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Image Feature based Navigation of Nonholonomic Mobile Robots with Active Camera

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Abstract: This paper proposes an image feature based navigation method for active camera mounted mobile robots that are affected by nonholonomic constraint. Since visual servo used for usual manipulators can't be applied to the nonholonomic mobile robots as it is, visual servo is applied to tracking control of the active camera to track targets in the center of image plane. Moreover, posture of nonholonomic mobile robots from targets is controlled by image features of targets that are related to relative distance and angle between robots and targets. It is confirmed that the proposed method can navigate a mobile robot in front of a target through simulations.

Keywords: Active camera, Image features, Nonholonomic mobile robots, Visual servo.

1. INTRODUCTION

Recently, robots are expected to perform tasks not only in manufacturing fields, such as factories but also in human environment such as hospitals and offices. However, they are dynamical environments that are not prepared for robots like factories. Therefore, robots are required to take surrounding environmental information through external sensors, and to act autonomously based on the information.

Some examples of external sensors for robots are distance sensors using laser or sonar [1, 2] and force sensors. Compared to these sensors, vision sensors such as CCD cameras are very useful for obtaining surrounding environmental information because they can obtain much environmental information visually.

As researches of mobile robots with cameras, a method to control mobile robots by instructed image or landmarks [3, 4] and an obstacle avoidance method utilizing a potential field formed by camera that placed on ceiling [5] have been proposed. In this research, we focus on visual servo [7] that feeds back images obtained from cameras to control robots [6]. Since the visual servo is "look and move" dynamical visual feedback, where vision sensors are inside feedback loop, robots can act reflexively using visual information. However, visual servo used for usual manipulators can't be applied to wheel type nonholonomic mobile robots as it is. Visual servo methods for nonholonomic mobile robots [8, 9] have been proposed. However, motion of mobile robots is restricted extremely because cameras mounted on mobile robots must be fixed to execute each method. This paper proposes an image feature based navigation method in front of targets, where the method expands movable range of nonholonomic mobile robots by applying active cameras for pan angle. Concretely, visual servo is applied to pan angle of cameras to track targets. Posture of nonholonomic mobile robots from targets is controlled by image features of targets captured by the active cameras that are related to relative distance and angle between robots and targets.

The paper is organized as follows. Chapter 2 shows the precondition in this research. Chapter 3 describes details of the proposal method. Chapter 4 shows effectiveness of the proposed method through simulation. Finally, Chapter 5 describes conclusion and problems of the method.

2. PRECONDITIONS

2.1 Coordinate systems of mobile robot

Fig. 1 shows the relation of the robot coordinate system and the camera coordinate system. The origin of the robot coordinate system is located in the center of the wheels and the running plane. y axis and z axis of the camera coordinate system coincide with the optical axis of the active camera and the rotation axis of the active camera, respectively. Δx and Δy are distance of origin for x and y direction from the robot coordinate system to the camera coordinate system. Moreover, the posture of the mobile robot from the active camera φ is anti-clockwise angle deviation from the camera coordinate system to the robot coordinate system around z axis.

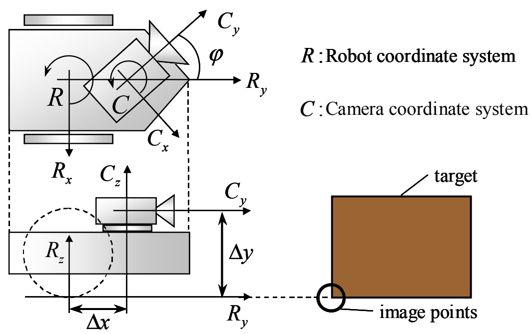

Fig. 1 Coordinate systems of mobile robot

2.2 Target and image plane

In this paper, it is assumed that both mobile robots and targets are placed on the same flat plane as shown in Fig. 2. Therefore, the distance to the target can be distinguished by vertical position of targets in image plane. The coordinate system of the image plane is determined as shown in Fig. 2, where an optical center of camera coincides with the center of the image plane. In addition, the optical axis is parallel to ground, and the image plane is parallel to the camera coordinate system. It is assumed that the left and right image points $L(x_L, z_L)$ and $R(x_R, z_R)$ toward the target can be extracted from the image plane by an appropriate image processing.

