Quick Robot Cell Calibration for Small Part Assembly
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Abstract: The requirement on quick and accurate robot cell calibration becomes crucial in the booming robot application of Small Part Assembly. In this paper, problems of traditional robot cell calibration have been discussed, while solutions for quick robot tool and work object calibration have been proposed. In particular, calibration experiments have been carried out in a dispensing robot cell. Experimental results show the efficiency, accuracy, and repeatability of the proposed quick robot cell calibration.

Keywords: Small Part Assembly, Robot Cell Calibration, TCP, Work Object

1 Introduction
Small Part Assembly (SPA) in 3C (Computing, Communication & Consumer Electronics) industry is identified as a booming application for industrial robot. New demands in SPA are: higher robot cell accuracy at sub-mm, quicker commissioning for short life cycle.

A proper robot cell calibration is essential for accurate robot motion by ensuring the position accuracy between robot and its peripherals (e.g. end-effector, fixture, tray) in a cell [1]. It enables the offline robot programing by aligning the coordinates from CAD model to the real cell. Moreover, cell calibration can reduce the reprogramming effort if the relative position between robot and peripherals gets changed in a collision crash or in transportation.

Traditionally, manual calibration by jogging the robot to reference points with a tapered tool is very time consuming and tedious. Its accuracy is determined by human eye observing, so the result is poor and varies depending on individual operator.

On the other hand, a lot of automated cell calibration solutions have been proposed. Among them, laser technology is widely used [2-4]. One famous solution is the Bull’s Eye[4] implemented in ABB robot welding application. It uses a single laser beam as a line constraints to calculate robot tool coordinates via a robot motion procedure. However, due to the complexity of the calibration algorithm, Bull’s Eye requires additional software option and special robot routines. It does not cover the work object calibration. Thus, it is not a generic solution could be easily accepted by the field engineers.

Alternatively, force control, sphere touching with trigger signal, mechanical constraints with soft robot servo are also attempted by academia and industrial researchers, as summarized by Bergström[5]. In general, considering the time-strict and frequent changing robot cell for SPA in 3C industry, these prior art solutions are complicated, expensive, hard-to-use, inefficient, and low flexible.

2 The Problem of Robot Cell Calibration
The purpose of the cell calibration is to identify the coordinate relationships between robot and its peripherals. According to tool holding status, there are two basic robot cell scenarios: moving tool scenario (e.g. a gripper hold by robot) and stationary tool scenario (e.g. a dispensing nozzle fixed in cell), as illustrated in Figure 1.

To program a robot to a target position on an object with a dedicated tool, the coordinates of tool and work object have to be determined.

![Figure 1 A scheme of robot coordinate system in a cell[6]: (a) moving tool scenario; (b) stationary tool scenario.](image-url)
For moving tool scenario in Figure 1(a), the tool coordinates are defined w.r.t. (with respect to) robot flange. The origin of the tool coordinates is the so-called TCP (Tool Center Point), which is the active point for approaching the target in space. The origin of robot flange coordinates is usually considered as TCP0. The work object coordinates are defined w.r.t. robot base.

For stationary tool scenario in Figure 1(b), the definition and tool and work object coordinates is contrary to that in moving tool scenario.

Taking the moving tool scenario as example, a TCP is traditionally calibrated with 4-point method as illustrated in Figure 2, where the robot is jogged to approach the tool tip on a world fixed tip with four different poses.

Thus the coordinates of the fixed tip can be expressed as

\[ \mathbf{P} = \mathbf{R}_0 \mathbf{TCP} + \mathbf{TCP}_0 \]

(1)

Where \( \mathbf{P} \) is the coordinates of the fixed tip w.r.t. the robot base, \( \mathbf{R}_0 \) and \( \mathbf{TCP}_0 \) (i=1-4) are the orientation and translation of robot flange w.r.t. robot base respectively. TCP is the interested coordinates of the tool tip w.r.t. robot flange.

Since the robot points the same fixed tip for four times, Eq(1) can be rewritten as

\[ (\mathbf{R}_0 - \mathbf{R}_0')\mathbf{TCP} = - (\mathbf{TCP}_0 - \mathbf{TCP}_0') \]

(2)

By using all distinct combination i, j of four robot poses, TCP can be calculated as the linear least square solution of the system equations.

The manual 4-point tool calibration is time consuming and operator dependent, since it requires the tips alignment by careful eye observing. It can easily take a skilful engineer 20 minutes to reach a proper tool calibration.

The error of tool calibration comes from the imperfect tip alignment as well as robot kinematics inaccuracy. Substituting the calibrated TCP into Eq.(1), the fixed tip coordinates are not exactly the same at four poses. The distances among the calculated four fixed tips are the so-called error for tool calibration. Typical error in a proper tool calibration is at 0.3~0.5mm.

With the calibrated tool, one can tell a position pointed by the tool tip w.r.t robot base. Therefore, work object coordinates can be identified by pointing at least 3 points on an object as illustrated in Figure 3.

