International Journal of the Korean Society of Precision Engineering Vol. 4, No. 1, January 2003.

Autonomous Sensor Center Position Calibration with Linear Laser-Vision Sensor

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ABSTRACT

A linear laser-vision sensor called 'Perception TriCam Contour' is mounted on an industrial robot and often used for 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 most 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, and the Perceptron sensor measurements on a specially devised jig which is essential for this calibration process. The algorithm is implemented on the Hyundai 7602 AP robot, and Perceptron`s measurement accuracy is increased up to less than 1.4mm.

Keywords : SCP (Sensor Center Position) Calibration, Linear Laser-Vision Sensor, Perceptron System

1. Introduction

In order to extend the use of an industrial robot to more sophisticated tasks such as position correction, visual servo and inspection of 3D parts, a linear laser vision sensor called "Perceptron TriCam Contour Sensor" is often mounted on a robot hand.

Whenever a sensor is mounted on a robot, it is important to determine the kinematic relationship between the sensor and hand coordinate frames for accurate measuring and precise robot positioning. The related kinematic parameters are 3 rotation 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 the SCP calibration is presented for the most 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 constraints must be deduced from the configuration of the calibration system: task constraints utilizing laser line tracking[2], plane measurements[1,4] and plane constraint with implicit loop method[5]. The presented 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 most accurate use of the robot -Perceptron system. First, Section 2 gives the brief description of Perceptron sensor. With this sensor, the problem of SCP calibration can be formulated in Section 3. Section 4 introduces the specially devised jig for this calibration process and explains its related parameter identification procedure. In Section 5, the obtained algorithm is implemented to show its effectiveness, on the Hyundai 7602 AP robot and the results are discussed in terms of the Perceptron's measurement accuracy.

2. Perceptron Sensor

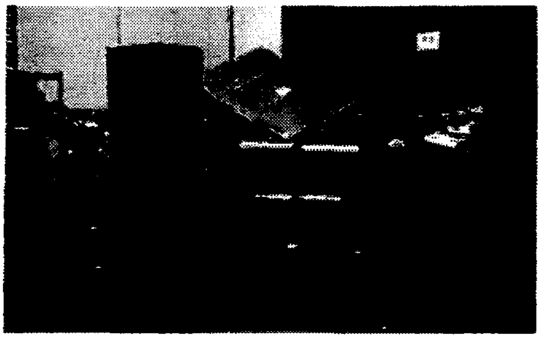


Fig. 1 The View of Measuring Gap and Flush by Perceptron

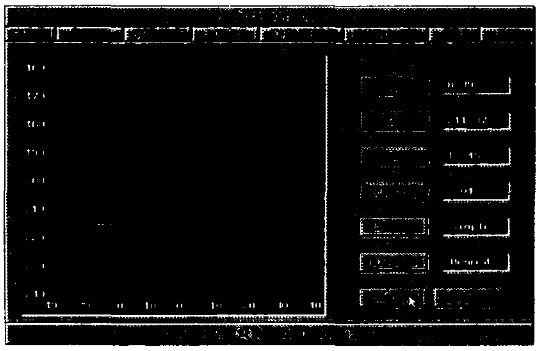


Fig. 2 The Process Window for the Measurement shown in Fig. 1

This section simply gives the brief description of Perceptron TriCam Contour Sensor for better understanding of the following sections. Perceptron sensor 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 result (Y,Z coordinate values) with respect to the sensor coordinate frame. Fig. 1 shows the view of measuring the gap and flush by using the Perceptron sensor and Fig. 2 shows the Process Window on a PC which processes the image data and computes measured values, corresponding to the measurement depicted in Fig. 1.

3. Autonomous SCP Calibration

Unlike the robot calibration with external end-point

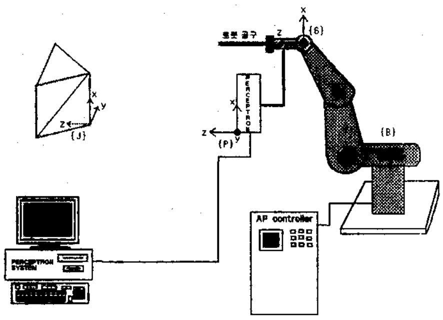


Fig. 3 Autonomous SCP Calibration

system measurements[6,7], autonomous calibration uses only robot's internal sensors and instead, requires the existence of internal constraints deduced from the entire calibration system. And no human intervention during measurement phase is allowed so that low cost and on-site calibration be possible in an industrial environment. Fig. 3 shows the system being considered currently. The Perceptron sensor is mounted on a robot hand. The transformation parameters from the robot hand coordinate frame to the sensor coordinate frame should be identified for accurate sensor measurement and precise robot positioning. Suppose that only 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 with the Perceptron sensor according to the various configuration change of the robot up to n configurations. For each configuration an angle set θ is recorded and the 6×1 position vector 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 the next section. The difference of the real position vector x^* and the computed position vector is expressed as

$$x_i - x^* = [\, J_\Phi \,]\, \Delta\Phi = [\, J_{\Phi_i} \; J_{a_i} J_{\Phi_i} J_{d_i} \,] \begin{bmatrix} \Delta\theta_{offset} \\ \Delta\alpha \\ \Delta a \\ \Delta d \end{bmatrix}$$

$$i = 1, 2, \ldots\ldots.. n \qquad (1)$$

where α , a, d are the twist angle, link length and link offset of DH parameter notation, respectively, and J is the conventional Jacobian and the joint angle error set from nongeometric factors is assumed as a constant vector θ_{offset} . That is, the true joint angle set is the sum of the joint sensor reading set and the offset vector. To eliminate the unknown x^* , i^{th} equation is subtracted from the first equation of (1). The results are

