High precise and zero-cost solution for fully automatic industrial robot TCP calibration

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Abstract

Purpose – The purpose of this study is to present a novel method for industrial robot TCP (tool center point) calibration. The proposed method offers fully automated robot TCP calibration within a defined cycle time. The method is applicable for large-scale installations due to its zero cost for each robot.

Design/methodology/approach – Precise and expensive measuring equipment or specially designed reference devices are required for robot calibration. The calibration can be performed by using only one plane plate in this method, and the calibration procedure is defined step by step: the robot moves to the target plane position. Then, the TCP touches the plane and the actual robot configuration is recorded. Then robot moves back into position and the same step is repeated for a new sample. Alternatively, the robot can be stationary and the plane can be moved towards the robot TCP. TCP is calculated by processing the difference of the contact points recorded at different positions. The process is fully automated. No special equipment is used. The calculations are very simple, and the robot controller can easily be realized.

Findings – The conventional manual robot TCP calibration process takes about 15 min and takes more time in case of the high accuracy. The proposed method reduces this time to less than 3 min without operator support. Practical tests have shown that TCP calibration can be performed with 0.1-0.6 mm of accuracy. This solution is an automated process and does not require special installation and it also has approximately zero cost. For this reason, this study recommends using the proposed solution widely in areas where even one or hundreds of robots are located.

Research limitations/implications – In this study, the data were directly taken from the robot controller without using any special measuring equipment. The industrial robot used in the tests has no absolute calibration. The classical "four-point method" was used for reference TCP data. It is the initial acceptance that this process conducted with extreme care and by using a needle-tipped tool will not produce exact values. It was observed that deviation of the TCP from a fixed point in reorient motions was not more than 0.5 mm. This method has been validated for different bits. The pilot works for different robot applications in Ford Otosan Gölcük Plant have been completed and dissemination has started.

Originality/value – Although the approach uses is clear and simple, it is surprising that the calculation of TCP using plane equations has so far not been mentioned in the literature. The disadvantage of using either fixed point or sphere as a reference is that the TCP cannot automatically guide to the target. This problem was overcome with the use of a larger target plane plate and the process was fully automated. The proposed method can be widely used in practical applications.

Keywords Industrial robot, Automatic calibration, Robot TCP, Tool calibration

Paper type Research paper

1. Introduction

Robot calibration refers to the function of identifying the actual geometric parameters of the kinematic structure of objects that interact with the robotic process. It is aimed to increase robot sensitivity by determining the deviation from the production values and technical drawings. Basically, there are three different calibration objects. Detection of manipulator parameters is known as general robot calibration. When performing work with robotic devices, the required target coordinates may sometimes have to be obtained via the position sensors attached to the robot flange. In this case, calibration is the definition of the relationship of the sensor coordinate system with robot coordinate systems. It is often referred to as hand–eye calibration. The position information of the contact points of the equipment that works directly by contacting the surface of the workpiece, such as welding gun, conveying apparatus and machining equipment, which is carried by the robot, is known as the TCP (tool center point) calibration. If the robot target positions are generated via computer-aided design (CAD) programs, the TCP must be determined precisely. As a result of an accurate TCP calibration, the position of the operation point corresponds to the exact values in the computer environment.

The real positions of the industrial robots (IRBs) and the values shown in robotic CAD (RobCAD) environments may vary from one to the other. This can be up to 8-15 mm. Absolute accuracy data sheet (ABB Robotics, 2011) indicates

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that the opening can be reduced to 5 mm for the same robot with special calibration. For the ABB brand, this is optional, and customers have to pay extra for absolute calibration. Information on the accuracy of different types of robots and measurement techniques is provided by Borrmann and Wollnack (2015). It should be emphasized again to avoid misunderstandings. The deviation is the difference between straight kinematic calculations and actual manipulator position. If programming is done in the RobCAD environment, it should be taken into consideration. In this manuscript for the verification of the proposed method, ABB IRB 1600-8/145 was used. Repeatability of this IRB is 0.12 mm and the accuracy is 0.42 mm. There are some good examples in the literature that shows these tolerances can be reduced. For example, Liu and Xi (2011) achieved 0.002 mm, and Jiang, *et al.* (2016) achieved the accuracy level up 0.021 mm (0.008 degree).

Target coordinate information is variable in some applications, such as in pick-and-place applications for feeding a machine. As the robot cannot be programmed for these variable points in advance, the position information should be taken from environmental sensors such as cameras. However, as the reference of these data is the sensor coordinate system, it must be transferred to the robot coordinate plane. This process, known as hand–eye calibration, has been studied by Deniz and Cakir (2018). In this publication, researchers compared the methods in the literature with the methods they proposed. They also included error metrics that could be used in calibration. The result of the hand–eye calibration is exactly the same as that of TCP calibration if the center of the sensor coordinate system is referred as an end-effector. It is a homogeneous transformation matrix that contains the amount of rotation and translation, which describes the position of this point relative to the robot flange.

Conventionally TCP calibration is done as follows: a well-trained operator moves the robot endpoint closer to a fixed point in the access zone. It repeats the same operation with different rotations and records these points each time. This operation is performed using a built-in function defined in almost all industrial robot brands. The process is time-consuming. This can be done only after stopping the production, and the result is dependent on operator skill. In Yin, *et al.* (2014), this method is partially subjected. As mentioned above, they evaluated the visual sensor as a robot end function and performed TCP calibration. In the method they developed, they used spheres as reference points. They reported that the elapsed time of the calibration is less than 10 min and the accuracy of about 0.5 mm.

