Mark Tracking: Position/Orientation Measurement using 4-Circle Mark and its Tracking Experiments

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ABSTRACT

Future space robots require position and orientation tracking with visual feedback control to track and capture floating objects and satellites. We developed a four-circle mark that is useful for this purpose. With this mark, four geometric center positions as feature points can be extracted from the mark by simple image processing. We also developed a position and orientation measurement method that uses the four feature points in our mark. The mark gave good enough image measurement accuracy to let space robots approach and contact objects. A visual feedback control system using this mark enabled a robot arm to track a target object accurately. The control system was able to tolerate a time delay of 2 seconds.

INTRODUCTION

The National Space Development Agency of Japan (NASDA) plans to conduct a series of space robot experiments on Engineering Test Satellite 7 (ETS-7)[1][2] scheduled to be launched in 1997. All experiments will study the feasibility of basic, rather than advanced, functions of the space robot. Technology for tracking objects using visual feedback control is essential to implementing tracking and capturing floating objects and satellites. The first step is to develop a technology that enables a robot arm to track a mark.

Our four-circle mark has four circles in a square. The position and orientation of the mark can be calculated by solving a perspective n-point problem from the four feature points extracted from the four circles by simple image processing. The robot arm tracked the mark using the results of mark position and orientation measurements.

PROBLEMS ADDRESSED BY THE MARK TRACKING EXPERIMENT

A visual feedback control system for a robot to track a mark must work in real-time. Onboard computers, however, have limited capacities, and are too slow to handle a large volume of image data. Processing and measuring the images of the mark being tracked require the following:

(a) A mark that allows feature points to be extracted by simple image processing.

(b) A measurement technique that does not require a high computer load to calculate position and orientation using extracted feature points.

A visual feedback control system also needs a control algorithm that involves less load on the onboard computer.

MEASUREMENT

Position and Orientation Measurement using the Four-Circle Mark

Generally, in a Perspective N-point problem (PnP) [3-5], if three or more feature points extracted from an image, the position and orientation of the mark can be determined from the positional relationships between these feature points and their corresponding points in the image. Our measurement determines the position and orientation of the mark from four feature points in the same plane with known positional relationships and their corresponding points in the image. This has the advantages of fewer feature points of interest, a unique solution, and lower calculation load.

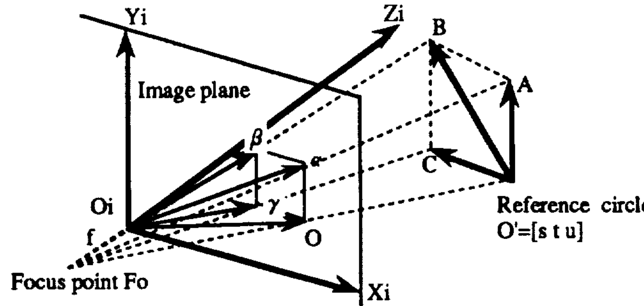
Figure 1 shows the position and orientation measurement using the four feature points. The transformation matrix T, which represents translation and rotation, denotes the position and orientations of the mark [6]. Vectors α , β and γ , A, B, and C, and O and O' are related to each other by a matrix that is represented by the product of the transformation matrix T and the perspective transformation matrix P. The six linear equations derived from these relationships can be ordered as shown below.

$$MN = B \qquad (1)$$

$$M=\begin{bmatrix} fa_1 & fa_2 & 0 & 0 & -\alpha_1 a_1 & -\alpha_1 a_2 \\ 0 & 0 & fa_1 & fa_2 & -\alpha_2 a_1 & -\alpha_2 a_2 \\ fb_1 & fb_2 & 0 & 0 & -\beta_1 b_1 & -\beta_1 b_2 \\ 0 & 0 & fb_1 & fb_2 & -\beta_2 b_1 & -\beta_2 b_2 \\ fc_1 & fc_2 & 0 & 0 & -\gamma_1 c_1 & -\gamma_1 c_2 \\ 0 & 0 & fc_1 & fc_2 & -\gamma_2 c_1 & -\gamma_2 c_2 \end{bmatrix} \qquad (2)$$

$$N=\left[\frac{n_{11}}{(u-f)}\ \frac{n_{21}}{(u-f)}\ \frac{n_{31}}{(u-f)}\ \frac{n_{12}}{(u-f)}\ \frac{n_{22}}{(u-f)}\ \frac{n_{32}}{(u-f)}\right]^T \qquad (3)$$