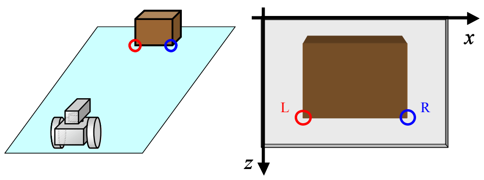

Fig. 2 Target and image plane

2.3 Kinematics of mobile robots

Velocity to R_y and angular velocity around R_z of the mobile robot v and $\dot{\theta}$ are obtained from angular velocity of wheels $\omega_{R/L}$ as follows.

$$\begin{bmatrix} v \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{R_R}{2} & \frac{R_L}{2} \\ \frac{R_R}{T} & -\frac{R_L}{T} \end{bmatrix} \begin{bmatrix} \omega_R \\ \omega_L \end{bmatrix} \tag{1}$$

where $R_{R/L}$ and T are radius of right/left wheels and tread, respectively.

By the inverse matrix of Eq. (1), the velocity command and the angular velocity command of the mobile robot v^{ref} and $\dot{\theta}^{ref}$ are transformed to the angular velocity command of the wheels $\omega_{R/L}^{ref}$ as follows.

$$\begin{bmatrix} \omega_R^{ref} \\ \omega_L^{ref} \end{bmatrix} = \begin{bmatrix} \frac{1}{R_R} & \frac{T}{2R_R} \\ \frac{1}{R_L} & -\frac{T}{2R_L} \end{bmatrix} \begin{bmatrix} v^{ref} \\ \dot{\theta}^{ref} \end{bmatrix} \tag{2}$$

3. PROPOSED METHOD

3.1 Navigation system of nonholonomic mobile robots

Fig. 3 shows the block diagram of the proposed navigation system for nonholonomic mobile robots. Here, $\mathbf{p}$ shows angles of the wheels obtained from encoders. ${}^I\mathbf{o}$, $\Delta {}^I\hat{\mathbf{o}}$, and ${}^I\hat{\mathbf{o}}$ show image points of targets obtained from image data, estimated displacement of targets during image processing time, and estimated image points of targets, respectively. Here, the estimated image points [10] are used for control of robots.

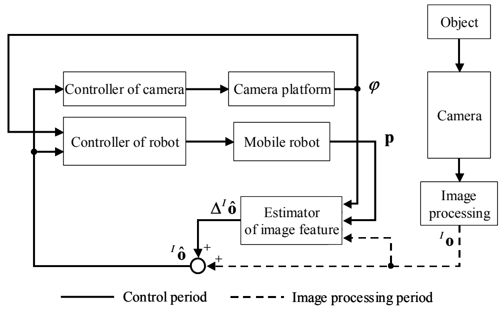

Fig. 3 Proposed navigation system of mobile robots

3.2 Control of active camera

The block "Controller of camera" in Fig. 3 makes the active camera keep the target at the center of image plane while the robot is moving as shown in Fig. 4.

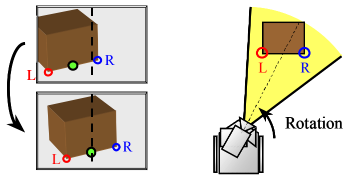

Fig. 4 Control of active camera

Here, visual servo is used for the tracking control of pan angle of the active camera. In this case, x coordinate of the middle between image points of targets x_m is used.

$$x_m = \frac{1}{2}(x_R - x_L) \tag{3}$$

The angular velocity command of the active camera from the mobile robot $-\dot{\varphi}^{ref}$ is given by

$$-\dot{\varphi}^{ref} = \mathbf{J}^{-1} K (x_d - x_m) - \dot{\theta}, \tag{4}$$

where K, x_d, and $\mathbf{J}$ are controller gain, center coordinates of image plane, and image jacobian matrix from angular velocity of active camera with respect to mobile robots to velocity of x coordinates of image point, respectively. The sine of Eq. (4) is inverted because the definition of φ is relative angle of mobile robots from active cameras.

3.3 Command to mobile robots

The block "Controller of robot" in Fig. 3 includes commands to mobile robots shown in Fig. 5 and their transformation to the angular velocity command of the wheel shown in Eq. (2).

Here, (a) in Fig. 5 generates the velocity command of the mobile robot v^{ref}. (b) and (c) in Fig.5 generate the angular velocity command of the mobile robot $\dot{\theta}^{ref}$. Detail of each method is described from now.