The accuracy of the position of the end-effector as a result of TCP calibration depends on precise position measurements. The use of coordinate measurement machines (CMM) provides the most accurate results, but the costs are high. Alternatively, measuring with image sensors is the solution. Möller *et al.*'s (2016) study is an example of the use of the camera. In this study, researchers have put special markers on the equipment to increase the accuracy of measurement. This solution can be evaluated only during the installation phase. It is not suitable for the manufacturing site. The researchers compared their results with the results obtained with the laser tracker. The precision level of 0.05 mm is very good, but the cost of the system they are referring to is €80, and the cost of their system is €50. Even in the study by Luo and Wang (2018), the cost, which is offered as a cheap solution, is close to $2,000. The solution presented in this study was compared with that of commercial CMM equipment such as Leica and FARO®. In Luo and Wang's (2018) study, the measurements were taken with cameras as in the similar ones. However, the difference from other methods is to perform error compensation using the deep neural network (DNN) instead of analytical solutions. Researchers have stated that the main problem in camera-based systems is the ambient lighting, and this problem can be easily overcome in the industrial environments. However, it is clear from the experience that industrial environments are not conditioned for secondary operations such as calibration. The main priority is the continuation of manufacturing.

TCP calibration is not a process that needs to be conducted only once during the installation phase. Repetition for reasons such as wear and tip change may be needed. This situation, which can be summarized as the position shifts in the process, is mentioned by Sun *et al.* (2009). Their solutions include to perform relative calibration instead of referenced position information to fixed objects known as absolute calibration. TCP is not on the manipulator in the process of interest. The center of the grinding wheel is taught as TCP. Another difference in this article is the goal of calibration procedures. The target in the study is to apply constant force on the contact point. For this reason, force sensors, together with position sensors, are used for measurements. Therefore, they have moved away from the effective cost solution they originally intended.

Different commercial equipment are available for TCP calibration. The ABB Bullseye is a system developed specifically for arc welding. Similarly, LEONI products are available for different ends. The majority of such systems have parameters that must be defined in the initial setup. Almost all of them cost over $1000. The advantages are that they can automate the process. In Zwierzchowski (2017), the introduced system was based on Bullseye and LEONI references.

In this and similar solutions, the TCP is moved towards a linear light barrier. When the tip passes the barrier, this point is recorded. The advantage of this solution applicable for symmetrical tips is that the operator invention does not needed. Movements are performed on a predefined path. Depending on the initial posture, these tools cannot be used if the endpoint is at a distance and the sensor area is narrow. Zwierzchowski (2017), without any detail, stated that this skewness was 3° for the tip shape which he used in the presentation of his work. Borrmann and Wollnack (2015) proposed the use of mechanical adapters to overcome the challenges of direct detection of TCP by measuring equipment. They applied the analytical method they developed on the milling equipment. The calibration unit introduced by Gordic and Ongaro (2016) is quite complicated. Their system is based on camera measurements. After positioning the TCP into a specially designed chamber for image acquisition, cameras take endpoint images. There are two cameras in the system and two orthogonally placed mirrors. Although the authors say that the process is automatic, this method as some drawbacks. The installation phase requires special effort, the complex design of the assembly and the volume of the image acquisition chamber

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restricts rotations. The study of Cai *et al.* (2018) is in part similar with the method described in that manuscript. As a target, a plane is used. But their approach is based on the position of the contact points. They perform the TCP calibration by processing the (x, y) coordinates of the touch point using the touch panel. The authors state that the fully automatic calibration with a precision of 0.25 mm in less than 1 min can be achieved.

In this paper, calibration process which can be performed automatically, without interfering the production cycle, is introduced. The main goal of the study is to minimize the cost of the whole setup while maintaining the calibration accuracy about 0.5 mm. After bringing the cost to the affordable price, this setup can be applied for all installed robots. Performing TCP calibration after competition of each production cycle is planned. These calibration checks will not only increase the quality of the production but also shorten the downtimes. The installation costs for the single unit, which is developed to be widely used in the manufacturing site, is \$10-15. Considering that the equivalent of \$1.000 is the lowest, and it can be considered as a zero cost.

TCP calibration can be done also to determine the orientation of the tool. This means that it is intended to obtain whole homogeneous transformation matrix of tool relative to the IRB's flange. This transformation can easily be decomposed into the translational and rotational parts. After one is computed, solution of the rest is straightforward. Determination of the tool orientation is not subjected in this paper.

In the next sections, theoretical information is given first. The flexible structure of the manipulator, zeroing errors and tool fastening errors are effective on position measurements. In the following section, the performance of the presented method is confirmed by synthetic data. Effects of measurements errors are discussed in this heading. Finally, practical test, same as the production lines, are performed and calibration results for different end shapes are given.

