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퍼셉트론 센서를 이용한 로봇의 센서 위치 캘리브레이션

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<요 약>

선형 레이저-비젼 센서인 'Perceptron TriCam Contour' 센서는 로봇에 부착되어, 로봇의 위치 보정 또는 부품 검사 등 다양한 로봇 응용에 사용된다. 본 논문에서는, 로봇에 퍼셉트론 센서를 부착하여 정밀 사용을 할 수 있도록 센서 위치 캘리브레이션 알고리즘을 제시한다. 제시된 알고리즘은 로봇 관절 센서값과 특별하게 고려하여 정밀 제작된 지그에 대한 퍼셉트론 센서의 측정값을 이용하여 산업 환경에서 바로 적용 가능한 장점이 있다. 개발된 알고리즘은 현대 7602 AP 로봇을 이용하여 실실험한 결과 퍼셉트론의 측정 정밀도(1.4 mm 이하)를 향상시킴으로써 그 유용성을 입증하였다.

Autonomous Sensor Center Position Calibration with Perceptron Sensor

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<Abstract>

A linear laser-vision sensor called 'Perceptron TriCam Contour' is mounted on an industrial robot and often used for the various application of the robot such as the position correction and the inspection of a part. In this paper, a sensor center position calibration is presented for the best accurate use of the robot-Perceptron system. The obtained algorithm is suitable for on-site calibration in an industrial application environment. The calibration algorithm requires the joint sensor readings, the Perceptron sensor measurements on a specially devised jig which

is essential for this calibration process. The algorithm is implemented using Hyundai 7602 AP robot such that the Perceptron's measurement accuracy is increased up to less than 1.4 mm.

1. Introduction

In order to extend the use of a industrial robot to more sophisticated tasks such as position correction, visual servo and inspection of 3D part, a linear laser vision sensor called 'Perceptron TriCam Contour Sensor' is often mounted on a robot hand. Perceptron is a fusion sensor of laser and vision, and gives more accurate measurements under the variation of environment than the conventional vision systems. The sensor measures by capturing the shape and position of the projected laser line as it strikes the contour of the surface being measured. The software calculates two dimensional results(Y, Z) with respect to the sensor coordinate.

Whenever a sensor is mounted on a robot, it is important to determine the kinematic relationship between the sensor coordinate frame and the hand coordinate frame for the accurate measuring and robot positioning. The related kinematic parameters are 3 rotation parameters and 3 translation parameters. The problem of determining these parameters is often referred to as sensor center position(SCP) calibration. In this paper, the Perceptron is mounted on a robot hand and SCP calibration is presented for the best accurate use of the robot-Perceptron system.

Autonomous robot calibration is defined as the automated process of determining a robot's model by using its internal sensors[1]. In this case, a kind of constraint must be deduced from the configuration of the calibration system: task constraints utilizing laser line tracking[2], plane constraint using a trigger probe[3], closed-loop constraints using robot joint readings and camera measurements[1,4] and plane constraint with implicit loop method[5]. The presenting SCP calibration can be understood as an autonomous robot calibration with consideration of the Perceptron sensor. The jig suitably devised for the Perceptron allows the closed-loop constraints, only using robot joint readings and Perceptron readings. Therefore, the calibration scheme can be implemented autonomously and is suitable for on-site calibration in an industrial environment.

In this paper, autonomous SCP calibration is presented for the best accurate use of the robot-Perceptron system. The problem of SCP calibration is formulated in Section 2. Section 3 shows the special jig for the Perceptron measurements and its related parameter identifications. In section 4, the obtained algorithm is implemented to show its effectiveness, using Hyundai 7602 AP robot and its results are discussed in terms of the Perceptron's measurement accuracy.

2. Autonomous SCP Calibration

Unlike the robot calibration with external end-point measurements[6,7], autonomous calibration uses only robot's internal sensors and instead, requires the existence of internal constraints deduced from the whole calibration system. And also no human intervention during measurement phase is allowed such that low cost and on-site calibration is possible in an industrial environment.