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

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

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

$$\Delta x = C\Delta\Phi \qquad (4)$$

Applying the iterative least square algorithm to Eq. (4) leads to the following procedure:

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

In order to prevent the transient singularity, step 2) can be replaced by $\Delta\Phi_i = (C_i^T C_i + \lambda I)^{-1} \Delta x_i$ where I and λ are the 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 for control of convergence speed[8].

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

In the last section, it was assumed that the transformation parameters from {P} to {J} coordinate frame could be identified using each Perceptron's measurement. Therefore, a jig must be designed such that 6 transformation parameters from {P} to {J} are possible to be derived from Perceptron's measurement values, whenever the laser line of the perceptron is projected on the jig. Then, the fixed jig coordinate frame becomes possible to be expressed with respect to the robot base coordinate frame. Various shapes of jigs satisfying the above requirement could be considered, however the shape of the jig was selected to be of 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 the above and bottom plates of the triangular pillar as shown in Fig. 4. 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 our measurement points. Based on the jig shown in Fig. 4, the algorithm which identifies the transformation parameters between {P} and {J} will now be explained. The jig coordinate frame {J} is placed on front vertex of bottom plate of the triangular pillar. Its x-direction corresponds with the upward direction of the triangular pillar and its z-direction is directed into the page as shown in Fig. 4. 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. 4 and their {P} coordinate descriptions are shown as

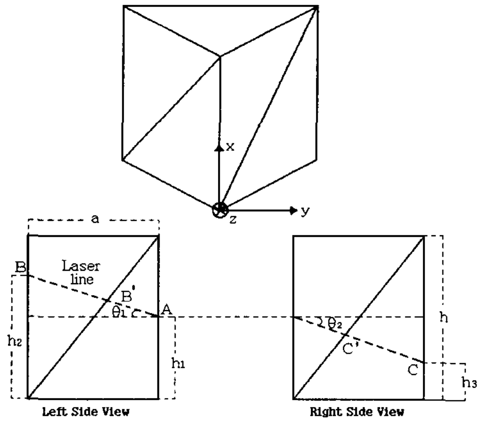


Fig. 4 The Shape of Jig

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

Also, {J} coordinate descriptions of A, B, C are

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

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

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

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

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

Set the distance between A and B to l_1, and that between A and C to l_2. They are expressed as

$$l_1=\sqrt{{}^{p'}y_b^{2}\,{}^{p}+{}^{p'}z_b^{2}},\quad l_2=\sqrt{{}^{p'}y_c^{2}\,{}^{p}+{}^{p'}z_c^{2}},$$

respectively. From the triangular relationship between these distances and the length of the side of the triangle, a, the equations are easily obtained as

$$\pm\theta_1=\cos^{-1}(\frac{a}{l_1}),\quad \pm\theta_2=\cos^{-1}(\frac{a}{l_2}).$$

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 point A from points B' and C' are set to d_1 and d_2, respectively. They are expressed as

$$d_1=\sqrt{{}^{p'}y_{b'}^{2}\,{}^{p}+{}^{p'}z_{b'}^{2}},\quad d_2=\sqrt{{}^{p'}y_{c'}^{2}\,{}^{p}+{}^{p'}z_{c'}^{2}}.$$

Recalling that these 5 points are made by the projection of single straight laser line, the following equality relation can be obtained:

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

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. Both origins of {J' and {P'} frame are identical at point A, and thus the rotation relationship ${}^{p}P={}^{p}_{J}R\,{}^{J}P$ can be applied to points B and C as

$$\begin{bmatrix} r_{11} & r_{21} & r_{31}\\ r_{12} & r_{22} & r_{32}\\ r_{13} & r_{23} & r_{33}\end{bmatrix}\begin{bmatrix}0\\ {}^{p'}y_b\\ {}^{p'}z_b\end{bmatrix}=\begin{bmatrix}h'_2\\ -\frac{a}{2}\\ \frac{\sqrt{3}}{2}a\end{bmatrix}\tag{8}$$

$$\begin{bmatrix} r_{11} & r_{21} & r_{31}\\ r_{12} & r_{22} & r_{32}\\ r_{13} & r_{23} & r_{33}\end{bmatrix}\begin{bmatrix}0\\ {}^{p'}y_c\\ {}^{p'}z_c\end{bmatrix}=\begin{bmatrix}h'_3\\ \frac{a}{2}\\ \frac{\sqrt{3}}{2}a\end{bmatrix}\tag{9}$$

