

Kinematic Method of Camera System for Tracking of a Moving Object

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Abstract— In this paper, we propose a kinematic approach to estimating the real-time moving object. A new scheme for a mobile robot to track and capture a moving object using images of a camera is proposed. The moving object is assumed to be a point-object and projected onto an image plane to form a geometrical constraint equation that provides position data of the object based on the kinematics of the active camera. Uncertainties in the position estimation caused by the point-object assumption are compensated using the Kalman filter. To generate the shortest time path to capture the moving object, the linear and angular velocities are estimated and utilized. The experimental results of tracking and capturing of the target object with the mobile robot are presented.

Index Terms— Mobile Robot, Tracking, Active camera, CCD camera, Image processing.

I. INTRODUCTION

MOBILE robots have many application fields because of their high workability [1,2]. They are especially necessary for tasks that are difficult and dangerous for men to perform [3]. Many researchers have shown interest in mobile robots. Most of them have focused on successful navigation [4-5], on reaching a fixed target point safely [6,7,8]. However, if a mobile robot is working under water or in space, the target object may move freely [9,10,11]. Therefore, the ability of a mobile robot to process moving targets is necessary. If an active camera system is applied to navigation and the tracking of moving objects, there will be many advantages [12]. An active camera system capable of panning and tilting should be able to automatically calibrate itself and keep track of an object of interest for a longer time interval without movement of the mobile robot [1]. There are several approaches that can be used to overcome the uncertainties of measuring the locations of the mobile robot or other objects.

In this paper, the position of an object was estimated using the kinematics of an active camera and images of the object assuming that it is flat and small on the floor. The linear and angular velocities of the object were

estimated for the mobile robot to predict the future trajectory of the object, which plans the shortest time path to track and capture the moving object. A state estimator was designed to overcome the uncertainties from the image data caused by the point-object assumption and physical noises, using a Kalman filter. Based on the estimated velocities of the object, the pose of the active camera was controlled to locate images of the object on the center of the image frame.

In Section 2, we discuss how to establish the kinematic model of an active camera. Section 3 deals with the problem of trajectory estimation of a moving object, and Section 4 deals with the motion planning involved in capturing a moving object. In Section 5, the advantages of our proposed method are illustrated through the simulation and experiment results. Section 6 presents conclusions drawn from this work.

II. KINEMATIC PARAMETER

A. System Architecture

The active camera system has the ability of panning and tilting, as shown in Fig. 1. The position and posture of the camera are defined with respect to the base frame. According to the Denavit-Hartenberg convention, the homogeneous matrix can be obtained after establishing the coordinate system and representing parameters, as shown in Table 1 and Eq. (1).

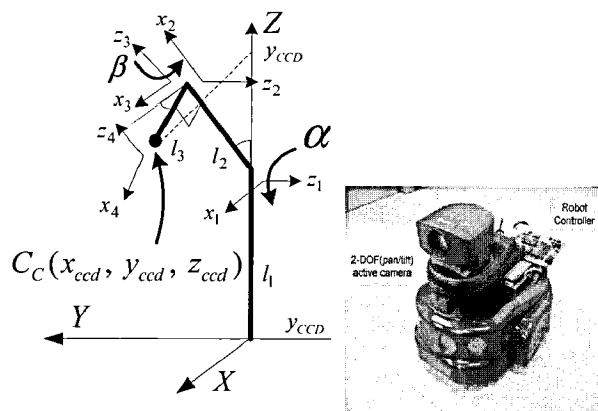


Fig. 1. Two d.o.f camera platform (Left) and its real image (Right).

