognition of the target is executed. In [2], a set of cameras hanging on the ceiling is used to form a sensor network and the positions of robot and human are determined in this network. To avoid losing target when cameras can not find the target, a voice recognition sensor is added so that the robot can inform the user and locate his position [3]. Another way to determine the distance from the robot to human or obstacles in some special conditions like smoky environment is using ultrasonic sensors [4], [5].

However, CCD camera can lose its information in gentle light environment such as dark room and ultrasonic sensors give low performance. Thus, in this research, we propose an infrared camera. So that high accuracy of relative position of a human and a robot can still be obtained even in gentle light.

The paper is organized into three parts. Section II shows system structure and how to estimate the relative positions between a human and a mobile robot. In Section III, an experiment is carried out to verify the quality of the proposed method. Some conclusions and future works are given on Section IV.

2. SYSTEM OVERVIEW AND BACKGROUND

2.1 System overview

The system is given in Fig 1. It consists of an infrared camera which is attached on human and captures four points of IR-LED installed on the robot. When the camera sees all of four IR-LEDs in the mobile robot, the position and orientation of the camera with respect to the mobile robot coordinate and vice versa will be calculated.

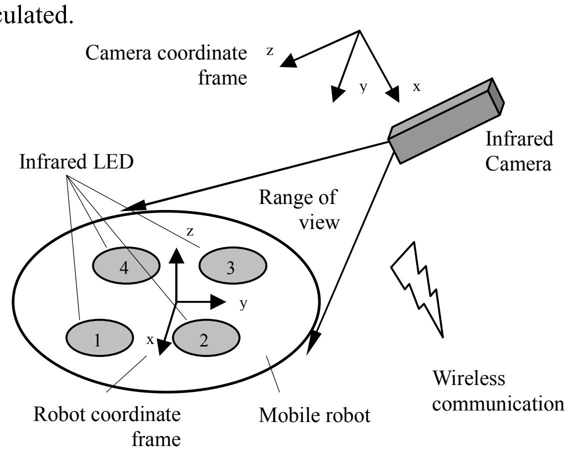

Fig. 1 The system overview.

After getting camera's position and orientation information, a virtual link between human and robot, which could be the distance from the robot to human, is created. The robot will move the same distance as human moved to maintain this virtual link.

Denote that at the initial time, the position of the camera is (x_0, y_0) according to the robot coordinate frame. After moving, new position of the camera is (x_1, y_1) and thus the change of the camera position is given by

$$\Delta_x = x_1 - x_0$$
$$\Delta_y = y_1 - y_0 .$$

To remain the distance from the robot to human, robot will move to the position (Δ_x, Δ_y) in its coordinate. The robot orientation, denoted φ_r , is the

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angle between y axis of the robot and the projection of x axis direction vector of the camera coordinate frame to the $z = 0$ plane in robot coordinate frame.

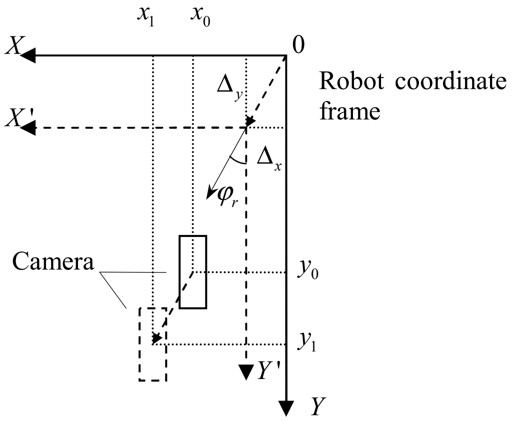

Fig. 2 Target coordinate of the robot.

Computed $\Delta_x, \Delta_y, \varphi_r$ are transmitted to the robot's controller so that robot will move to a new position with the direction based on φ_r.

2.2 Background algorithm

At least four points of IR-LED are necessary for position and orientation computing [6] so that we use four points of IR-LED as in Fig. 1. The positions and labels (counterclockwise) of these points are known in the robot coordinate frame.