This is the traditional work object calibration procedure conducted by engineers in most of the existing robot cells. Like the traditional tool calibration, it introduces again the inaccuracy and operator-dependency during the manual jogging with human observing.

3 The Proposed Robot Cell Calibration System

As illustrated in Figure 4, the proposed robot cell calibration system is composed of a linear touch sensor, a cross beam sensor, robot, and geometry features in the cell. The main idea is to properly combine the small range measurement device, binary positioning device, and geometry features to cover most of the cell scenarios in SPA.

In particular, the linear touch sensor provides the robot a 3D measuring capability of a touch point in space by calculating with robot’s own kinematics. The selected GT2-H12K[7] by Keyence has 12mm measuring range with 1µm measuring accuracy. By touching multiple points on geometry features like planes, slopes, or spheres,
A mathematic description of a coordinate system can be obtained via fitting of the measured positions.

The cross beam sensor is composed of two optical beam sensors FU-55 by Keyence with a mechanical frame. Digital output changes from 1 to 0 when the beam gets blocked. The cross beam sensor provides the robot an automatic positioning capability of a fixed point in space.

It is plug-and-play to connect the linear touch sensor and cross beam sensor with the robot controller via communication bus (e.g. RS232, Ethernet) and digital input respectively. According to the calibration scenario in a dedicated cell, one can switch over installing these two sensors either on robot or on a fixed position in a cell.

4 Quick Tool Calibration

The on/off digital feedback of beam sensor enables the robot to automatically locate a cylinder shaped tool at the center of the cross beam in an arbitrary orientation, as illustrated in Figure 6.

If the robot can move along the Z direction of tool, both X and Y beam will keep blocked until the tool tip leaves the beam center. Thus, the tool tip aligns with the beam center by recording the robot pose when a negative flank of the beam signal occurs.

Repeating the above beam center searching for four times with different tool orientations, the 4-point tool calibration in Figure 2 can be proceeded automatically. Such an automatic tool calibration only requires the operator to teach a start searching point near the cross beam center.

Two main steps for automating the tool calibration with cross beam sensor are:

- planar searching for locating the cross section of the tool at the beam center;
- tool tip searching by identifying the Z direction of tool.

As illustrated in Figure 7, a start searching point is taught near the center of the cross beam. The robot first moves along the Y direction to locate the tool on the beam Y by averaging two beam hitting position as shown in Figure 7 (c) and (e).

Similarly, the robot then moves along X direction to locate the tool on beam X. Consequently, the beam center is found.

The key step for tool tip searching is to identify tool Z direction vector V w.r.t robot flange. Referencing the principle in [9], planar searching for the tool is repeated two times with different depth, as illustrated in Figure 8.

The vector generated by two TCP0s is parallel to the Z orientation of tool which can be expressed as

$$V' = (\text{TCP0}_2 - \text{TCP0}_1)/|\text{TCP0}_2 - \text{TCP0}_1|$$

where V’ is the tool Z orientation vector w.r.t. robot base, and TCP01, TCP02 are the tool center points of robot flange in two planar searches.

Thus, the tool orientation w.r.t. robot flange is

$$V = R_0^{-1} V'$$

where $R_0$ is the rotation matrix for the robot flange. The Euler angle of Z orientation vector along X and Y axis of robot flange frame can be calculated as

$$\text{angleX} = \text{asin}(-V.y)$$

$$\text{angleY} = \text{acos}(-V.z/cos(\text{angleX}))$$
As long as the tool orientation is achieved, the tool tip can be located properly on the beam center by programming the robot to move along the Z direction of tool.

The proposed automatic tool calibration can be implemented directly for tools with a tip (e.g. nozzle in dispensing, welding). For other tools without tips (e.g. gripper, vacuum cup), a tip accessory can be mounted on them, as an example for gripper illustrated in Figure 9. In particular, the tool orientation along Z axis can even be obtained with the help of the second tip on accessory.

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5 Quick Work Object Calibration
The linear touch sensor can be considered as a special robot tool for measuring purpose. Thus, the TCP of linear touch sensor can be identified with the tool calibration solution in Sec 4.

So that, a spatial point coordinates \((x_p, y_p, z_p)\) can be calculated with the measured touching displacement as
\[
\begin{align*}
x_p &= x_t + n_x \cdot L \\
y_p &= y_t + n_y \cdot L \\
z_p &= z_t + n_z \cdot L
\end{align*}
\]
where \((x_t, y_t, z_t)\) are the coordinates of TCP, \((n_x, n_y, n_z)\) are elements of the Z orientation vector of the tool, and \(L\) is the displacement along the Z axis of tool.

In order to ensure the touch in measurement, the TCP of linear touch sensor is offset at the middle of the displacement range, as illustrated in Figure 10.

