

# A Three-Dimensional Position Measurement Method Using Two Pan-Tilt Cameras

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## 2台のパン - チルトカメラを用いた3次元位置計測

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### Abstract

We have developed a 3D measuring system that uses two pan-tilt cameras to accurately measure the position of a robot's hand. With this system, a target is set up at the tip of the robot's hand. The pan-tilt cameras are controlled so that the mid-point of the target view is centered within the camera frames. Then, its 3D position is calculated using a triangulation method from the azimuth and elevation angles of the two cameras and the distance between them. Because measurement precision is essential to such a

system, we proposed a new method of the target with the concentric circle patterns, for which the center was measured precisely from the gravity centers of those circles. As a result, we achieved a high degree of precision (within 0.03 mm) with a single camera, for a camera-target distance of between 200 and 1000 mm, and where the tilt angle of the target relative to the camera was less than 70°. It was verified, by experiment, that the 3D measurement precision of the trial system is 0.15 mm for a 500-mm cube.

### Keywords

Measurement, 3D Position, Robot, Triangulation, Image processing, Gravity center, Concentric circle

### 要 旨

ロボットハンドの3次元位置を精度良く計測するために、2台のパン - チルトカメラを用いて3次元位置を計測する方式を考案し、システムを試作した。このシステムでは、ロボットハンド先端に取り付けたターゲットの中心をカメラ画面の中心に一致するようにパン - チルト台を制御して、2台のカメラ間の距離とタ - ゲットの方位角・仰角から三角測量により3次元位置を算出する。そのため、カメラでターゲット中心を検出する精度が非常に重要である。そこで我々は、ターゲット

に同心円パターンを持たせ、複数の円の重心から正確なターゲット中心を計測する方法を考案した。これにより、1台のカメラによるターゲット中心計測精度0.03mmを以下の広い条件で達成した。条件はカメラ - ターゲット間距離200から1000mmかつカメラに対するターゲットの傾きが70度以下である。また、試作したシステムを用いた実験で、500mm立方の範囲を精度0.15mmで計測可能なことを確認した。

### キーワード

計測，3次元位置，ロボット，三角測量，画像処理，重心，同心円

## 1. Introduction

When robots are deployed in a manufacturing facility, a major expense is incurred in the teaching that is needed to compensate for the differences between individual robots. This teaching is necessary to ensure that the positional coordinates of the robot correspond to the global coordinates. In practice, the robots are taught the position by using the actual objects with which they will be working. This incurs a further problem, however, in that teaching becomes necessary each time the workpieces, or the way in which the robot handles them, are changed.

On the other hand, the absolute precision of the robot is in the order of several millimeters, while its repetition precision is less than 0.1 mm. Therefore, if it were possible to compensate for a coordinate error with a global one after the robots had been set up, the offline teaching that many groups are currently studying could be introduced, which would reduce teaching costs considerably.

One potential method of compensating for the coordinate errors of robots involves the use of a compensating table that defines the differences between the robot coordinates and the global coordinates. To achieve this, the coordinates of the robot hands need to be measured very accurately by some external means.

The measuring instruments used for this must be able to satisfy the following condition: the scope of the measurement must exceed the range of movement of the robot (about a 500-mm cube), and its measuring precision must be higher than the repetition precision of the robot (about 0.1 mm). One typical technique that satisfies the above conditions involves measuring the distance between the target and a single reference point, as well as the angles of azimuth and elevation to the target.<sup>1)</sup> Another technique involves measuring the distance to the target from three reference points.<sup>2)</sup> Both, however, require the use of very expensive laser interferometers for measuring the distance. Neither, therefore, are practical for use in a manufacturing facility.

Therefore, we are proposing a low-cost method for measuring the position of a robot's hand. This

method is based on triangulation using two pan-tilt cameras, which are mounted on turntables with two rotating axes. In this paper, we will explain the details of the measuring method as well as the experimental system we built in the laboratory.