2. TCP calibration

The geometric parameters of the end point of the equipment attached to the robot flange, usually called *tool_0*, are obtained after the TCP calibration process. The attached device to the flange of the manipulator will be called as *tool_1* in this paper. The solution of the calibration equations identifies $T_{tool_1,org}$ the displacement vector between the center of the two coordinate systems and $R_{tool_0}^{tool_1}$, the rotation of the *tool_1* coordinate system relative to the *tool_0* coordinate system. Almost all commercial robot programs offer a choice of actual coordinate systems. Especially when the jog is done with hand terminals, the motion is performed referring to the active coordinate system. The position and rotations shown on the information screens are presented according to the selected coordinate system.

Calibration can be performed by using CMM even without moving the robot. Usually, the necessary data for the TCP calibration are collected by a series of measurements made at different postures of the robots. Figure 1 shows data collection postures for different methods. The approach on the left is the traditional method. Operator control is required. Processes can be automated when TCP can be guided to interact with the target as specified in Figure 1(b) and (c).

For the conventional method, TCP is positioned at $P_1^c = P_2^c \ldots = P_i^c$ positions that are fixed but unknown. Using notation R_i to represent the rotation of the *tool_0* coordinate system at the *i.* posture, relative to the base coordinates, and P_i^r to represent the position of the *tool_0* in base coordinates, for each postures where TCP is positioned at P_i^c, the values of R_i, P_i^r are stored. Each of these records satisfies equation (1).

$$R_i T + P_i^r = P_i^c \tag{1}$$

Because the fixed reference point is not known, the following arrangement is used to remove P_i^c from equality.

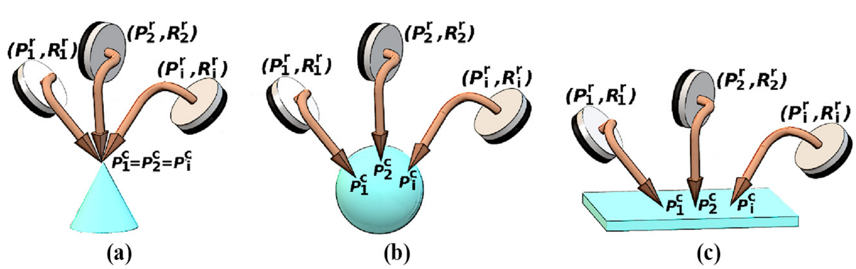
$$(R_i - R_j)T = P_j^r - P_i^r \tag{2}$$

This can be written as well-known $AX = B$ equation where $A = R_i - R_j$ and $B = P_j^r - P_i^r$. The linear equation system created by this final arrangement is solved by methods such as pseudo inverse, SVD, QR decompositions. This equation does not exist as a function in robot programming languages. However, the size of A and B matrices is limited by the number of samples. It is not difficult to write the algorithm and calculate the solution in the robot controller. Programmers can prepare their own calibration routines by applying the flow in Algorithm 1.

Algorithm 1 Editing the AX = B variables for the conventional method.

$$
\begin{array}{l}
k = 1 \\
for\ i = 1\ to\ (n-1)\{ \\
\quad for\ j = (i+1)\ to\ n\ \{ \\
\quad\quad A(k : k+2, 1 : 3) = R_i - R_j \\
\quad\quad B(k : k+2, 1) = P_j^r - P_i^r \\
\quad\quad k = k+3 \\
\quad \} \\
\}
\end{array}
$$

Figure 1 Different data collection approaches for TCP calibration.



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This conventional calibration method is available as a built-in function almost in all industrial brands. After invoking the relevant screens, the operator is responsible to register the IRB's positions. Each time he places the TCP at the target point with different rotation. TCP information is presented after pressing on the relevant command from the corresponding menus. The operator must bring the endpoint to the same position for each rotation with high skill so that the error is low. According to the selected method, by increasing the number of points recorded, accuracy can be increased

3. Proposed method

In the conventional TCP calibration method, the data collection work is done by the operator. The operator locates the TCP at the fixed reference point as in Figure 1(a). When the target has a large surface rather than a point, during the motion in the direction of the target, the robot can be stopped automatically at the time of contact to record the information. The processes in Figure 1(b) and (c) can be automated.

The method presented does not require a custom installation. As a target, it is sufficient to have a large plane within the access area of the robot. The whole process consists of two steps. First the normal vector of the plane is obtained. To do this, the robot is guided from the different points to the plane while maintaining the same rotation as shown in Figure 2(c). The position information of the *tool_0* at the point where the tip comes into contact with the plane is recorded. Because the rotation is kept constant, these points are on the same plane, and this plane is parallel to the target plate plane.

Using the recorded *Tool_0* positions $\overrightarrow{P}_{3x1} = (P_x, P_y, P_z)^T$

$$\overrightarrow{n}_{1x3} = (a, b, c) = \frac{\overrightarrow{(N)}}{\|\overrightarrow{N}\|} \tag{3}$$

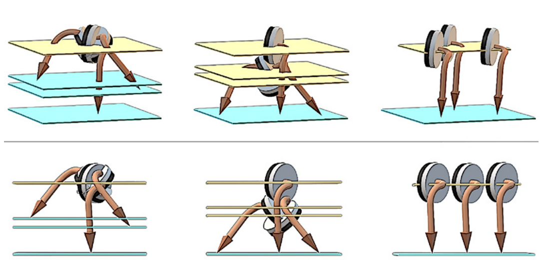
where $\overrightarrow{n}$ is the unit normal vector of the calibration plane

$$\overrightarrow{n} \cdot \overrightarrow{P} + d = 0, \tag{4}$$

the plane equation should be obtained. Because only $\overrightarrow{n}$ will be required in the following step, if the average value of $\overrightarrow{P}$ vectors is deducted to write $d = 0$, then the system is reduced to three unknown parameters. A solution procedure can be simplified for only three (a, b, c) values.