$P_{i,c}, P_{i,w}$ $(i = 1,2,3,4)$ are IR-LED points in the camera coordinate frame and robot coordinate frame, respectively.

$$P_{i,c} = s_i \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix}_c \quad P_{i,w} = \begin{bmatrix} x_i \\ y_i \\ 0 \end{bmatrix}_w$$

where s_i are scaling scalars.

We have the following basic equation [7]:

$$P_{i,c} = C_w^c P_{i,w} + r_c$$

or

$$s_i \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} = C_w^c \begin{bmatrix} x_i \\ y_i \\ 0 \end{bmatrix} + r_c \tag{1}$$

where C_w^c and r_c are the rotation matrix and the transition vectors from the robot coordinate frame to the camera coordinate frame, respectively.

Assume that $C_w^c = \begin{bmatrix} r_1 & r_2 & r_3 \end{bmatrix}$ and U_i, X_i are defined by

$$U_i = \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} \quad \mathrm{X}_i = \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix}.$$

From the equation (1), we have:

$$s_i \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} = \begin{bmatrix} r_1 & r_2 & r_3 \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ 0 \end{bmatrix} + r_c$$

or

$$s_i U_i = P X_i, \tag{2}$$

where $P = \begin{bmatrix} r_1 & r_2 & r_c \end{bmatrix}$.

Since X_i $(i = 1,2,3,4)$ are on the same plane, X_4 can be expressed by other points:

$$\alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 = X_4 \tag{3}$$

and the same to U_i

$$\beta_1 U_1 + \beta_2 U_2 + \beta_3 U_3 = U_4. \tag{4}$$

It is easy to find α_i and β_i from

$$\begin{aligned} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} &= \begin{bmatrix} X_1 & X_2 & X_3 \end{bmatrix}^{-1} X_4 \\ \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} &= \begin{bmatrix} U_1 & U_2 & U_3 \end{bmatrix}^{-1} U_4. \end{aligned} \tag{5}$$

From (2), (3), (4) and (5), we have

$$P\left(\alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3\right) = P X_4 = s_4 U_4$$

or

$$\alpha_1 s_1 U_1 + \alpha_2 s_2 U_2 + \alpha_3 s_3 U_3 = s_4 \left(\beta_1 U_1 + \beta_2 U_2 + \beta_3 U_3\right).$$

Thus we have

$$\alpha_i s_i = s_4 \beta_i \quad \left(i = 1,2,3\right).$$

Note that

$$\alpha_i s_i U_i = \alpha_i P X_i \Rightarrow s_4 \beta_i U_i = \alpha_i P X_i \Rightarrow s_4 \frac{\beta_i}{\alpha_i} U_i = P X_i.$$

Defying $\gamma_i = \dfrac{\beta_i}{\alpha_i}$, we have the following

$$s_4 \gamma_i U_i = \begin{bmatrix} r_1 & r_2 \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} + r_c \quad \left(i = 1,2,3\right).$$

s_4, r_1, r_2 and r_c are computed from the following optimization problem

$$\min_{s_4, r_1, r_2, r_c} \sum_{i=1}^{3} \left\| s_4 \gamma_i U_i - r_c - \begin{bmatrix} r_1 & r_2 \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} \right\|_2^2 \tag{6}$$

And it can be solved from following

$$\min \sum_{i=1}^{3} \left\| s_4 \tilde{U}_i - \begin{bmatrix} r_1 & r_2 \end{bmatrix} \begin{bmatrix} \tilde{x}_i \\ \tilde{y}_i \end{bmatrix} \right\|_2^2 \tag{7}$$

where

$$\tilde{x}_i = x_i - \bar{x} \qquad \bar{x} = \frac{1}{3} \sum_{i=1}^{3} x_i$$

$$\tilde{y}_i = y_i - \bar{y} \qquad \bar{y} = \frac{1}{3} \sum_{i=1}^{3} y_i$$

$$\tilde{U}_i = \gamma_i U_i - \bar{U} \qquad \bar{U} = \frac{1}{3} \sum_{i=1}^{3} \gamma_i U_i.$$