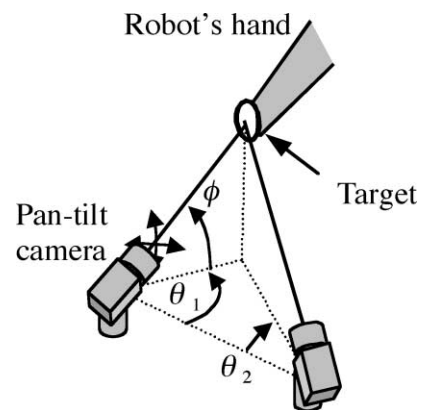
## 2. Basic theory of measurement

**Figure 1** shows the basic configuration for measuring the position of a robot's hand using pan-tilt cameras. By controlling the turntables so that the center of the target view is aligned with the cameras' frames, we can measure the azimuth ( $\theta_1$ ,  $\theta_2$ ) and elevation ( $\phi$ ) angles from the angles through which the turntables rotate. The 3D position of the target fixed on the tip of the robot's hand is calculated using a triangulation method from the azimuth ( $\theta_1$ ,  $\theta_2$ ) and elevation ( $\phi$ ) angles and the distance ( $L$ ) between the cameras.

## 3. Equipment

### 3.1 Cameras and target

To be able to capture target images within the entire range of the robot's hand movement, the imaging system is required to provide a deep focusing range and compensation for variations in the target image size. To achieve this, a zoom lens is usually used. However, the system with the zoom lens has several disadvantages such as high cost, a huge size, difficulty in treating, and especially an unstable optical axis that reluctantly changes the target position in the frame. The developed system realizes a deep focusing range by using a small aperture lens and a light-emitting target to



**Fig. 1** Basic configuration for measuring the position of a robot's hand using pan-tilt cameras.

compensate for the reduction in the incidence light power. Furthermore, a target with concentric circles is used to compensate for changes in the image size that are inversely proportional to the distance between the target and the imaging system. By detecting the center of a concentric circle image of the most appropriate size available in the camera's field of view, the accurate measurement of the target center is achieved.

The center of the image is determined by detecting the gravity center of the circle, because this method offers good resolution. By analyzing the perspective error caused by tilting the target, a high degree of precision method of the center detection has been developed. **Figure 2** shows the analysis model of this novel method.

In Fig. 2, the origin of the coordinate system is the principal point of the imaging lens. There is a circle on the target, whose center coordinate is  $(x_c, y_c, z_c)$ . The tilt angle is  $\alpha$ . The image captured by the camera is similar to the projection of the circle onto the plane at  $z = z_c$ .

The next two equations represent the circle  $(x_s, y_s, z_s)$  on the intersecting line of a sphere and a plane.

$$(x_s - x_c)^2 + (y_s - y_c)^2 + (z_s - z_c)^2 = r^2 \quad \dots\dots\dots (1)$$

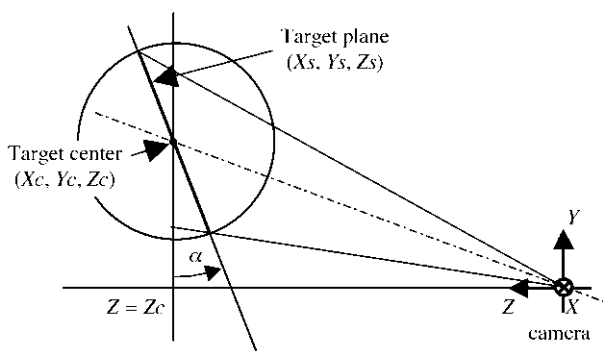
$$z_s - z_c = (y_s - y_c) \tan \alpha \quad \dots\dots\dots (2)$$

The circle projection  $(x, y)$  onto the  $z = z_c$  plane is expressed in Eq. (3).

$$x = z_c x_s / z_s, \quad y = z_c y_s / z_s \quad \dots\dots\dots (3)$$

Eq. (1) to (3) can be solved for  $x$ .