In the second step, for each different rotation, the distance variation of the TCP in the direction of the normal of the target plane is processed. After the surface normal vector is obtained, we can apply two different approaches. The first approach is shown in Figure 2(a). The robot keeps the *tool_0* at fixed position and motion reoriented. The robot is stationary in that case, and the target plate is moved in the direction of the plane normal vector. With simple potentiometric linear rulers, the distance from the starting zero position to the contact point can be measured. Using this approach, sampling time can be reduced and measurement accuracy can be increased. In the second option, Figure 2(b), the plane is completely fixed. The robot moves to the plane with the new rotation. At the time when TCP touches the plane, the *tool_0* position is registered.

Figure 2 Positions at which the robot's tip is in contact with calibration plane



The P_i^c target points shown in Figure 1 are not known in the calibration process. In the proposed method presented, these points are on the same plane and provide equation (5).

$$\overrightarrow{n} \cdot P_1^c = \overrightarrow{n} \cdot P_2^c \ldots = \overrightarrow{n} \cdot P_i^c = -d \tag{5}$$

using equation (1):

$$0 = [abcd]^c \cdot (R_i T + P_i^r)$$

$$0 = [abcd]^c_{1x4} \cdot \left(\begin{bmatrix} r_{11} & r_{12} & r_{13} & P_x^r \\ r_{21} & r_{22} & r_{23} & P_y^r \\ r_{31} & r_{32} & r_{33} & P_z^r \\ 0 & 0 & 0 & 1 \end{bmatrix}_{4x4} \begin{bmatrix} T_x \\ T_y \\ T_z \\ 1 \end{bmatrix}_{4x1} \right) \tag{6}$$

can be written. Currently, (a, b, c), R_i, P_i^r values are known. Because d^c is not known, in equation (7), it is necessary to make an arrangement in equation (8) to eliminate this term.

$$(n \cdot R_i)T = -(n \cdot P_i^r + d^c) \tag{7}$$

$$n \cdot (R_i - R_j)T = n \cdot (P_j^r - P_i^r) \tag{8}$$

$$\begin{aligned} A &= n_{1x3}(R_i - R_j)_{3x3} \\ B &= n_{1x3}\left((P_j^r + \epsilon_j) - (P_i^r + \epsilon_i)\right)_{3x1} \end{aligned} \tag{9}$$

After this arrangement, $AX = B$ form is reached again. The solution is provided by the flow shown in Algorithm 2.

Algorithm 2. Editing the AX = B variables for the proposed method

$$\begin{array}{l}
for\ i = 1\ to\ n\ \{ \\
\quad M(i, 1:3) = (n \cdot R_i) \\
\quad D(i, 1) = -(n \cdot P_i^r) \\
\} \\
k = 1 \\
for\ i = 1\ to\ (n-1)\ \{ \\
\quad for\ j = (i+1)\ to\ n\ \{ \\
\qquad A(k, 1:3) = M(i, 1:3) - M(j, 1:3) \\
\qquad B(k, 1) = D(i, 1) - D(j, 1) \\
\qquad k = k + 1 \\
\quad \} \\
\}
\end{array}$$

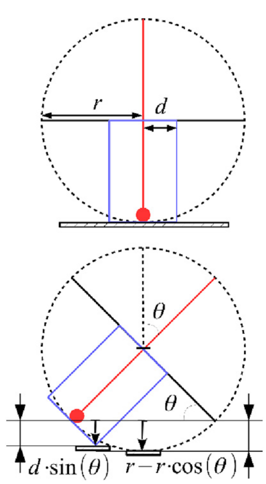
$D(i, 1) - D(j, 1)$ is the difference between the points P_i^r recorded at i posture and P_j^r at j posture, in the direction of the plane unit normal vector. If the calibration plane is moved by keeping the *tool_0* constant, it is equal to the difference between the measured values for both stops.

For the proposed solution, the positions at the time the end point is in contact with the plane must be recorded. Two restrictions will be encountered during this registration. First, it relates to the need to obtain position information as soon as the contact of the moving robot is detected. Owing to the sensor delay and the moment of the robot, whether the interrupt routines are used or the commands such as "SearchL.", the recording points will belong to the robot's next stop. The logic information from the contact sensor must reach the controller in the fastest way possible to minimize the error that can be made here. Through the interface controllers such as programmable logic controller, long-response-time sensors should be avoided. Nevertheless, the proposed method will be affected very little by these kinds of error sources. Even if faulty measurements are made, it will be ineffective on the calculation according to equation (9), as it will be systematically equal in all measurements. However, to avoid such effects, keeping the robot speed low will help achieve good results.

The second constraint concerns the detection of the end point's contact with the plane. Electrical conduction may not be suitable for all types of tips to detect contact. Mechanical contact may not be preferred at very delicate tools. In this case, optical sensors can be considered as an alternative. For some tool shapes, the end point may not be brought into contact with the plane in every rotation. In this case, additional calculations may be used.