Figure 1 shows the current considering system. The Perceptron sensor is mounted on a robot hand and the transformation parameters from the robot hand coordinate to the sensor coordinate should be identified for accurate sensor measurement and precise robot positioning. Suppose that one Perceptron sensor measurement on the specially devised jig is enough to identify the transformation parameters from Perceptron sensor coordinate frame {P} to the jig coordinate frame {J}. Next section will show in detail how it is possible. In this situation, fix the jig on any convenient place inside the robot workspace, and measure on the jig by the Perceptron according to the various configuration change of the robot up to n configurations. For each configuration, an angle set $\boldsymbol{\theta}$ is recorded and the 6x1 position vector $\boldsymbol{x}$ is computed from the robot base coordinate to the same fixed {J}, using both the nominal values of robot kinematic parameters and the transformation parameters between {P} and {J} obtained in next section. The difference of the real position vector $\boldsymbol{x}^*$ and the computed position vector is expressed as

$$\boldsymbol{x}_i - \boldsymbol{x}^* = \Delta \boldsymbol{x}_i = [J_{\Phi i}]\Delta\boldsymbol{\Phi} = [J_{\theta i} \ \vdots\ J_{\alpha i} \ \vdots\ J_{ai} \ \vdots\ J_{di}] \begin{bmatrix} \Delta\boldsymbol{\theta}_{offset} \\ \Delta\boldsymbol{\alpha} \\ \Delta\boldsymbol{a} \\ \Delta\boldsymbol{d} \end{bmatrix} \qquad i = 1,2,\ldots,n \qquad (1)$$

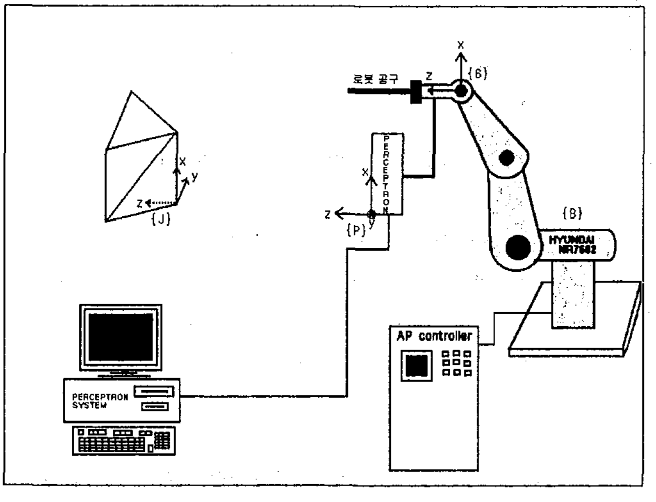


Figure 1. Autonomous SCP Calibration System

where α, a, d is the twist angle, link length and link offset of DH parameter notation, respectively, and J is the conventional Jacobian and it is assumed that joint angle error set from nongeometric factors is assumed as a constant vector θ_{offset} . That is, the true joint angle set is the addition of joint sensor reading set and the offset vector.

For elimination of the unknown x^* , the subtraction of the i^{th} equation from the first equation of (1) results as

$$(x_1 - x^*) - (x_i - x^*) = x_1 - x_i = [J_{\Phi 1}]\Delta\Phi - [J_{\Phi i}]\Delta\Phi \quad i = 2,3,\ldots,n \tag{2}$$

The (n-1) vector equations of (2) can be augmented into single matrix equation as shown in Eq. (3) and is expressed in a simple notation as shown in (4).

$$\begin{bmatrix} x_1 - x_2 \\ x_1 - x_3 \\ \vdots \\ x_1 - x_n \end{bmatrix} = \begin{bmatrix} J_{\Phi 1} - J_{\Phi 2} \\ J_{\Phi 1} - J_{\Phi 3} \\ \vdots \\ J_{\Phi 1} - J_{\Phi n} \end{bmatrix} \Delta\Phi \tag{3}$$

$$\Delta x = C\Delta\Phi \tag{4}$$

Applying the iterative least square algorithm to Eq. (4) leads to the procedure as bellow

1) Compute Δx_i and C_i for $\Delta x_i = C_i \, \Delta\Phi_i$ based on the current nominal values $\theta_i, \alpha_i, d_i, a_i$
2) $\Delta\Phi_i = (C_i^T C_i)^{-1} C_i^T \Delta x_i$
3) $\Phi_{i+1} = \Phi_i + \Delta\Phi_i$
4) Repeat above steps until $\Delta\Phi$ becomes the considered tolerance value near **0.**

In order to prevent the inevitable transient singularity, step 2) can be replaced by $\Delta\Phi = (C^T C + \lambda I)^{-1} C^T \Delta x$ where I and λ is an identity matrix and a weight value, respectively. Selection of a weight value affects the convergence characteristics of the above algorithm and the switching technique can be considered[8].