The solution for (7) is

$$\begin{bmatrix} r_1' \\ r_2' \end{bmatrix} = \begin{bmatrix} v & 0 \end{bmatrix} u' \Rightarrow \begin{bmatrix} r_1 & r_2 \end{bmatrix} = u \begin{bmatrix} v' \\ 0 \end{bmatrix},$$

where u and v are obtained from singular value decomposition:

$$\sum_{i=1}^{3} \tilde{U} \begin{bmatrix} \tilde{x}_i & \tilde{y}_i \end{bmatrix} = u \begin{bmatrix} \Sigma \\ 0 \end{bmatrix} v'.$$

Once r_1 and r_2 are computed, r_3 can be obtained from $r_3 = r_1 \times r_2$.

And r_c can be calculated from matrix form of the optimization problem (6)

$$\min \sum_{i=1}^{3} \left\| \begin{bmatrix} \gamma_i U_i & -I \end{bmatrix} \begin{bmatrix} s_4 \\ r_c \end{bmatrix} - \begin{bmatrix} r_1 & r_2 \end{bmatrix} \begin{bmatrix} x_i \\ y_i \end{bmatrix} \right\|_2^2 = \min \left\| A \begin{bmatrix} s_4 \\ r_c \end{bmatrix} - b \right\|$$

where

$$A = \begin{bmatrix} \gamma_1 U_1 & -I \\ \gamma_2 U_2 & -I \\ \gamma_3 U_3 & -I \end{bmatrix}, \quad b = \begin{bmatrix} \begin{bmatrix} r_1 & r_2 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} \\ \begin{bmatrix} r_1 & r_2 \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \end{bmatrix} \\ \begin{bmatrix} r_1 & r_2 \end{bmatrix} \begin{bmatrix} x_3 \\ y_3 \end{bmatrix} \end{bmatrix}.$$

The solution is given by

$$\begin{bmatrix} s_4 \\ r_c \end{bmatrix} = \left(A'A \right)^{-1} A'b.$$

2.3 Position and orientation estimation

After C_w^c and r_c are obtained, at the initial time, the virtual link between human and robot is calculated by the projection of human in $z = 0$ plane of robot's coordinate. Since the camera is attached on the human, the position of the human is $(0,0,0)$ in the camera coordinate frame.

From the basic equation, we have

$$\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} = C_{0w}^c \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} + r_{c0} \Rightarrow \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} = -\left(C_{0w}^c \right)' r_{c0}.$$

Where we used the fact that C_w^c is an orthogonal matrix. We obtain (x_0, y_0, z_0) which is the initial position of human in robot's coordinate frame. As human moves to new position (x_1, y_1, z_1), the position is calculated by

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = -\left(C_{1w}^c \right)' r_{c1}.$$

So that in $z = 0$ plane of robot's coordinate frame, the human moves amount of

$$\Delta_x = x_1 - x_0$$
$$\Delta_y = y_1 - y_0.$$

To maintain the distance with human, robot will move to position (Δ_x, Δ_y).

The orientation of the robot φ_r is defined by the angle of the projection direction vector of x axis (camera coordinate) to the $z = 0$ plane (robot coordinate) and y axis of robot coordinate.

Let the points in $z = 0$ plane of robot coordinate frame where x and z axis of camera coordinate point to be $(x_p, y_p, 0)$, $(x_t, y_t, 0)$, respectively. From

$$\begin{bmatrix} m \\ 0 \\ 0 \end{bmatrix} = C_w^c \begin{bmatrix} x_p \\ y_p \\ 0 \end{bmatrix} + r_c \text{ and } \begin{bmatrix} 0 \\ 0 \\ n \end{bmatrix} = C_w^c \begin{bmatrix} x_t \\ y_t \\ 0 \end{bmatrix} + r_c$$

we can easily get (x_p, y_p) and (x_t, y_t) when C_w^c and r_c are known. Therefore, φ_r is calculated by $\varphi_r = \arctan 2(x_p - x_t, y_p - y_t)$.