If the contact point of the used equipment for each rotation to the target plane is its center point, the calibration is completed by the steps in Algorithm 2 without any further calculation. If the end is spherical, the calculated TCP indicates the center of the sphere. Such as milling, for some kinds of applications conical, cylindrical or spherical bits might be used. In this case, the contact point will be different at each time, as shown in Figure 3. For the spherical tips, to move the TCP from the center of the sphere to the surface in the direction of the line which $\theta_i = 0$ or for flat ends with circular cross section, additional correction given in equation (10) should be done. In that formula, abbreviation r is the radius of the sphere and d is the radius of circular cross section.

Figure 3 Difference between the point of contact and TCP



$$D_i = -\left(n \cdot P_i^r\right) - max[d \cdot \sin(\theta_i), r \cdot (1 - \cos(\theta_i))] \qquad (10)$$

The calculation made by equation (10) should be used in Algorithm 2. θ here is the angle between the contact plane and the target plate. To obtain this value, one of the rotations performed while collecting data should be made parallel to both planes, in other words, $\theta_i = 0$. Condition should be satisfied with one of the known posture. Other θ_i angles can be calculated analytically by reference to the rotation in this position.

4. Validation and verification of the proposed method

The equipment that kind of the CMM is not used to measure position values in the proposed methods. Because the cost of the system is desired to be low and it is intended for automatic processing, no additional controllers or calculators are used. For this reason, the program will be able to record the R_i, P_i^r values and execute the flow of the commands in Algorithm 2. To solve the $AX = B$ equation with the QR decomposition is prepared for the robot language.

The picture of the target plane used for the proposed method is shown in Figure 4. As it is known, the manipulator chassis is generally at the earth potential. The interface circuit shown in the picture is used to get the logic high signal when the TCP touches this target plane. The cost of the system is $10.

As stated before, the normal vector of the target plane should be calculated first. For this, as shown in Figure 5 (a), the robot is moved to in the target plane direction starting from different *tool_0* positions by keeping the rotation constant. The motion with different rotations in the second step is shown in Figure 5 (b).

4.1 Test with synthetic data

In the proposed method, the data required for the calibration are obtained by recording the position of the *tool_0* at which the TCP is in contact with the target plane board. The success of the TCP calibration is proportional to the accuracy of the IRB's position and orientation values. By increasing the number of

Figure 4 Target plane for calibration

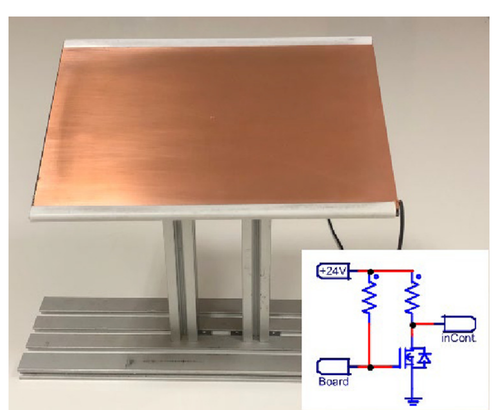
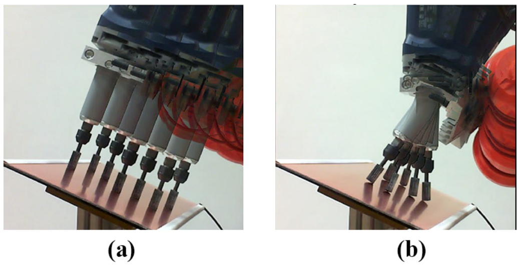


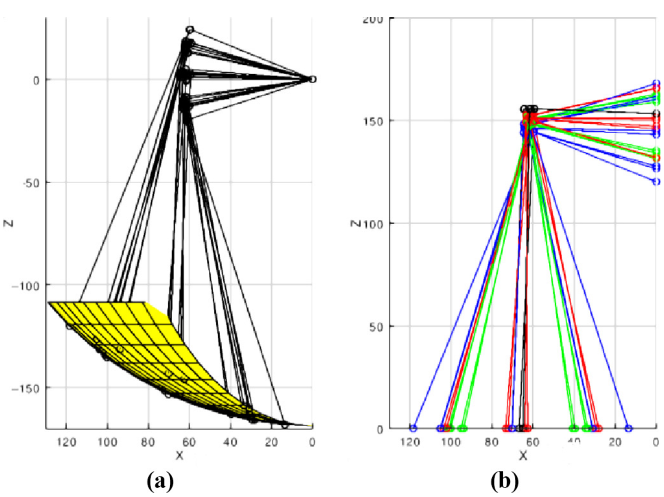
Figure 5 The positions at which the robot stops to record data



samples, it can be ensured that the solution of the overdetermined system is less affected by measurement errors. Under this heading, the effect of errors on the proposed method will be discussed. After obtaining the normal vector of the target plane, in the second step, IRB is reoriented to the different rotations. Figure 6 shows the postures of the tool in these orientations. Two different noise levels were tested for 27 different samples. Robotic measurements, recorded *tool_0*'s orientation and position when TCP touches the plane, illustrated in Figure 6(b), are disrupted with the uniformly distributed noise in the range [0.0.5] and [0.0.2]. Figure 6(a) shows an alternate approach. To speed up the process and increase the accuracy, *tool_0* can be fixed, and measurement can be acquired with any distance sensor for example linear ruler mounted in the direction of the plane normal can be used. For these measurements, noise was applied at half of the value above.