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$${}^0H_4 = {}^0H_1 \cdot {}^1H_2 \cdot {}^2H_3 \cdot {}^3H_4 = \quad (1)$$

$$\begin{bmatrix} \cos(\alpha)\cos(\beta) & -\cos(\alpha)\sin(\beta) & \sin(\alpha) & l_2 \sin(\alpha) + l_3 \cos(\alpha)\cos(\beta) \\ \sin(\beta) & \cos(\beta) & 0 & l_3 \sin(\beta) \\ -\sin(\alpha)\cos(\beta) & \sin(\alpha)\sin(\beta) & \cos(\alpha) & l_1 + l_2 \cos(\alpha) - l_3 \sin(\alpha)\cos(\beta) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

TABLE I
DH LINK PARAMETERS

Link	θ	D	a	α
1	0	l_1	0	-90°
2	$90^\circ - \alpha$	0	l_2	0
3	90°	0	0	90°
4	β	0	l_3	0

In Fig. 1, $C_c(x_{ccd}, y_{ccd}, z_{ccd})$ represents a position vector from the center of the mobile robot to the center of camera lens. Each component of the vector can be represented in terms of tilting angle, α , and panning angle, β , of the CCD camera as follows:

$$x_{ccd} = l_2 \sin(\alpha) + l_3 \cos(\alpha) \cos(\beta) \quad (2)$$

$$y_{ccd} = l_3 \sin(\beta) \quad (3)$$

$$z_{ccd} = l_1 + l_2 \cos(\alpha) - l_3 \sin(\alpha) \cos(\beta). \quad (4)$$

Also, an attitude vector of the homogeneous matrix represents Roll(θ_R), Pitch(θ_p) and Yaw(θ_y) angles by tilting and panning angles of the camera as follows:

$$\theta_R = \tan^{-1} \left(\frac{\sin(\alpha)\sin(\beta)}{\sqrt{\cos^2(\alpha)\sin^2(\beta) + \cos^2(\beta)}} \right) \quad (5)$$

$$\theta_p = \tan^{-1} \left(\frac{\sin(\alpha)\cos(\beta)}{\sqrt{\cos^2(\alpha)\cos^2(\beta) + \sin^2(\beta)}} \right) \quad (6)$$

$$\theta_y = \beta. \quad (7)$$

B. Cameral coordinate

To measure the distance from a camera to an object using the camera images, at least two image frames that are captured for the same object at different locations, are necessary. Usually a stereo-camera system has been used to obtain the distance information [7]. However there exist uncertainties in feature point matching and it takes too much time to be implemented in real-time. This

approach requires only a frame to measure the distance to the object from the CCD camera. Since the approach becomes possible by assuming that a point-object is located on the floor, there also exist uncertainties in the position estimation. To minimize the uncertainty in the position estimation and to estimate the velocities of the moving object together, a state estimator is designed based on the Kalman filter.

The image coordinates for the point object, (j, k) , is transformed to the image center coordinates which is orientation invariant in terms of the Roll angle in Eq. (6), θ_R , and the size of the image frame, P_x and P_y , (j', k') :

$$\begin{bmatrix} j' \\ k' \end{bmatrix} = \begin{bmatrix} \cos(\theta_R) & -\sin(\theta_R) \\ \sin(\theta_R) & \cos(\theta_R) \end{bmatrix} \begin{bmatrix} j - \frac{P_x}{2} \\ k - \frac{P_y}{2} \end{bmatrix} \quad (8)$$

where P_x and P_y represent x and y directional size of the image frame in pixels, respectively.

To estimate the real location, (x_0, y_0) , $\hat{\theta}_0$ and \hat{r}_0 are estimated using the linear relationship between the real object range within the view angle and the image frame. That is, for a given set of $(\hat{\theta}_0, \hat{r}_0)$, there is one-to-one correspondence between the real object point and the image point.

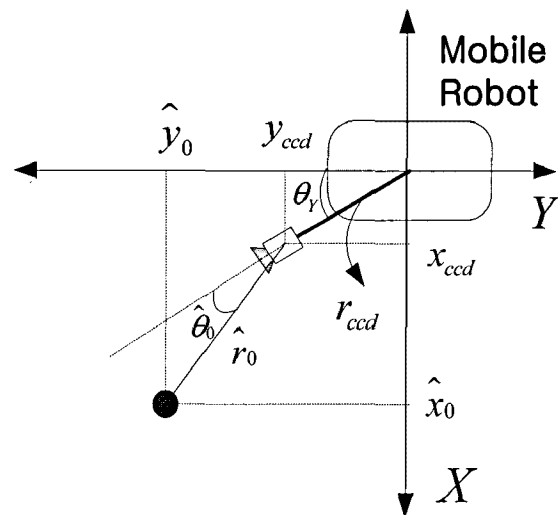


Fig. 2. Estimation of position information from a mobile robot.