The N vector can be solved by applying the inverse matrix of M to both sides of Eq.(1). Since $nx=[n11, n21, n31]^T$ and $ny=[n12, n22, n32]^T$ have a norm of 1, the values of u, nx, and ny can be determined from the N vector. The value of nz can be determined from the outer product of nx and ny, and the values of s and t can be determined from the relationship between O and O'.



$$T=\begin{bmatrix} n_{11} & n_{12} & n_{13} & s \\ n_{21} & n_{22} & n_{23} & t \\ n_{31} & n_{32} & n_{33} & u \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad P=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1/f & -1 \end{bmatrix}$$

$A=[a1\ a2\ 0]^T \quad B=[b1\ b2\ 0]^T \quad C=[c1\ c2\ 0]^T \quad O=[o1\ o2\ 0]^T$

$\alpha=[\alpha 1\ \alpha 2\ 0]^T \quad \beta=[\beta 1\ \beta 2\ 0]^T \quad \gamma=[\gamma 1\ \gamma 2\ 0]^T$

Fig. 1 Position/orientation measurement using 4-circle mark

Mark Geometry

The geometry of the tracking mark should allow feature points to be extracted accurately by simple image processing. The tracking mark should not be affected by variations in illumination in space. To meet these requirements, we chose a mark with four black circles placed in a square in a white plane (Figure 2). The geometric center positions of the four circles are associated with four feature points. The position in the image that corresponds to each feature point can be determined by calculating the weighted mean from the vertical and horizontal projection deviations of the circle. This results in an imaging accuracy of one subpixel. One of the four circles is made larger than the others to define the correspondence between the feature points in the mark and the corresponding points in the image.

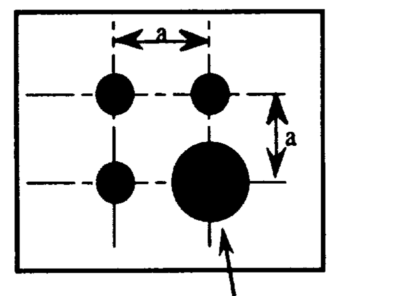


Fig. 2 Four-circle mark

TRACKING ALGORITHM

The robot arm is controlled in the mark tracking experiment by the basic control system shown in Figure 3. This proportional plus derivative (PD) control system calculates the deviation in the position and orientation of the tip of the robot arm from those of the mark by image processing and measurement. This deviation is multiplied by a proportional gain and a differential gain to generate a travel velocity command for the tip of the robot arm. This travel velocity command is transformed into the base coordinate system of the robot, then translated again into

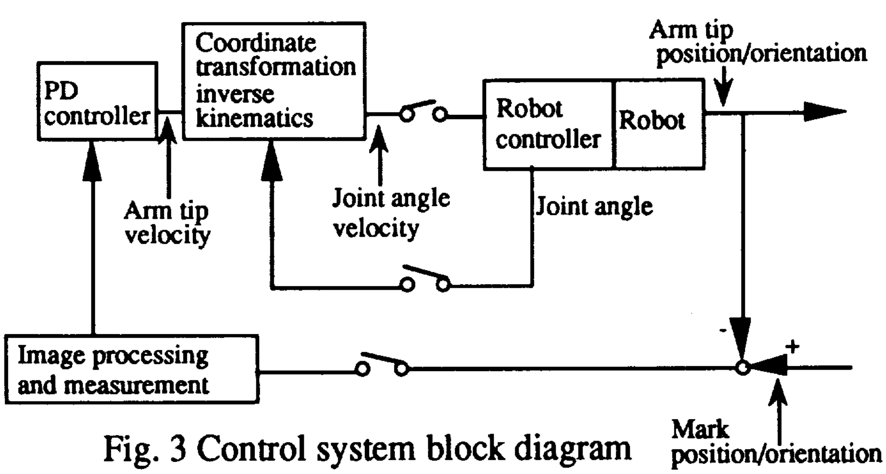


Fig. 3 Control system block diagram

the joint coordinate system as a joint angle velocity command. The joint angle velocity command is fed back to the robot controller as a velocity command.