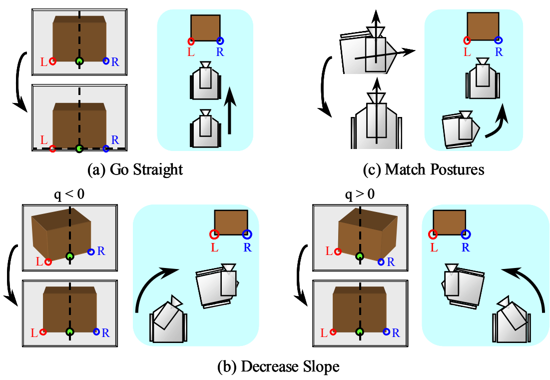

Fig. 5 Command to mobile robot

3.3.1 Command approaching to targets

Fig. 6 shows the graph of the velocity command v^{ref} that is constant until z_R or z_L is less than the threshold value $z_{threshold}$. In order to stop the mobile robot, the velocity command is decreased by the linear function of the monotone decrease until z_R or z_L reaches the bottom value of image plane z_{bottom}.

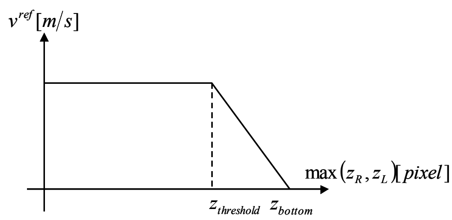

Fig. 6 Velocity command of mobile robot

3.3.2 Navigation in front of targets

In order to navigate mobile robots in front of targets, the angular velocity command $\dot{\theta}^{ref}$ of mobile robots in Eq. (2) is generated by

$$\dot{\theta}^{ref} = K'(\varphi_d - \varphi), \tag{5}$$

where K' and φ_d are controller gain and posture command of mobile robots from active cameras, respectively. Derivation of φ_d is explained in the next section.

3.3.3 Posture command of mobile robot from active camera

The slope between image points of targets q as shown in Eq. (6) is used to give posture command of mobile robots from active cameras φ_d.

$$q = \frac{z_R - z_L}{x_R - x_L} \tag{6}$$

If the slope q is positive or negative, the posture command of mobile robots from active cameras φ_d is $\pi/2$ or $-\pi/2$ so that the slope q decreases as shown in Fig. 5 (b). If the slope q is close to zero, posture command of mobile robots from active cameras φ_d is null so that mobile robots face targets as shown in Fig. 5 (c).

In order to make both the slope q and the posture of mobile robots from active cameras φ to null, the posture command φ_d for the slope q shown in Eq. (7) and Fig. 7 is given by the sigmoid function.

$$\begin{aligned}
\varphi_d &= -\frac{\pi}{2} + \left(\frac{\frac{\pi}{2}}{(1+\exp(-600 \cdot q - 7.2))} \right) && \cdots q < 0 \\
\varphi_d &= 0 && \cdots q = 0 \\
\varphi_d &= \frac{\frac{\pi}{2}}{(1+\exp(-600 \cdot q + 7.2))} && \cdots q > 0
\end{aligned} \tag{7}$$

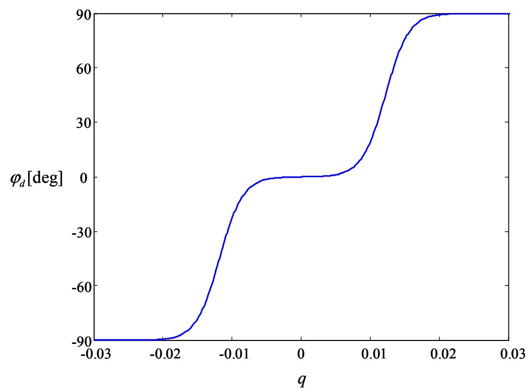

Fig. 7 Posture command of mobile robots from active cameras

Here, the parameters are adjusted through repetition of simulations. The posture command shows that the motion in Fig. 5 (b) and (c) are executed if the slope q is large and small, respectively.

The posture command of mobile robots from active cameras φ_d shown in Fig. 7 makes mobile robots to adjust their position in front of targets initially. Therefore, their trajectory becomes long if the distance from mobile robots to targets is long. In order to prevent the phenomenon, the posture command of mobile robots from active cameras φ_d is inhibited if the distance is long. Since the distance is related to value of the middle between image points of targets z_m, Eq. (8) is utilized.

$$z_m = \frac{1}{2}(z_R + z_L) \tag{8}$$

Fig. 8 and Eq. (9) show the weight for the posture command of mobile robots from active cameras φ_d.