3. Design of the Jig for the Perceptron and Transformation from {P} to {J}

In the last section, we assumed that the transformation parameters from {P} coordinate frame to {J} coordinate frame could be identified by using each Perceptron's measurement. Therefore, a jig must be designed such that 6 transformation parameters from {P} to {J} is possible to be derived from Perceptron's measurement values, whenever the laser line of the perceptron is projected on the jig. And then, the fixed jig coordinate frame is possible to be expressed with respect to the robot base coordinate frame.

Various shapes of jig satisfying the above requirement could be considered, but the shape of the jig is selected as a triangular pillar due to its ease of manufacturing. The jig is constructed by connecting a fine string to the vertices of the regular triangle made by drilling on up and bottom plates of the triangular pillar and is shown in Fig. 2. The selection of the fine string allows easy image processing of the projected laser line, because the intersection points of the laser line and fine strings can be recognized as the points of our measurement.

Based on the jig shown in Fig. 2, the algorithm which identify the transformation parameters between {P} and {J} will be explained now. The jig coordinate frame {J} is placed on front vertex of bottom plate of the triangular pillar. Its x-direction is consistent with the upward direction of the triangular pillar and its z-direction is into the page shown in Fig. 2. When the projected laser line of the Perceptron is set to intersect with 5 fine strings of the jig, the Perceptron captures 5 point images and gives the two dimensional results (y, z) for each point with respect to the sensor coordinate frame {P}. Those points are A, B, B', C, C' as shown in Fig. 2 and their {P} coordinate descriptions are shown as

$$
{}^{p}A=[0,{}^{p}y_a,{}^{p}z_a],\quad {}^{p}B=[0,{}^{p}y_b,{}^{p}z_b],\ B'=[0,{}^{p}y_{b'},{}^{p}z_{b'}],
$$
$$
{}^{p}C=[0,{}^{p}y_c,{}^{p}z_c],\quad {}^{p}C'=[0,{}^{p}y_{c'},{}^{p}z_{c'}].
$$

And also, {J} coordinate descriptions of A, B, C are

$$
{}^{J}A = [h_1,\ 0,\ 0],\ {}^{J}B = [h_2,\ -\frac{a}{2},\ \frac{\sqrt{3}}{2}a],\ {}^{J}C = [h_3,\ \frac{a}{2},\ \frac{\sqrt{3}}{2}a]
$$

A new coordinate frame {P'} is set by translating the origin of {P} frame to the point A. The expressions of the points A, B, C, B' and C' with respect to the new {P'} frame are as follows

$$
\begin{aligned}
&{}^{p'}A=[0,0,0],\\
&{}^{p'}B=[0,\ {}^{p}y_b-{}^{p}y_a,\ {}^{p}z_b-{}^{p}z_a]=[0,\ {}^{p'}y_b,\ {}^{p'}z_b],\\
&{}^{p'}C=[0,\ {}^{p}y_c-{}^{p}y_a,\ {}^{p}z_c-{}^{p}z_a]=[0,\ {}^{p'}y_c,\ {}^{p'}z_c],\\
&{}^{p'}B'=[0,\ {}^{p}y_{b'}-{}^{p}y_a,\ {}^{p}z_{b'}-{}^{p}z_a]=[0,\ {}^{p'}y_{b'},\ {}^{p'}z_{b'}],\\
&{}^{p'}C'=[0,\ {}^{p}y_{c'}-{}^{p}y_a,\ {}^{p}z_{c'}-{}^{p}z_a]=[0,\ {}^{p'}y_{c'},\ {}^{p'}z_{c'}].
\end{aligned}
\tag{5}
$$

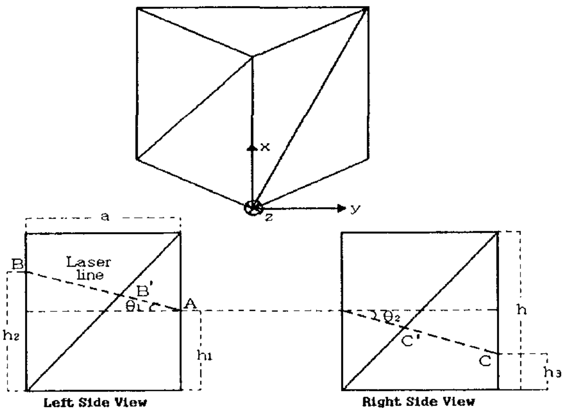


Fig. 2. The Shape of Jig

Another new coordinate frame {J'} is set by translating the origin of {J} frame to the point A. The expressions of the points (A, B, C) with respect to the new {J'} frame are as follows

$$^{J}A = [0,\ 0,\ 0],\ ^{J}B = [h_2',\ -\frac{a}{2},\ \frac{\sqrt{3}}{2}a],\ ^{J}C = [h_3',\ \frac{a}{2},\ \frac{\sqrt{3}}{2}a] \tag{6}$$