$$x = \frac{z_c - y \tan \alpha}{z_c - y_c \tan \alpha} x_c \pm \frac{\sqrt{(z_c - y_c \tan \alpha)^2 r^2 \cos^2 \alpha - (y - y_c)^2 z_c^2}}{(z_c - y_c \tan \alpha) \cos \alpha} \quad \dots\dots\dots (4)$$



**Fig. 2** Geometry of imaging. Origin is camera position.  $(x_c, y_c, z_c)$  is center of circle.  $\alpha$  is tilt angle of target.

The gravity center of the projection equals the integral of the difference between the two  $x$  values. The value of  $y$  is obtained similarly to  $x$ .

$$g(x, y) = \left( \frac{z_c^2}{z_c^2 - r^2 \sin^2 \alpha} x_c, \frac{z_c^2 y_c - z_c r^2 \sin \alpha \cos \alpha}{z_c^2 - r^2 \sin^2 \alpha} \right) \quad \dots\dots\dots (5)$$

The difference  $\Delta g$  from the genuine center  $(x_c, y_c)$  is

$$\Delta g(x, y) = \frac{r^2}{z_c^2 - r^2 \sin^2 \alpha} (x_c \sin^2 \alpha, y_c \sin^2 \alpha - z_c \sin \alpha \cos \alpha) \quad \dots\dots\dots (6)$$

By converting the difference into the angle  $\Delta\phi$  from the origin, Eq. (6) is arranged as

$$\tan \Delta\phi = \frac{\Delta g(x, y)}{z_c} = \frac{r^2}{z_c^2 - r^2 \sin^2 \alpha} \left( \frac{x_c}{z_c} \sin^2 \alpha, \frac{y_c}{z_c} \sin^2 \alpha - \sin \alpha \cos \alpha \right) \quad \dots\dots\dots (7)$$

It can generally be assumed that  $x_c, y_c, r \ll z_c$ . Therefore, the quadratic terms can be neglected, and Eq. (7) can be simplified to:

$$\Delta\phi \cong \left( 0, -\frac{r^2}{2z_c^2} \sin 2\alpha \right) \quad \dots\dots\dots (8)$$

From Eq. (8), it is found that the difference angle  $\Delta\phi$  is expressed by the quadratic equation of the circle of radius  $r$  while the genuine center is obtained as the gravity center at  $r = 0$ , which can be calculated from the gravity centers of concentric circles with different radii.

### 3.2 Image processing

In this section, we describe the method used to calculate the center of a target from the image obtained by the camera. **Figures 3 and 4** show the target pattern that is made up of concentric circles, and a flow chart of the image processing by which the target center is calculated. Initially, to classify the obtained target image into black areas and white areas, the image is binarized by using a threshold of half of the maximum image brightness. Then, the gravity center and the size of each area are calculated.

The next procedure involves eliminating noise from the image, such as bright windows, lights and their reflections. The elimination procedure is based on the viewpoint that the valid gravity centers of the concentric circle images of the target are

concentrated in a small area around the genuine center, whereas the centers of the noise images are not. The difference  $\Delta G$  between the genuine center of the target and the gravity centers of a concentric circle is expressed by Eq. (9).

$$\overline{\Delta G} = \frac{(r_1^2 + r_2^2)}{2z} \sin 2\alpha = \frac{S}{\pi} \cdot \frac{r_1^2 + r_2^2}{r_1^2 - r_2^2} \sin \alpha \dots (9)$$

where  $r_1$  and  $r_2$  are the outer and inner radii of a ring image of the concentric circle, and  $S$  is the area of the circle image. By setting the target concentric circle radii to the geometric series of  $\beta$ , Eq. (9) can be rewritten as:

$$\frac{\overline{\Delta G}}{S} = \frac{1}{\pi} \cdot \frac{\beta^2 + 1}{\beta^2 - 1} \sin \alpha \leq \frac{1}{\pi} \cdot \frac{\beta^2 + 1}{\beta^2 - 1} \dots (10)$$