When an point image is captured at (j', k') on the image center frame, the real object position, $\hat{\theta}_0$ and \hat{r}_0 , can be estimated as follows, as it is illustrated in Fig. 3:

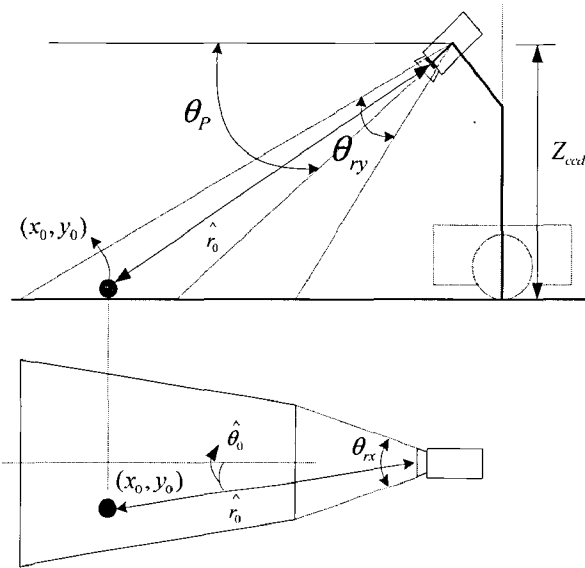


Fig. 3. Estimation of \hat{r}_0 (upper) and $\hat{\theta}_0$ (lower).

$$\hat{r}_0 = \frac{z_{ccd}}{\cos\left(\frac{\pi}{2} - \theta_p + \frac{k'}{P_y} \theta_{ry}\right)} \quad (9-a)$$

$$\hat{\theta}_0 = \frac{j'}{P_x} \theta_{rx} \quad (9-b)$$

where θ_{rx} and θ_{ry} represent the x and y directional view angles of the CCD camera, respectively.

The position of the object with respect to the robot coordinates, (x, y) can be estimated using the $\hat{\theta}_0$ and \hat{r}_0 [8] as follows:

$$\hat{x}_0 = r_{ccd} \cdot \cos(\theta_y) + \hat{r}_0 \cdot \cos(\theta_y + \hat{\theta}_0) \quad (10)$$

$$\hat{y}_0 = r_{ccd} \cdot \sin(\theta_y) + \hat{r}_0 \cdot \sin(\theta_y + \hat{\theta}_0) \quad (11)$$

where θ_y represents the angle between the robot and the active camera, and $r_{ccd} (= \sqrt{x_{ccd}^2 + y_{ccd}^2})$ represents the distance from the robot to the center of the camera.

C. Inverse kinematics

In the case of using an active camera, visual information on the area to be searched can be obtained through the inverse kinematics. The inverse kinematics equations that describe the attitude of the actuator used to place the center of an image onto a desired position, can be derived from Eq.'s (2)-(4) as follows:

$$\alpha_d = \cos^{-1} \left(\frac{-ll_2 + \sqrt{l_1^2 l_2^2 - (l_1^2 + r_d^2)(l_1^2 - r_d^2)}}{(l_1^2 + r_d^2)} \right) \left(\frac{1}{\sin(\beta_d)} \right) \quad (12)$$

$$\beta_d = \tan^{-1} \left(\frac{y_d}{x_d} \right) \quad (13)$$

where α_d and β_d are the attitude of the camera, (x_d, y_d) represents the desired position of the camera, and r_d is $\sqrt{x_d^2 + y_d^2}$.

Table 2 shows parameters for the camera system, which were used in the Eq.'s (12) and (13).