Set the distance between A and B to l_1 , and between A and C to l_2 . They are expressed as $l_1 = \sqrt{^{p'}y_b^2 + ^{p'}z_b^2}$, $l_2 = \sqrt{^{p'}y_c^2 + ^{p'}z_c^2}$, respectively. From the triangular relationship between these distances and the length of the side of the triangle, a, the equations are easily obtained as $\pm\theta_1 = \cos^{-1}(\frac{a}{l_1})$, $\pm\theta_2 = \cos^{-1}(\frac{a}{l_2})$. Here, the four sign combinations of θ_1 and θ_2 represent the four different measurement configurations between the Perceptron and the jig. In order to determine the current real measurement configuration, we use the intersection points (B', C') of the laser line and the diagonally connected strings. The distances to the point A from the points B' and C' are set to d_1 and d_2 respectively. They are expressed as $d_1 = \sqrt{^{p'}y_{b'}^2 + ^{p'}z_{b'}^2}$, $d_2 = \sqrt{^{p'}y_{c'}^2 + ^{p'}z_{c'}^2}$. Recalling that these 5 points are made by the projection of single straight laser line gives the following equality relation as

$$h_1 = h - d_1\cos(\theta_1)\frac{h}{a} - d_1\sin(\theta_1) = d_2\cos(\theta_2)\frac{h}{a} - d_2\sin(\theta_2) \tag{7}$$

Now, the true values of θ_1 and θ_2 satisfying Eq. (7) can be determined to be consistent with a real measurement configuration. Once the true values of θ_1 and θ_2 are determined, The unknowns h_2' and h_3' shown in Eq. (6) can be determined by using the following equations as $h_2' = l_1 \sin(\theta_1)$ and $h_3' = l_2 \sin(\theta_2)$, respectively. The both origins of {J'} frame and {P'} frame are identical at the point A, and thus the rotation relationship as $^{p}\boldsymbol{P} = {}^{p}_{J}R\,^{J}\boldsymbol{P}$ can be applied to the points B and C as

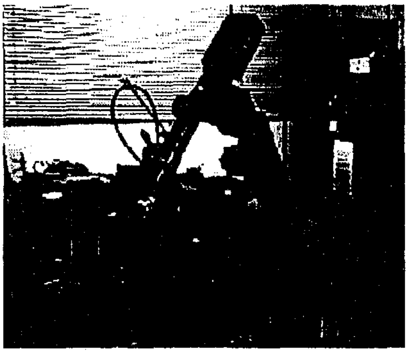


Fig. 3. Calibration System

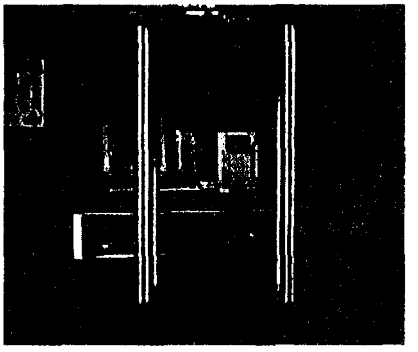


Fig. 4. The Jig as an Object of Measurement

$$\begin{bmatrix} r_{11} & r_{21} & r_{31} \\ r_{12} & r_{22} & r_{32} \\ r_{13} & r_{23} & R_{33} \end{bmatrix} \begin{bmatrix} 0 \\ {}^{p'}y_b \\ {}^{p'}z_b \end{bmatrix} = \begin{bmatrix} h_2' \\ -\frac{a}{2} \\ \frac{\sqrt{3}}{2}a \end{bmatrix} \text{ and } \begin{bmatrix} r_{11} & r_{21} & r_{31} \\ r_{12} & r_{22} & r_{32} \\ r_{13} & r_{23} & R_{33} \end{bmatrix} \begin{bmatrix} 0 \\ {}^{p'}y_c \\ {}^{p'}z_c \end{bmatrix} = \begin{bmatrix} h_3' \\ \frac{a}{2} \\ \frac{\sqrt{3}}{2}a \end{bmatrix} \quad (8)$$