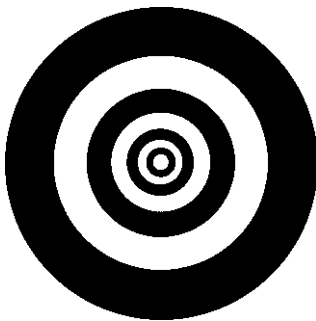
For the boundary condition (10), valid concentric circle images can be distinguished precisely from the noise images. This method is very easy and tolerant of noisy environments such as those found in factories.

The above procedure is used to precisely calculate the center position.

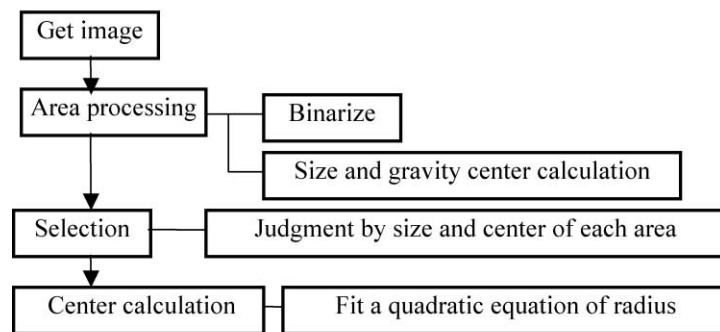
## 4. 3D coordinate measurement system

### 4.1 System configuration

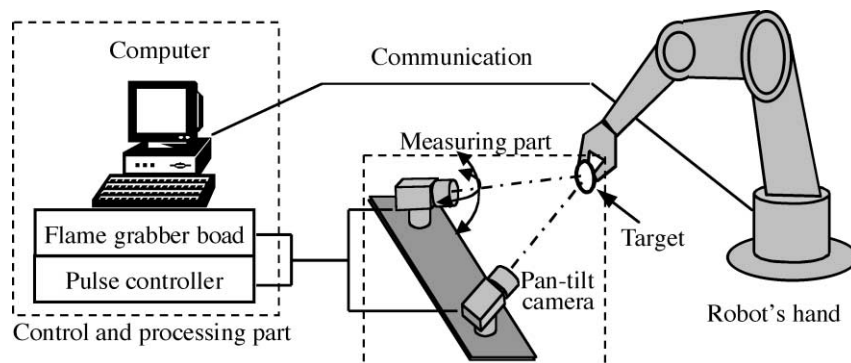
**Figure 5** shows the experimental system for performing 3D coordinate measurement of a robot's hand. The system is constructed with a control-processing part and a measuring part (**Fig. 6(a)**) the latter of which consists of two pan-tilt cameras (Fig. 6(b)) mounted on a base plate and a light-emitting target with concentric circle patterns. The distance between the cameras is 700 mm. The control processing part consists of a computer, driver circuits for the servo motors of the pan-tilt camera, and frame-grabber circuits for capturing image data from the camera output. The measurement of the robot's hand coordinates is done using the computer that controls the motors such that the target image center corresponds to the vision field center of the camera, and by communicating with the robot controller about the approximate hand-top coordinates.



**Fig. 3** Target pattern.



**Fig. 4** Flow-chart of image processing.



**Fig. 5** Component of measurement system.

The target, shown in **Fig. 7**, consists of a back light unit of LED array in a stainless hemispherical housing, and an “opal” diffusing glass plate onto which concentric aluminum circles are deposited. By using the target and the above-mentioned image processing, an accurate recognition of the target, shown in **Fig. 8**, can be performed against a complex background.