The maximum number of the samples was 27 in the tests. As shown in Figure 7(a) and (b), even if 6 samples were used, the error did not exceed 1 mm. For the proposed method in this paper, systematic, repeated errors in the same direction, are not very important as pointed in the equation (9). For example, if the contact point is detected at 2-3 mm away than the correct position for all samples, the calculated result accuracy will not be affected as the difference between the measurements is processed.

Figure 6 Posture demonstrations for data acquisition used in calibration; $TCP = [150, -10, 50]$



Numerical results calculated with 27 samples are presented in Table I to take a clear look. The conventional method using four samples is labeled as P4 and that containing 27 samples is labeled as P27. Considering that the accuracy of industrial robots is about 0.1 mm, the results are very positive. In the case of a noise level of 0.2 mm, the recommended method was far and away the best comparing the conventional four-sample calculations.

4.2 Genuine execution

In the practical tests, the machining bits shown in Figure 7 are used. These inserts are fitted to the Bosch GGS 28 LCE die grinder. A simple design jig was used to place the TCP at the same point. The exact TCP measurements are not available. The correct values to be considered as the reference are obtained by the traditional method presented in Figure 9 for the needle shape.

The values used in the calculations, presented in Table II, were obtained by positioning the end-effector at the fixed reference point in different rotations as in Figure 8. This process is dependent on operator skill. Table III presents the calculation results. The units of measurement are in millimeters. High care was taken to achieve the accuracy level close to 0.02 mm. The calibration time is approximately 10 min. It is an observation that we have reached after a long time at production plant, it takes at least 5 min for a skilled operator to calibrate a typical gas torch with sufficient precision.

The performance of the proposed method has been tested using the ABB IRB 1600-8/1.45 manipulator. The model does not have absolute accuracy option. Sampled positions are obtained by using the command "*SearchL\Stop, di_01, tcpPOS {id}, TEMAS2, vs_5, tool0*". This command directs the manipulator to the target position labeled as "*TEMAS2*" moving the *tool0* linearly with a velocity of 5 mm/s. In place of contact with the target plane, input "di_01" goes high, manipulator stops as quick as possible, the remaining part of the path is canceled and the current posture is saved in the robtarget variable "*tcpPOS{id}*" which stores orientation and position data. In ABB's technical reference manual on rapid instructions, it is written that "repetition accuracy for search hit position with TCP speed 20-1000 mm/s is 0.1-0.3 mm. Typical stop distance using a search velocity of 50 mm/s: without TCP on path (switch\Stop) is 1-3 mm".

As shown in Figure 5, the calibration process consists of two stages. First the normal vector of the target plate is obtained. Then, for each different rotation, the distance variations of *tool_0* through the plane direction are processed. About the first stage, considering the Figure 10, it can be stated that the calculated normal direction values are almost the same for different tip shapes because the rotation is kept constant for each motion. Measurement repeatability can be commented as very high because when the number of samples is increased, the results do not change much. The statistical box plots in Figure 10(b) are proving this. Very low, deviations at the level of 1E-4 indicate that the normal vector of the target plane can be obtained with very high accuracy by the apparatus shown in Figure 4.

One of the objectives in the presented method is to complete the calibration process in a reasonable time caring the production considerations. Thus, after each process cycle, a re-

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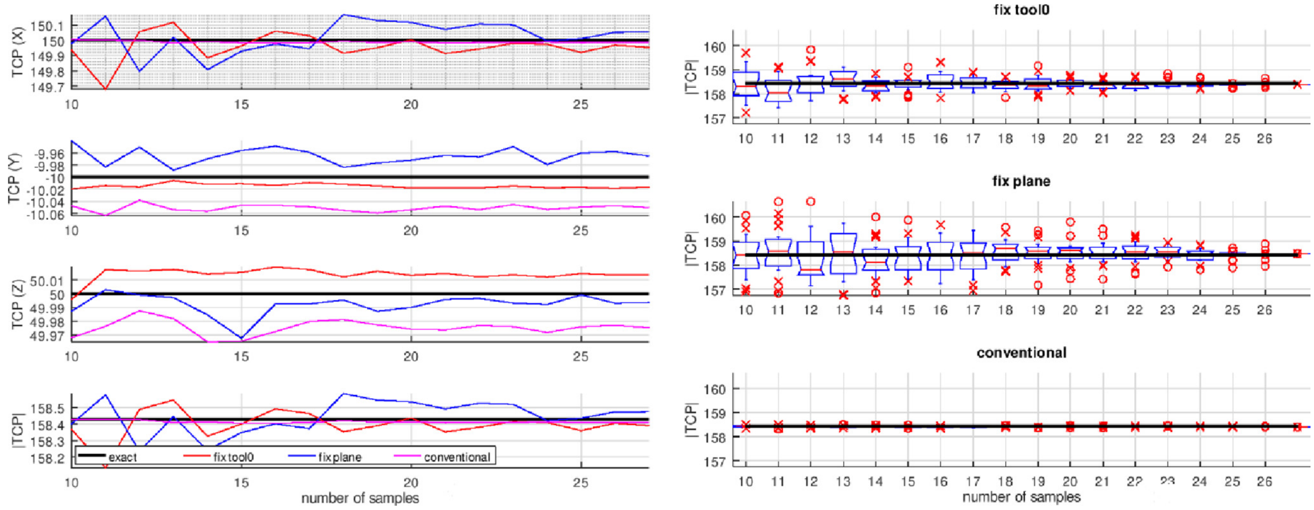
Figure 7 Computed TCP parameters and statistical analysis of the calculated TCP length for 50 different noise generation with a uniform noise in the interval (0.0.2)