The robot becomes a 3D measuring device eventually. By touching multiple points on a regular geometry surface, the mathematic description of the geometry can be obtained through a least square fitting\(^{[10]}\).

6 Experimental Results
6.1 The Experimental Robot Cell

As illustrated in Figure 12, the proposed quick cell calibration solution is implemented in a robot cell for dispensing process. It is a cell scenario with stationary tool, where a substrate picked by vacuum cup is a work object while the nozzle of the dispenser is the tool.

The cross beam sensor is hold by the robot, while the linear touch sensor is fixed in the cell near the nozzle.

Calibration tasks in this robot cell are listed as following:
- Calibrating the tool coordinates of nozzle
- Calibrating the tool coordinates of linear touch sensor
- Calibrating the work object coordinates of a substrate

6.2 Result of Tool Calibration
Figure 14 illustrates the automated tool calibration procedure with cross beam sensor. The robot locates the dispensing nozzle tip on the center of cross beam with the searching method in Sec 4. The tool coordinates is calculated in robot controller with the equations in Sec 2. The max error of the tool calibration is around 0.25mm, as displaced on the UI (User Interface) of teach pendant in Figure 13. It is a good tool calibration result can only be achieved by extreme careful operation with the traditional tool calibration.

In order to evaluate the repeatability of the automated tool calibration, the above procedure is repeated for five times. As shown in Table 1, the largest TCP deviation is no more than 0.1mm. This is a stable and accurate result which can be hardly achieved in manual tool calibration.

![Figure 13 Tool calibration result displayed on the robot teach pendant.](image)

![Figure 14 Tool calibration on the experimental platform: (a) searching 1st point; (b) searching 2nd point; (c) searching 3rd point; (d) searching 4th point.](image)

<table>
<thead>
<tr>
<th>Test No.</th>
<th>X of TCP (mm)</th>
<th>Y of TCP (mm)</th>
<th>Z of TCP (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>428.538</td>
<td>21.885</td>
<td>640.028</td>
</tr>
<tr>
<td>2</td>
<td>428.438</td>
<td>21.964</td>
<td>640.080</td>
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<tr>
<td>3</td>
<td>428.511</td>
<td>21.874</td>
<td>639.950</td>
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<tr>
<td>4</td>
<td>428.512</td>
<td>21.895</td>
<td>640.005</td>
</tr>
<tr>
<td>5</td>
<td>428.502</td>
<td>21.886</td>
<td>639.918</td>
</tr>
</tbody>
</table>

6.3 Result of Work Object Calibration
As illustrated in Figure 15, a substrate for the dispensing is a regular housing with orthogonal planes: plane X, plane Y, and plane Z. The work object coordinate of this substrate is defined at the top left corner. The work object coordinates can be obtained by identifying the plane equation of these three planes.

Figure 16 illustrates the automated calibrating procedure by touching the geometry features of the work object with the linear touch sensor. With the acquired touching data, plane fitting and coordinate frame are calculated in robot controller.

![Figure 15 Planes in the work object.](image)

![Figure 16 Work object calibration on the experimental platform: (a) touching Z plane; (b) touching Y plane; (c) touching X plane.](image)

It is worth noting that the preprogrammed touching targets are based on the nominal work object coordinate, where the nominal reading of the linear touch sensor is 6mm. Since the practical work object deviates from the
nominal one, the sensor reading will also deviates from the nominal reading, as illustrated in Figure 17. After the actual work object is obtained via the calibration, the reading of linear touch sensor should return to be nominal value while the robot goes to the touching points again. Therefore, the reading the touch sensor can be a criteria for justifying the accuracy of the work object calibration.

Figure 17 Work object deviation from nominal coordinates.

Figure 18 shows the experimental result of the touch sensor reading. Before the calibration, the work object position deviation alone Y axis (robot target 8-11) and X axis (robot target 12-15) is up to 4 mm from the nominal value robot expects, while position deviation alone Z axis (robot target 1-7) is limited since the substrate is constrained by vacuum gripper in Z direction. After the calibration and the new work object is updated in robot controller. Verification touch reading shows the calibration error is within 0.1mm.

In order to evaluate the repeatability of work object calibration. The substrate is placed with five random poses. For each pose, a calibration and verification procedures are carried out.

As shown in Figure 19, the reading deviation among different calibrated work object is within 0.1mm. It means that a taught robot target in an original work object frame is still valid in a new work object frame with error smaller than 0.1mm.

Figure 19 Repeatability analysis of work object calibration.

7 Conclusions

In this paper, a quick robot cell calibration solution is presented by understanding the new requirement in SPA and clarifying the problem of robot cell calibration.

With ease-of-use devices and automated procedures, the proposed robot cell calibration significantly reduces the engineering time and effort by more than 50%.

As evaluated in a robot cell for dispensing process, the calibration accuracy reaches sub-mm level with high consistent repeatability. Such a quick robot cell calibration enables the quick cell setup and recovery with reliable accuracy in SPA.

References

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