## 4. 2 Determining the degree of precision

### 4. 2. 1 Verifying the precision of the target

#### center measurement with a single camera

The precision of the target center measurement with a single camera was verified experimentally, as follows:

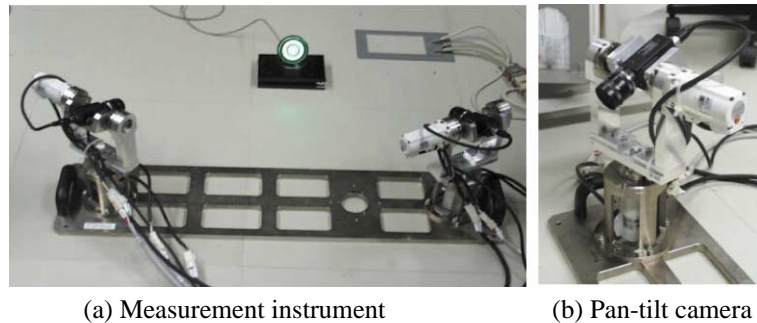
The distance  $L$  between the target and the camera was 200, 400, 700 and 1000 mm. The tilt angle  $\epsilon$  of the target relative to the camera was varied from  $-85^\circ$  to  $+85^\circ$  in  $5^\circ$  steps. Under the every condition, the target center position was measured 25 times.

**Figure 9** shows the experimental result of measurement error. The plots and error bar indicate the average error and the  $\pm 3\sigma$  dispersion for the 25 measurements. It was found that the average error

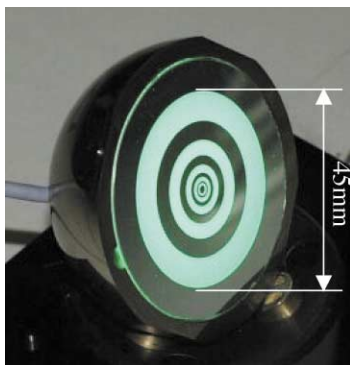
and the dispersion increased with increasing the tilt angle  $\theta$  and the distance  $L$ . The results can be explained in terms of the increase in the quantizing error with an increase in the elliptical deformation of the target image. In addition, the millimeter conversion of the quantizing error is proportional to the distance. By utilizing the calculations made on several concentric circle centers, however, the quantizing error was markedly reduced. Thus, a high degree of precision (within 0.03 mm) was achieved under a broad range of conditions, where the camera-target distance was between 200 and 1000 mm, and the tilt angle was less than  $70^\circ$ .

### 4. 2. 2 Verifying the precision of 3D position measurement

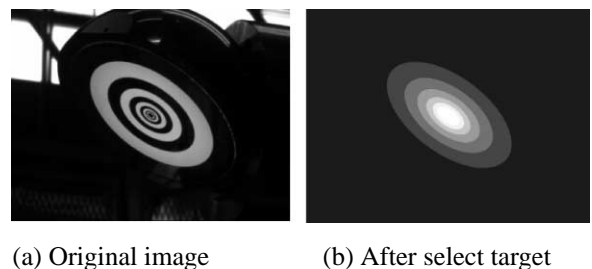
In this section, we describe the verification of the precision of 3D coordinate measurement with the experimental system shown in Fig. 5. The robot's hand to be measured was moved along a virtual spatial grid that encompassed the entire scope of the robot's movement. Using the experimental system, 3D coordinate measurement of the target position was performed at each point on the grid. The actual



**Fig. 6** Picture of measuring part.



**Fig. 7** Picture of target.



**Fig. 8** Images before and after processing.

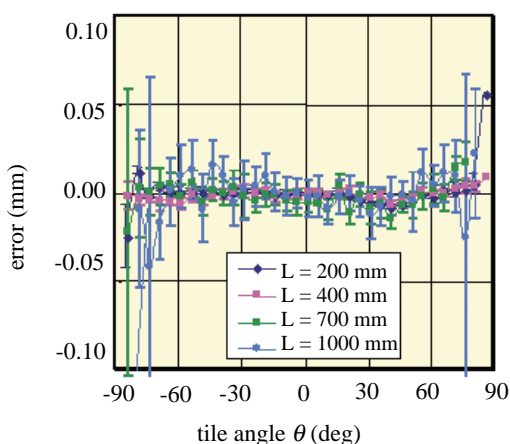
position of the top of the robot's hand was measured using a different 3D measuring instrument with a guaranteed accuracy better than 0.02 mm. The deviation between the measured position and the actual position was recorded as 3D measurement error of the experimental system.