(a) **(b)**

Table I Comparison of the calibration results using 27 synthetic samples

Calibration data	TCP [*x*,*y*,*z*]	|TCP|	δ
Reference	[150 −10 50]	158.43	0
Uniform noise [0,0.5]			
fix tool_0	[149.19 −9.9873 49.956]	157.65	0.81129
fix plane	[150.42 −9.9713 49.922]	158.80	0.42814
P4	[150.27 −10.322 50.056]	158.72	0.42393
P27	[150.09 −9.9217 49.842]	158.47	0.19798
Uniform noise [0,0.2]			
fix tool_0	[149.97 −10.019 50.014]	158.41	0.03817
fix plane	[150.05 −9.9583 49.993]	158.47	0.06548
P4	[149.89 −10.234 50.002]	158.34	0.25857
P27	[149.98 −10.051 49.975]	158.41	0.06021

Table II Recorded positions and rotations used in conventional TCP calculations

	X/q1	Y/q2	Z/q3	q4
P'_1	759.591	0.0521296	1017.88	
P'_2	759.594	−80.9964	999.41	
P'_3	759.594	58.3247	1004.2	
P'_4	703.31	21.0845	977.291	
Q_1	0.707091	−1.52943E-05	0.707123	3.38065E-05
Q_2	0.682154	0.18619	0.682177	0.1861
Q_3	0.694275	−0.133908	0.694335	−0.133977
Q_4	0.836741	0.0278446	0.542571	−0.0685992

calibration, for the TCP control will not affect the manufacturing cycle time. Measuring 3 points is sufficient for the normal vector of the plane. In our experiments, sampling of three points was performed in 20 s and sampling of 17 points was measured in 117 s, and the required time per sample was about 3 s. It is obvious that by increasing the velocity parameter of the "SearchL …" command or modifying the initial position, the elapsed time can be shortened. However, unless the position of the plane is changed, there is no need to recalculate the normal vector in each calibration cycle.

Figure 8 Machining bits used in practices

A different design is used in Figure 11 to show that the placement of the target plane board and its normal vector direction does not matter. To keep the TCP position at the same point, it was previously mentioned that the jig was used. There may still be minor deviations for different inserts. In

Table III TCP Manual calibration values and error analysis

TCP	[157.8107, −6.5428, 64.7019]
$\lVert \mathbf{TCP} \rVert$	170.685024
$\bar{P}^c$	[824.2837, −6.4978, 860.1106]
$\lVert \left(P_i^c - \bar{P}^c\right) \rVert_{RMS}$	0.026903
$\bar{r} = \overline{\lVert \left(P_i^r - \bar{P}^c\right) \rVert}$	170.685029
$(\bar{r} - r_i)_{RMS}$	0.016471

Figure 9 Conventional TCP calibration for acicular tip

Figure 11 Validation of the proposed method for different-shaped inserts

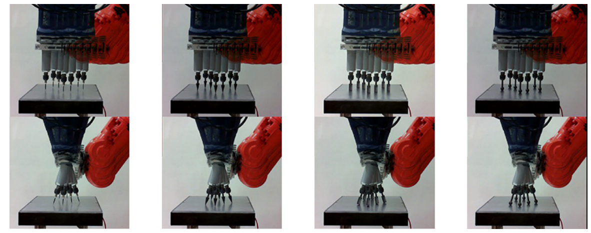
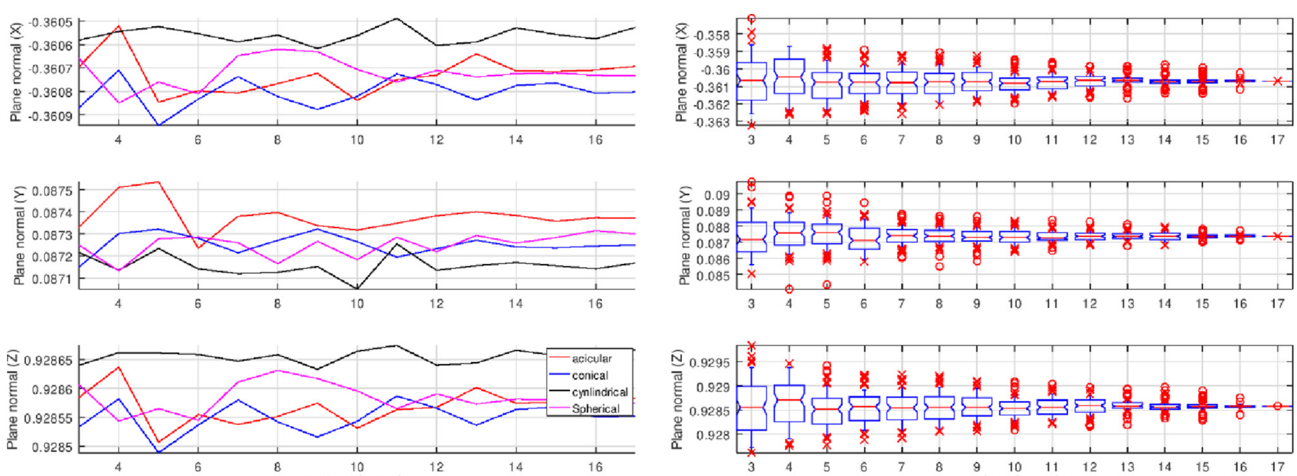