Eq. (8) can be expressed in detail as 6 equations with 6 unknowns. They could be analytically solvable. The additional orhogonality condition of rotation matrix allows to determine all components of the rotation matrix for {P} to {J}. And then, the translational parameters from {P} to {J} can be determined by applying the following equation to the point A as

$${}^{p}P_{Jorg} = {}^{p}P - {}^{p}_{J}R\,{}^{J}P = \begin{bmatrix} 0 \\ {}^{p}y_a \\ {}^{p}z_a \end{bmatrix} - {}^{p}_{J}R \begin{bmatrix} h_1 \\ 0 \\ 0 \end{bmatrix} \quad (9)$$

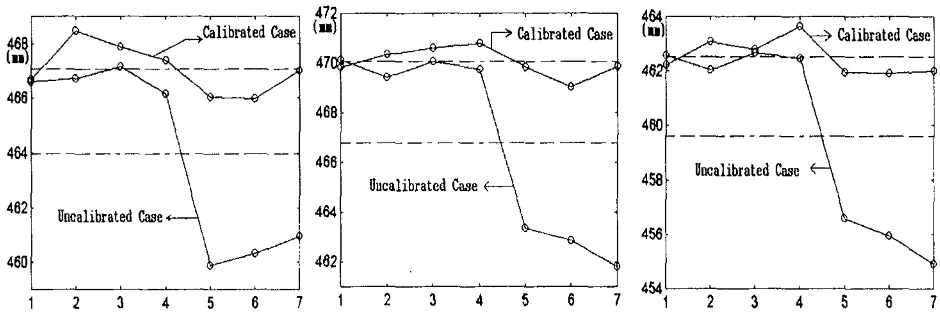
Now, we develop the algorithm of transformation parameters from {P} to {J} which are indispensable to the considering autonomous SCP calibration for the Perceptron. However, the success of the algorithm considerably depends on not only the accuracy of the Perceptron measurement but also manufacturing precision of the jig. Therefore, both must be increased as high as possible.

4. Implementation and Results

In this section, the obtained method for the SCP calibration of the Perceptron is implemented using Hyundai 7602 AP robot and its results are discussed in terms of the Perceptron's measurement accuracy. Fig. 3 shows the experimental set-up for data collection. The jig for Perceptron measurement is manufactured with its error tolerance 0.1 mm, shown in Fig. 4. The last 3 joints of the AP robot are used to reduce the positioning error of the robot occurred by the error of its link lengths and link offsets. For this implementation, the jig is placed at 3 locations as A, B, C, respectively and 7 sample configurations were taken at each location for

Table 1. Calibration results

	Rot(X_6)	Rot(Y_6)	Rot(Z_6)	Trn(X_6)	Trn(Y_6)	Trn(Z_6)
calibrated parameters	-1.5241°	1.5871°	22.5287°	-16.8786	-75.5423	116.5369
design values	0°	0°	20°	-17	-76	117



(a) Distance to A (b) Distance to B (c) Distance to C

Fig. 5. Comparison of Computed Distance Values between the Calibrated- and the Uncalibrated Case about 7 Sample Points at Each Position A, B and C

the data collection of the Perceptron's measurement. The SCP calibration results(3 rotation parameters and 3 translation parameters) are shown in Table 1 with the initial design values for mounting the jig on the robot. For the effectiveness of the presented calibration method, a of base frame of the robot to the origin of {J} coordinate frame at each location A, B, C is computed respectively, using both initial design parameters and its calibrated parameters. (Here, suitable evaluation of the calibration results is necessary. Therefore, each distance from the origin the base frame of the robot is the initially fixed 4^{th} joint coordinate frame, as addressed before.) The results are shown in Fig. 5. It can be easily observed that the deviations from their average values in calibrated case are quite small in comparison with those in uncalibrated case. The maximum deviation, 1.4 mm, in the calibrated case in comparison with that, 5 mm in uncalibrated case shows the effectiveness of the presented autonomous SCP calibration method.

5. Conclusion

An autonomous SCP calibration method for the Perceptron sensor has been developed with the specially designed jig. The method allows automated process of implementation and is suitable for on-site calibration in an industrial environment. The effectiveness of this method was shown through the real implementation using Hyundai 7602 AP robot such that the Perceptron's measurement accuracy is increased up to less than 1.4 mm in comparison with that of the uncalibrated case. The success of the method quite depends on the manufacturing accuracy of a jig and then special care must be taken with manufacturing it. Therefore, our future work will investigate jig-free autonomous SCP calibration for the Perceptron..

6. References

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