To accurately calculate the 3D position with the angles of the pan-tilt stages, the positions of the cameras and motor axes are modeled using modified DH parameters<sup>3)</sup>, which are estimated by measuring eight points around the measuring area.

The experimental measurement was performed on the two regions shown in **Fig. 10**, namely regions (A) and (B). The measuring points were 27 mm and 216 mm inside (A) and (B), where the grid period was 100 mm and each region was a 200- and 500-mm cube. Region (A) was assumed to offer the best precision and region (B) was within the region in which the robot's hand can move.

This experimental results, shown in **Table 1**, indicate a very high degree of precision, within 0.05 mm in region (A), and a sufficiently high precision of within 0.15 mm in region (B). For one side, the measurement required eight minutes for 216 points, that is, 5 s/point. Most of this time was “wasted” on moving the robot and the stages and on waiting for the vibration to stop. The time spent for actual image processing was less than 1 s/point.

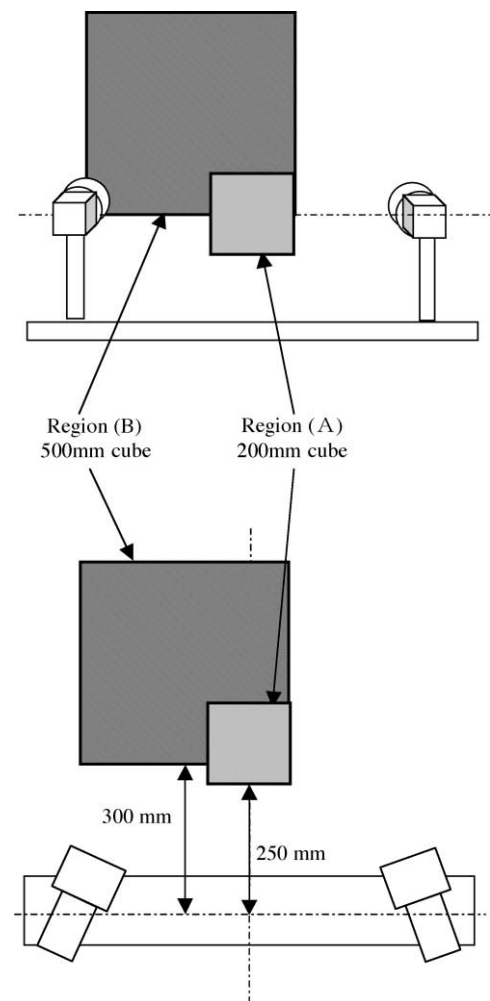
## 5. Conclusion



**Fig. 9** Experimental result by single camera. Error bars show  $\pm 3\sigma$  divergence.

We have proposed and demonstrated a 3D measurement system that uses two pan-tilt cameras and a concentric circle target. Using this target, the error was less than 0.03 mm with a single camera, where the camera-target distance is between 200 and 1000 mm, and the tilt angle of the camera relative to the target is less than  $70^\circ$ . It was experimentally verified that the  $3\sigma$  accuracy is within 0.15 mm for a 500-mm cube.

By applying this system to a manufacturing facility, we can easily have the position coordinate



**Fig. 10** Measuring region according to instrument.

**Table 1** Experimental results for precision investigation.

Region	Error [mm]		
	Average	Max	$3\sigma$
A	0.03	0.05	0.09
B	0.04	0.14	0.15

of the robot correspond to a global one by, for example, fixing this system on a table that carries the workpieces.

This concept of using a camera to precisely measure the center of a target can be applied to many other practical problems.

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