$$weight = \left(\frac{1.0}{(1+\exp(-0.08 \cdot z_m - 24.0))} \right) \tag{9}$$

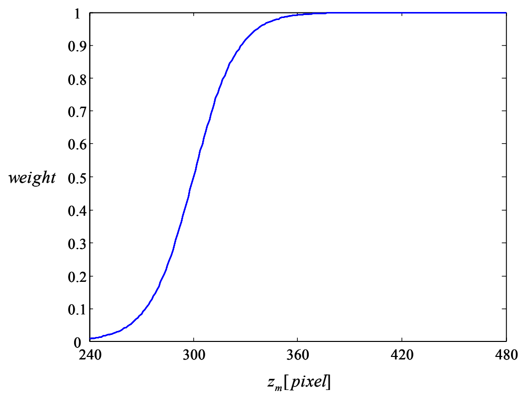

Fig. 8 Weight corresponding to z_m

The weight is multiplied to the posture command of mobile robots from active cameras φ_d to obtain a new command φ_d^{new} shown in Fig. 9.

$$\varphi_d^{new} = weight \cdot \varphi_d \tag{10}$$

As shown in Fig. 8, the weight becomes small near 240[pixel] that is the vanishing line in image plane. Therefore, the mobile robots go straight to targets if the distance is long by using the posture command of mobile robots from active cameras φ_d^{new} shown in Fig. 9.

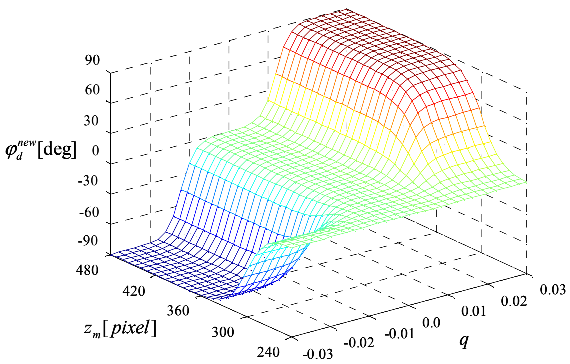

Fig. 9 Posture command of mobile robots from active cameras weighted by distance to targets

4. SIMULATION

4.1 Simulation condition

Table 1 Parameters of mobile robot

Mass	[kg]	10.0
Inertia	[kgm^2]	0.12363
Inertia of each wheel	[kgm^2]	5.4×10^{-4}
Inertia of each motor	[kgm^2]	6.89×10^{-7}
Friction coefficient of each wheel	[kgm^2/s]	0.02
Tread	[m]	0.337
Radius of each wheel	[m]	0.065

Table 2 Parameters of camera

Focal length	[m]	0.016
Pitch of pixel	[mm]	0.01375
Size of image plane	[pixel^2]	640×480
Δx	[m]	0.3
Δy	[m]	0.2

To confirm the effectiveness of the proposal technique, simulation is performed by an active camera mounted nonholonomic mobile robot as shown in Fig. 1. Table 1 and Table 2 show parameters of the mobile robot and the camera, respectively. Moreover, the control period is assumed to be 1[ms], and the image processing period is assumed to be 50[ms].

4.2 Simulation results

Fig. 10 shows simulation results of the posture commands φ_d shown in Fig. 7 and φ_d^{new} shown in Fig. 9.

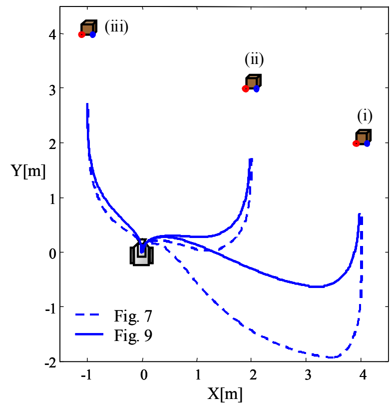

Fig. 10 Trajectory results

The result is plotted on the world coordinate fixed to an initial pose of the mobile robot. It is understood that the mobile robot is navigated in front of the targets by these methods. The trajectory of φ_d^{new} shown in Fig. 9 and Eq. (10) is shorter than the one of φ_d shown in Fig. 7 and Eq. (7) because of the weight for distance as shown in Fig. 8 and Eq. (9).

Table 3 shows final poses of the mobile robot, i.e. x coordinates, y coordinates, posture of the mobile robot θ, and execution time of simulation results shown in Fig.10.

Table 3 Final pose and execution time for the result shown in Fig. 10

Fig. 7 / Fig. 9	x[m]	y[m]	θ[deg]	Time[s]
(i)	4.00 / 3.97	0.73 / 0.73	90.04 / 88.52	19.35 / 14.24
(ii)	1.99 / 1.98	1.73 / 1.73	89.47 / 88.74	10.00 / 9.25
(iii)	-1.00 / -0.99	2.73 / 2.73	90.18 / 90.30	9.10 / 8.95

Even though the final poses are almost the same, the trajectory and execution time becomes small by the posture command weighted by distance φ_d^{new} shown in Fig. 9.