TABLE II
PARAMETERS FOR THE CAMERA SYSTEM

l_1	40 cm	l_2	7.5 cm
l_3	4 cm		
P_x	320 pixel	P_y	240 pixel
θ_{rx}	50°	θ_{ry}	40°

III. MODELING OF A MOVING OBJECT

When the velocity and acceleration of the target object can be estimated, the next target position (\bar{T}_x, \bar{T}_y) can be predicted as follows [2]:

$$\bar{T}_{x+\delta t} = \bar{T}_x + \bar{V}_x \delta t + \frac{1}{2} \bar{A}_x \delta t^2 \quad (14)$$

$$\bar{T}_{y+\delta t} = \bar{T}_y + \bar{V}_y \delta t + \frac{1}{2} \bar{A}_y \delta t^2 \quad (15)$$

where δt is the sampling time, and (\bar{T}_x, \bar{T}_y) , (\bar{V}_x, \bar{V}_y) and (\bar{A}_x, \bar{A}_y) are the current Cartesian coordinate estimates of the target position, velocity and acceleration respectively.

In the X-Y coordinates, movement of the object can be decomposed into the linear velocity element and the angular velocity element, as follows [3]:

$$\delta x_{k+\delta t, k} \approx v_k \cos(\theta_k) \delta t - \frac{1}{2} \omega_k v_k \sin(\theta_k) \delta t^2 \quad (16)$$

$$\delta y_{k+\delta t, k} \approx v_k \sin(\theta_k) \delta t + \frac{1}{2} \omega_k v_k \cos(\theta_k) \delta t^2 \quad (17)$$

$$\delta \theta_{k+\delta t, k} = \omega_k \delta t \quad (18)$$

$$\delta v_{k+\hat{\alpha},k} = \xi_v \quad (19)$$

$$\delta \omega_{k+\hat{\alpha},k} = \xi_\omega \quad (20)$$

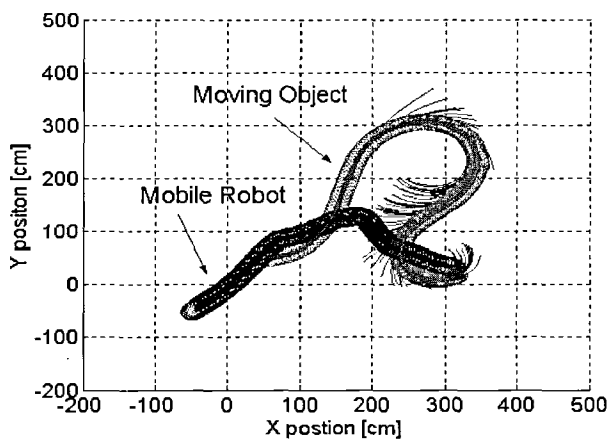
where v_k and w_k are linear velocity and angular velocities of the target object, and ξ_v and ξ_ω are the variations of linear velocity and angular velocity, respectively. From (16)-(20), we can obtain the state transition matrix, as follows:

$$\begin{aligned} \mathbf{x}_k &= \Phi_{k,k-1} \mathbf{x}_{k-1} + \mathbf{w}_{k-1} \\ \mathbf{Z}_k &= \mathbf{H}_k \mathbf{x}_k + \mathbf{v}_k \end{aligned} \quad (21)$$