EXPERIMENTS

Experimental System Setup

Figure 4 shows the Experimental System Setup. The robot arm has the same six degrees of freedom as the orbiting arm on the ETS-7. The arm is manipulated by inputting joint angle velocity commands to the robot controller. For mark movement, an XYZ- θ stage capable of moving the mark with four degrees of freedom was used to simulate the behavior of a slow spinning satellite.

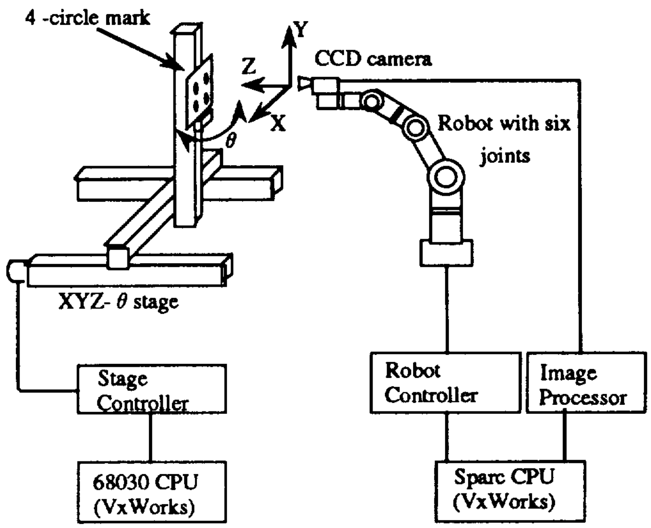


Fig. 4 Experimental system setup

Experiment Results and Discussions

Figure 5 shows the measurement accuracy with respect to the distance to the mark. The mark has a circle-to-circle distance of 100 mm. Translation errors are less than 5 mm up to the distance of 700 mm in the x and y axis directions, and less than 2% of the distance in the z axis direction. Orientation errors are less than 2 degrees in the roll, pitch, and yaw rotations. These errors are sufficient for the robot arm, which has force control to approach an object of interest.

Figure 6 shows the measurement accuracy at a distance of 500 mm when the mark rotates around y axis (pitch angle). Accuracy drops as the pitch angle increases. At a pitch angle of 20 degrees, measurement errors are about 2% of the measurement distance in the x,y, and z directions, and about 2 de-

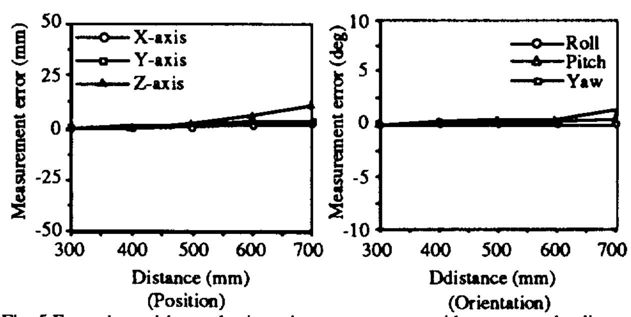


Fig. 5 Errors in position and orientation measurement with respect to the distance (Circle-to-circle distance: 100 mm)

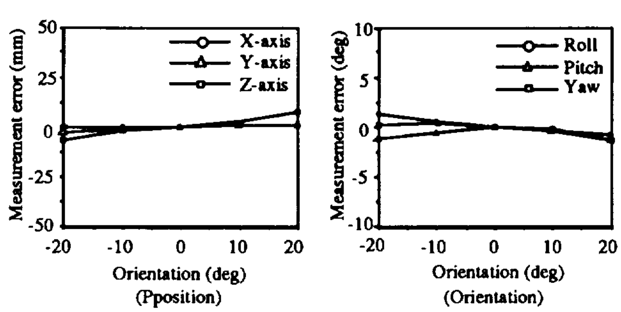


Fig. 6 Errors in position and orientation measurement with respect to the orientation (Circle-to-circle distance: 100 mm)