3. EXPERIMENTS

The camera board includes a Nintendo Wii camera and an ATMega128 processor. The data from Wii camera is transmitted to PC through RS232 to calculate C_w^c, r_c, Δ_x, Δ_y and φ_r.

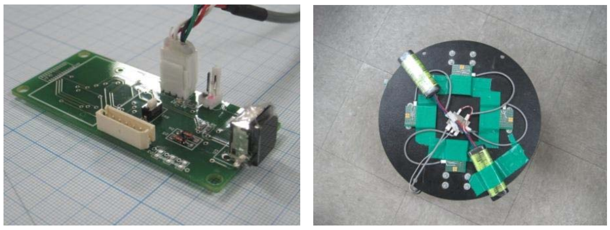

Fig. 4 Infrared Wii camera board and four IR-LEDs mobile robot.

In the first experiment, we verify the accuracy of proposed algorithm by capturing four IR-LEDs which are installed on a panel and have the center point at 15cm height from the table. In this experiment, the panel is fixed and the camera is attached on a box with 7cm height (see Fig. 5). Since the camera always points to the center of four LEDs but has 8cm difference in height (y axis) so that the r_c will be $(0, -8, r_{cz})$ cm. Take some data of r_c when camera moves in different angle, denoted φ, with respect to z axis of panel's coordinate. The results, in centimeter, are given in following table:

Table 1 $\varphi = 20^0$.

$r_{cz-real}$	r_{cx}	r_{cy}	r_{cz}
60	-0.18	-7.90	59.67
70	0.13	-7.92	68.64
80	0.07	-7.89	79.26
90	0.17	-7.74	88.50
100	-0.16	-7.74	99.11

Table 2 $\varphi = 10^0$.

$r_{cz-real}$	r_{cx}	r_{cy}	r_{cz}
60	-0.16	-7.80	59.09
70	-0..5	-7.84	68.99
80	-0.14	-7.70	78.93
90	-0.16	-7.62	88.70
100	0.14	-7.90	98.93

Table 3 $\varphi = 0^0$.

$r_{cz-real}$	r_{cx}	r_{cy}	r_{cz}
60	-0.04	-7.79	58.92
70	-0.10	-7.82	69.00
80	-0.23	-7.69	78.92
90	-0.54	-7.57	88.67
100	-0.07	-7.94	98.88

Table 4 $\varphi = -10^0$.

$r_{cz-real}$	r_{cx}	r_{cy}	r_{cz}
60	-0.34	-7.77	59.01
70	-0.56	-7.78	68.40
80	-0.37	-7.62	78.45
90	-0.04	-7.48	89.53
100	-0.07	-7.68	99.37

Table 5 $\varphi = -20^0$.

$r_{cz-real}$	r_{cx}	r_{cy}	r_{cz}
60	-0.57	-7.91	59.52
70	-0.29	-7.80	68.84
80	-0.40	-7.47	77.65
90	-0.65	-7.49	89.67
100	-0.38	-7.19	98.02

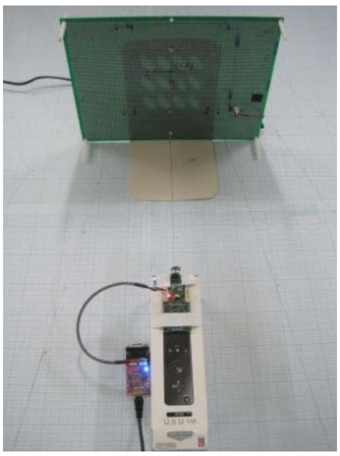

Fig. 5 Four IR-LED points panel and Wii camera

The average values are:

$\overline{r}_{cx} = 0.25$ $\overline{r}_{cz-60} = 59.24$ $\overline{r}_{cz-80} = 78.64$ $\overline{r}_{cz-100} = 98.86$

$\overline{r}_{cy} = 7.72$ $\overline{r}_{cz-70} = 68.77$ $\overline{r}_{cz-90} = 89.01$

That means the errors are acceptable (less than 1.5cm) when using this system in real-life application such as following carts in supermarkets.