Figure 11, images in the top row are overlapped screenshots taken during the first stage. In this cycle the orientation is kept constant and, IRB's *tool_0* positions are used to obtained the normal vector of the plane. At the second stage of the proposed method, IRB is reoriented, the *tool_0*'s (x, y) coordinates are kept constant and the contact point is searched with the relevant command through the motion in the z direction. The lower row shows this stage for 27 different rotations.

The sampling for the 27 different rotations in the second stage lasted 240 s. Figure 12 shows the calculated results for different tips and different sample numbers. Figure 12(b) shows that the calculation deviation for the number of samples greater than about 20 is less than 0.5 mm. Elapsed time for the 20 different posture is 3 min.

The numerical values obtained as a result of the calibration made by using 27 samples are presented in Table IV for a clearer evaluation. Because the ground truth values are not available, the first line of the table obtained from traditional method can be accepted as a reference for the comparison. Because the inserted bit is needle-shaped, the point that touches the calibration plane is always TCP for all samples. Without any additional correction as in equation (9), TCP is determined with accuracy greater than 0.5 mm. The elapsed time for the calibration process can be expressed as 3 min, except when the first stage is not always required and 20 samples are considered sufficient.

Figure 10 Computed normal vector parameters of the target plane and statistical analysis



(a) (b)

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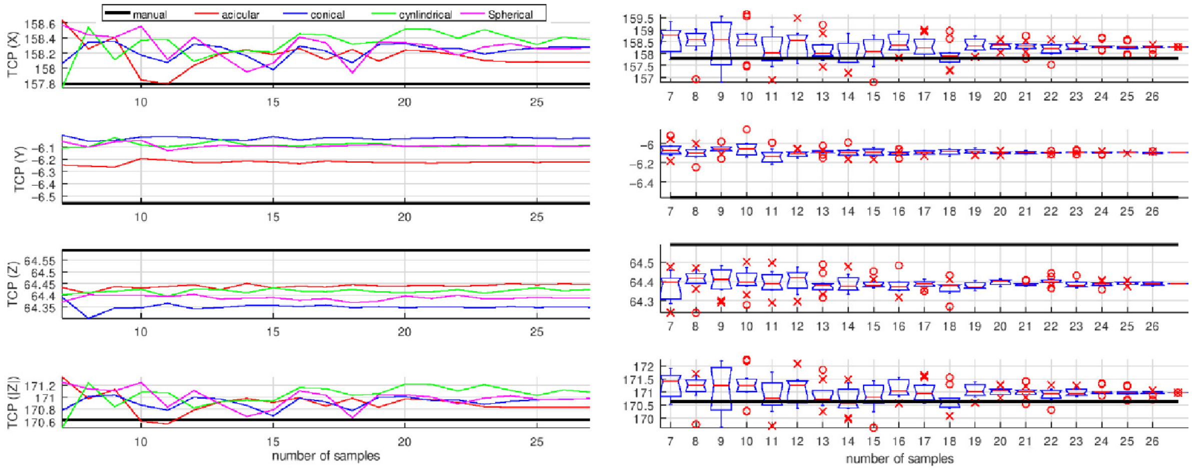
Figure 12 TCP values of different shaped inserts. Variation distribution by the sampling number



(a) **(b)**

Table IV TCP Parameters obtained by the proposed method using 27 genuine samples

	TCP [x,y,z]	|TCP|	| δ |
manual	[157.79 −6.5605 64.592]	170.63	0
acicular	[158.08 −6.2234 64.445]	170.83	0.46587
conical	[158.28 −6.0299 64.348]	170.97	0.76055
cylindrical	[158.37 −6.0849 64.424]	171.08	0.76834
spherical	[158.27 −6.0916 64.388]	170.98	0.7

5. Conclusion

In many studies, researchers have tried different equipment to use in the robot TCP measurements. CMM, cameras, optic barrier sensors are widely used for this process. Almost all of these devices are highly costly. Generally, trained operators are needed for their operation. They also have limitations to prevent their use in manufacturing conditions.

In this study, a new method that is automatically performed by IRB is introduced without the need for operator control for robot TCP calibration. The proposed method requires only one plane plate as external calibration equipment and an interface circuit that can detect the contact of the tip with this plane. Because all the contact points provide the plane equation, TCP calculation was performed similar to the conventional method. The applicability of the proposed method for different tip shapes has been confirmed by practical tests. The difference between the TCP values in the proposed automatic calibration process and the values calculated with the conventional method is below 0.5 mm.

The only cost of the developed method is the target plane to be placed in the robot working area. In the test setup, this plane and simple interface circuit, which does not require any extra features, has a cost below $10. This is an affordable price that can be met for each robot in the manufacturing site. The calibration process takes approximately 3 min. It can be reduced to a much shorter time by increasing the IRB speed and reducing the number of samples.

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Further reading

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