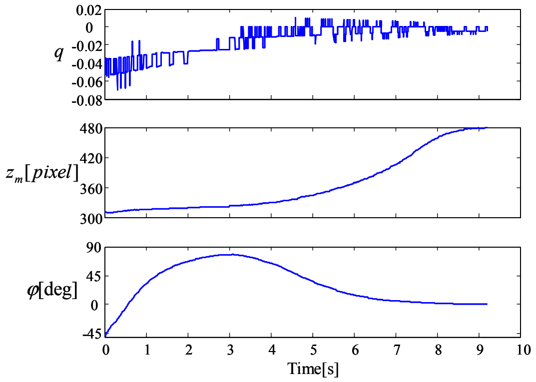

Fig. 11 Change of posture of mobile robot from active camera according to distance and slope

Fig. 11 shows time response of slope between image points q, vertical position of the middle between image points z_m, and the posture of the mobile robot from the active camera φ for the result using φ_d^{new} shown Fig. 10 (ii). The result shows that the posture of the mobile robot from the active camera φ is controlled by q and z_m. Here, the slope q is affected quantum error of image.

Moreover, effectiveness of the proposed system except for vertical targets to the mobile robot as shown in Fig.10 is also confirmed by simulations.

5. CONCLUSIONS AND PROBLEMS

This paper proposes a navigation method of nonhorononomic mobile robots with active cameras. Visual servo is applied to pan angle of active cameras during control of nonhoronomic mobile robots to keep targets in image. Since slope of targets q and the vertical position of targets in image plane z_m are related to relative angle and distance from mobile robots to targets, respectively, these image features are utilized to navigate mobile robots in front of targets. Moreover, the simulation results show that the proposed method enables navigation of a nonholonomic mobile robot with an active camera to some targets with proper direction. On the other hand, it is necessary to design a method under the environment where obstacles exist.

REFERENCES

[1] T. Yata, A. Ohya, and S. Yuta, "A Fast and Accurate Reflecting Points Measurable Sonar - ring System", *Journal of the Robotics Society of Japan*, Vol. 17, No. 8, pp. 1173-1182, 1999.

[2] T. Nakamoto, A. Yamashita, and T. Kaneko, "3-D Map Generation in a Dynamic Environment by a Mobile Robot Equipped with Laser Range Finders", *IEICE technical report. Welfare Information technology*, Vol. 106, No. 144, pp. 25-30, 2006.

[3] H. Makino, S. Yamamoto, T. Azukizawa, and T. Hashimoto, "An Experiment on Mobile Robot Navigation by Instruction Using Digital Camera Images", *Review of the Faculty of Maritime Sciences, Kobe University*, Vol. 1, pp. 131-136, 200 4.

[4] Y. Fuchikawa, S. Kurogi, K. Matsuo, S. Miyamot o, and T. Nishida, "Mobile Robot Navigation Using Guideposts and a Single Camera", *The Soci ety of Instrument and Control Engineers*, Vol. 4 2, No. 1, pp. 62-69, 2006.

[5] S. Katsura, and K. Ohnisi, "Dynamic Obstacle Avoidance of Autonomous Mobile Robot Based on Probabilistic Potential Field", *The Transactions of the Institute of Electrical Engineers of Japan. D*, Vol. 121, No. 12, pp. 1284-1290, 2001.

[6] K. Hashimoto, "Vision and Control", *SICE Work Shop*, 2001.

[7] K. Hashimoto, T. Ebine, and H. Kimura, "Visual Servoing –Optimal Control Approach-", *Journal of the Robotics Society of Japan*, Vol. 12, No. 5, pp. 773-778, 1994.

[8] K. Hashimoto, T. So, and T. Noritsugu, "Visual Feedback Control of Cart based on Path Planni ng in Image Plane", *Transactions of the Japan Society of Mechanical Engineers. C*, Vol. 66, No. 652, pp. 172-178, 2000.

[9] H. Zhang, and J. P. Ostrowski, "Visual Motion Planning for Mobile Robots", *IEEE TRANSACTI ON ON ROBOTICS AND AUTOMATION*, Vol. 1 8, No. 2, pp. 199-208, 2002.

[10] S. Komada, M. Yoshida, and T. Hori, "Visual Ser voing of Robots using Estimated Image Feature s", *The Transactions of the Institute of Electrical Engineers of Japan. D*, Vol. 123, No. 10, pp. 1200 -1205, 2003.