In the second experiment, a two wheel mobile robot follows a human in a straight line. Instead of using single IR-LED, to increase the infrared light and range of view, four groups of IR-LED are installed on the top of the robot. The camera board is attached at human's back and point to the robot. As human walks, the robot follows. The distance between the camera position and the point where the camera is pointing to in robot coordinate frame will be maintained (see Fig. 6). The mobile robot moves to the destination point so that a virtual bar is created between the human and the robot.

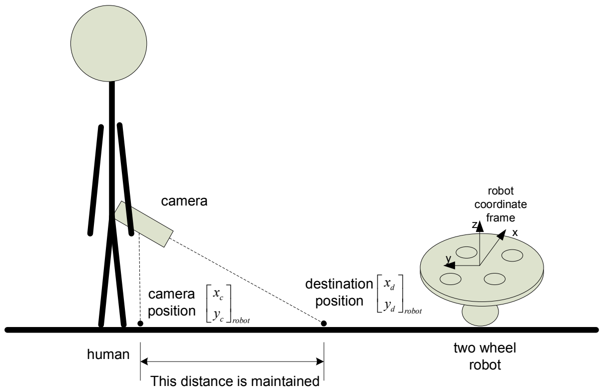

Fig. 6 Overview of the second experiment.

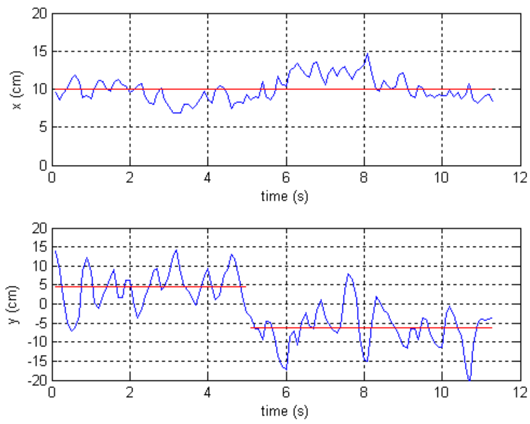

Fig. 7 The coordinates of the robot's destination in the robot coordinate frame.

Since human moves in a straight line, only the y coordinate of the robot's destination where the camera is pointing to is considered. A threshold of 5cm is created around the destination. If the robot is in this circle, it will not move. As can be seen from Fig. 7, the human moves forward and backward in a straight line which is 10cm off from y-axis of the robot coordinate frame. Fig.

8 is the position of the camera inside the robot coordinate frame. It indicates that the position of the camera is in around of (10cm, -50cm) point of the robot coordinate frame.

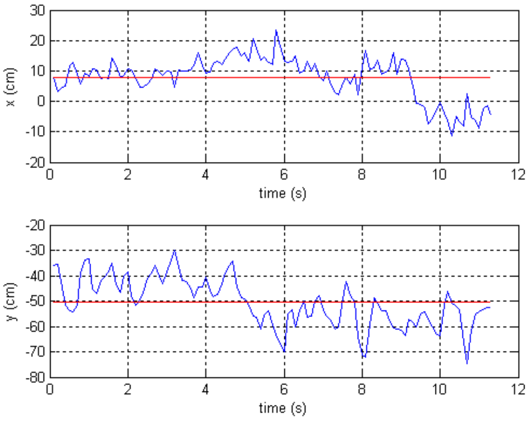

Fig. 8 The coordinates of the camera in the robot coordinate frame.

4. CONCLUSIONS AND FUTURE WORKS

A new approach for a human-following robot is proposed. Using infrared lights as artificial landmarks is developed in some researches such as [8], [9]. The useful application is using this system in gentle light environment where grey or color CCD cameras are limitative. Nintendo Wii infrared camera is used in this research. The advantage of this camera is its low cost so that this research could be applied in real life such as in automatic following cart in super markets.

Future research is to integrate an inertial sensor for improving the accuracy of the system and avoiding losing position when IR-LEDs are out of camera's range of view.

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