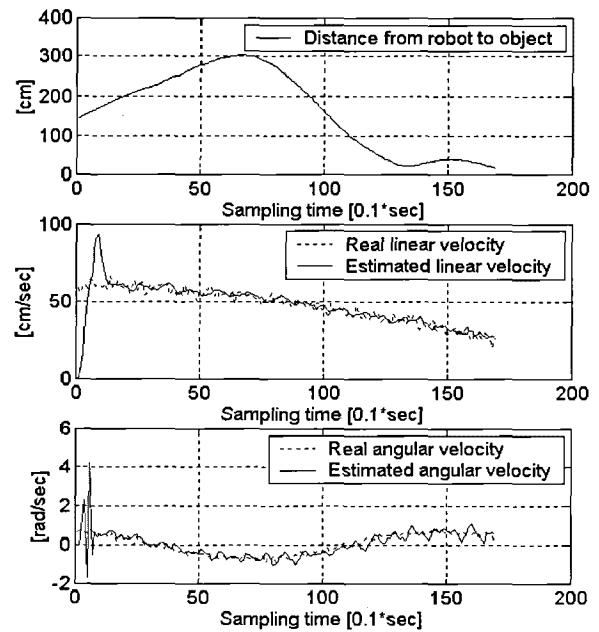
Notice that Φ_k is the state transition matrix, \mathbf{w}_k is the vector representing process noise, \mathbf{Z}_k is the measurement vector, \mathbf{H}_k represents the relationship between the measurement and the state vector, and γ_x and γ_y are x and y directional measurement errors, respectively.

IV. MOTION PLANNING FOR TRACKING

To estimate and track a moving object, the mobile robot needs to be controlled by considering the relation between the position of the mobile robot and the position of the moving object.



(a) Trajectory.



(b) Estimated state.

Fig. 4. Results of simulation.

Fig. 4(a) presents the trajectory of a moving object and the mobile robot trying to capture the object by estimating the trajectory. Fig. 4(b) represents the distance between the mobile robot and the moving object, the error between the estimated velocity and the real velocity, and the error between the estimated angular velocity and the real angular velocity, respectively. Although the error of the estimated velocities is high at first, they converge to zero immediately. Experiments that include the proposed algorithm were applied to a mobile robot named PIONEER, as shown in Fig. 5.

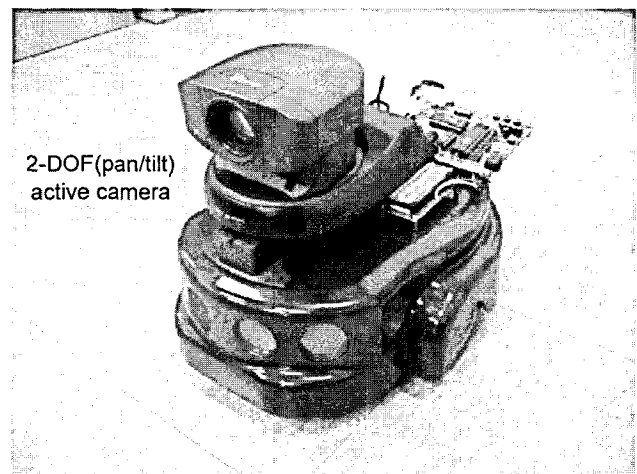


Fig. 5. Components of PIONEER.

PIONEER, the mobile robot used for this experiment, recognizes an object in the 3D space, approaches to the object to capture, and carries it to a goal position. For this purpose, PIONEER has a 2 d.o.f active camera to search and to track an object and a gripper to capture the object. The two-wheel differential driving mechanism supports flexible motion on a floor following the commands based on the image captured by the 2 d.o.f pan/tilt camera. To control the wheels in real time, a distributed control system is implemented using a CAN based network. Three CAN-based controllers are connected to the network, among which a controller gathers the gyro sensor data and sends them to the wheel controllers. The CAN network was connected to a higher-level ISA bus which connects the 2 d.o.f pan/tilt camera controllers to a main controller (a Pentium PC board). Every 100msec, the position of an object in 3D space was calculated using the posture of the camera and the object position on the image frame to plan the trajectory of the mobile robot. The planned trajectory commands were sent to the wheel controllers that uses PID algorithm to control the angle every 10 msec.

V. CONCLUSIONS

This paper proposes a method of tracking and capturing a moving object using an active camera mounted on a mobile robot. The effectiveness of the proposed method is demonstrated by the simulation and experiments. The approach enables real time tracking and capturing operations since it extracts the distance information from a single image frame and estimates the next motion using the Kalman filter which provides a closed form solution.

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