Eqs. (8)-(9) can be expressed in detail as 6 equations with 6 unknowns. They could be analytically solved. The additional orthogonality condition of rotation matrix allows to determine all components of the rotation matrix for {P} to {J}. Then, the translational parameters from {P} to {J} can be determined by applying the following equation to point A as

$$ {}^{p}P_{Jorg} = {}^{p}P - {}^{p}_{J}R\ {}^{J}P = \begin{bmatrix} 0 \\ {}^{p}y_a \\ {}^{p}x_a \end{bmatrix} - {}^{p}_{J}R \begin{bmatrix} h_1 \\ 0 \\ 0 \end{bmatrix} \quad (10) $$

Now, we develop the algorithm of transformation parameters from {P} to {J} which are indispensable to the considered autonomous SCP calibration for the Perceptron sensor. However, the success of the algorithm considerably depends not only on the accuracy of the Perceptron measurement but also one the manufacturing precision of the jig.

5. Implementation and Results

In this section, the obtained method for the SCP calibration of the Peceptron is implemented on the Hyundai 7602 AP robot and its results are discussed in terms of the Perceptron's measurement accuracy. Fig. 5 shows the experimental set-up for data collection. The jig for Perceptron measurement is manufactured with its error tolerance of 0.1 mm, and is shown in Fig. 6. 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 and 7 sample configurations were taken at each location for the data collection of the Perceptron's measurement. The SCP calibration results (3 rotation 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, The distances from the origin of the robot base coordinate frame to the origin of {J} coordinate frame are computed for each jig location A, B, C respectively,

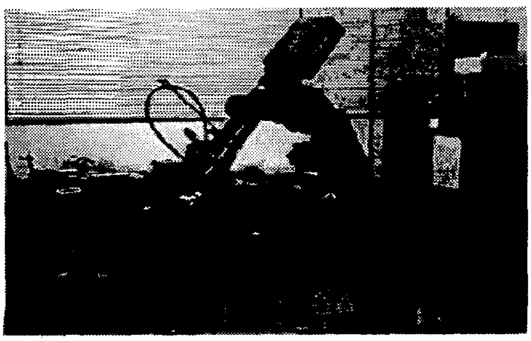


Fig. 5 Robot-Perceptron System

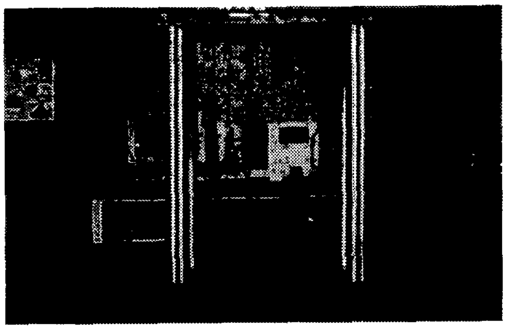


Fig. 6 the Jig as an Object of Measurement

with both initial design and its calibrated parameters. The results are shown in Fig. 7. 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.

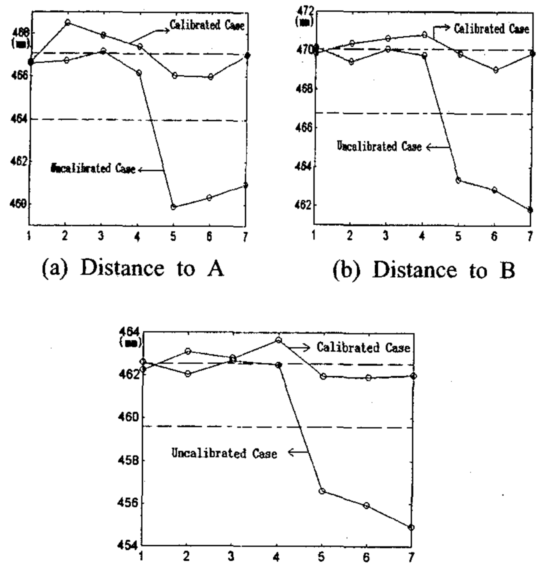
6. Conclusions

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 on the Hyundai 7602 AP robot such that the Perceptron's measurement accuracy is improved 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 the jig and thus special care must be taken when manufacturing it Therefore, a jig-free autonomous SCP calibration for the Perceptron will be investigated in the future.

Table 1 Calibration Results

	Rot(X_6)	Rot(Y_6)	Rot(Z_6)
calibrated Parameter	-1.5241°	1.5871°	22.5287°
Design Value	0°	0°	20°

	$Trn(X_6)$	$Trn(Y_6)$	$Trn(Z_6)$
calibrated Parameter	-16.8786	-75.5423	116.5369
Design Value	-17	-76	117



(a) Distance to A

(b) Distance to B

(c) Distance to C

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

Acknowledgement

The Author would like to acknowledge the finacial support of University of Ulsan, and appreciate Hyundai Motor Company for help in providing equipment.

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