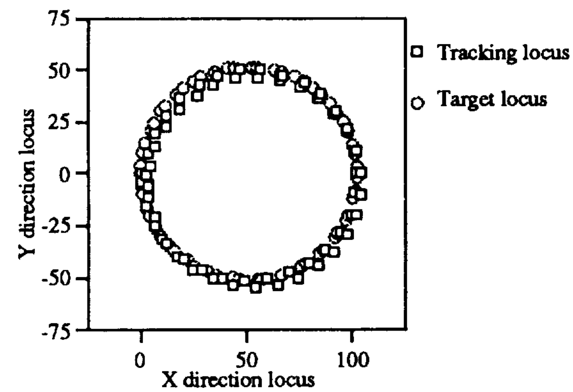


Fig. 7 Target locus and tracking locus in the X-Y plane

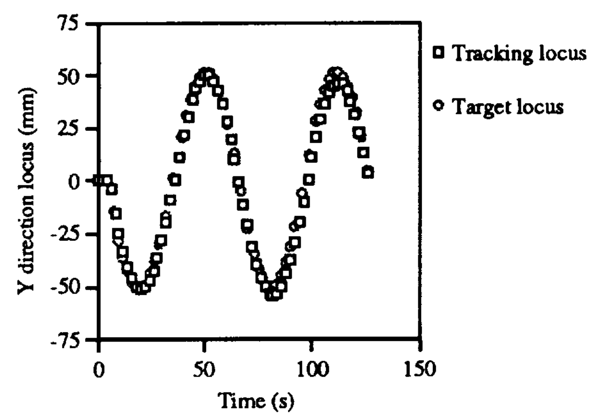


Fig. 8 Time response of the target locus and tracking locus in the Y-axis direction

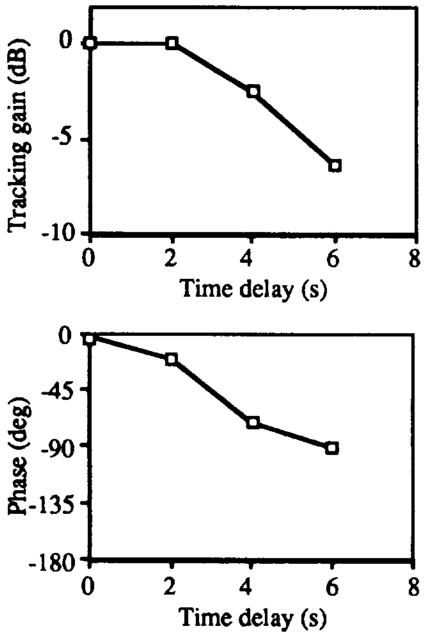


Fig. 9 Tracking gain and phase by time delay
mark velocity: 60 s/cycle
With a time delay of 8 seconds, tracking fails and the mark moves outside the image

grees in orientation angle. This loss of accuracy is caused by distortion of the circles in the image plane, if the pitch angle is large. Accuracy at an orientation angle around 0 degrees is sufficient for the robot arm to approach the mark perpendicularly.

Based on our findings, we conducted a four-circle mark tracking experiment by simulating the behavior of a slow spinning satellite as a target for tracking and capturing. The slow spinning satellite has the mark on its tip. As the mark moves, it draws a circular locus with a diameter of 100 mm. With a circle-to-circle distance of 50 mm, the mark travels in a circular locus at a rate of 60 seconds per rotation. Figure 7 shows the target locus and the tracking locus in the X-Y plane with respect to the behavior of the mark at a distance of 500 mm. Figure 8 shows the tracking locus in the Y direction. The results show that the robot arm tracked the locus of the mark accurately, with a phase delay of about 5 degrees. The sampling time from image processing to computing the joint angle velocity was about 0.2 s at a distance of 500 mm. These performances enable the robot arm to track and capture floating objects.

Figure 9 shows tracking gain and phase delay as time delay increases. The robot arm could track the target locus accurately with time delays up to 2 seconds, and the phase delay was about 20 degrees.

CONCLUSIONS

We developed a real-time position and orientation measurement method that uses a four-circle mark. These simple image processing and measurement algorithms will be used in orbit.

The measurement method was accurate enough to enable the space robot to approach an object of interest.

We built a visual feedback control system using the four-circle mark and conducted mark tracking experiments. The robot arm tracked the locus of the mark with a phase delay of about 5 degrees with respect to the locus of the mark. Accuracy was therefore good enough to track and capture objects.

We also performed a mark tracking experiment that used tracking data with a time delay to simulate teleoperation from the ground. The robot arm tracked the target locus accurately with phase delays for time delays of up to 2 seconds. Furthermore, predictive tracking control will be effective in tracking objects accurately when the tracking data has large time delay.

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