Calibration of an SMT Robot Assembly Cell

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Received May 9, 1993; revised July 14, 1993
Accepted August 5, 1993

A new calibration method for an assembly robot cell is described. The proposed method is a combination of a model-free, numerical, relative robot calibration procedure and a procedure for the robot periphery calibration. Two important simplifications based on the study of an assembly process are introduced into the calibration strategy. A robot is calibrated in a task (Cartesian) space. The robot workspace and the number of calibrated degrees of freedom (dof) in the task space are reduced in accordance with the *difficulty measure* of the task. An automatic measurement system for measuring the relative robot accuracy was developed. An original principle of transforming the robot endpoint approach distance into the one-dimensional position displacement error is introduced. The accuracy errors of each particular calibrated dof in the task space is measured separately. The error tables are used in a direct robot calibration procedure that is based on the linear interpolation of the discrete position-error functions. An iterative inverse calibration algorithm used in a particular robot cell is described. An efficient sensor-based system for an additional simultaneous robot periphery calibration is presented. The implementation of the proposed calibration methodology in the pick-and-place robot cell for Surface Mount Technology (SMT) is presented. *© 1994 John Wiley & Sons, Inc.*

ここでは、組み立てロボット・セルの新しい校正方法について説明する。今回提案する方法では、モデルフリー、数値、比例校正の手順と、ロボット末端を校正する手順を組み合わる。また、組み立て工程の研究に基づいた２つの重要な簡略化法を、校正方法に取り入れている。ロボットは、タスク（Cartesian）空間内で校正される。タスクの難易度測定を行い、その結果を使って、ロボットの作業空間、およびタスク空間における d.o.f. の次元数を必要に応じて減らす。この校正方法の手順を用いて、比例ロボットの精度を測定するための自動測定システムを開発した。

Journal of Robotic Systems 11(4), 301–310 (1994)

CCC 0741-2223/94/040301-010

このシステムは、ロボットのエンドポイントの接近距離を1次元の変位誤差に変換する、独自の方法を採用している。タスク空間内で校正された各 d.o.f. の精度誤差は、個別に測定される。不連続な位置誤差関数の1次補間を用いる直接校正の手順では、誤差テーブルを使う。この発表では、特定のロボット・セルに使われる反復転換校正アルゴリズムについて説明する。また、付加的な、ロボット末端の同時校正に有効な、センサ・ベースのシステムについても説明する。最後に、Surface Mount Technology (SMT) 用の pick-and-place ロボット・セルへ、今回提案した校正方法を応用した例についても説明する。

1. INTRODUCTION

The capability of precisely placing the end-effector at the predefined position and orientation, i.e., robot *pose,* inside the workspace is an important characteristic required by modern industrial robots.

The robot pose error is a combination of the repeatability and the accuracy errors. Robot repeatability can be improved only by using component parts of higher quality. On the other hand, robot accuracy can be significantly increased with appropriate software. This procedure is usually called robot calibration and is divided into an *analytic* and a *numerical* approach.

Analytic calibration methods[1–4] are based on the principle of mathematical modeling of the error sources. The *kinematic* accuracy errors are provoked by using wrong values of kinematic parameters (distances, angles) in the robot kinematic model. The effects of friction, gravitational forces, backlash, or elastic properties of the robot segments, actuators, and joints are among the most significant sources of *nonkinematic* accuracy errors.

The implementation of some analytic calibration method into real robotic cell is extremely complicated, time-consuming, and costly. The main reasons are as follows. The particular error source must be identified, modeled, quantified for the particular robot, and then applied in the kinematic model.[5] Because the modified models become considerably extended, longer computational times are needed and the robot speed is reduced. Complicated measuring equipment and procedures for the estimation of correct kinematic parameters are usually required.[1,3,6,7] In addition, most control systems used by modern, commercially available assembly robots do not support programming on the level of changing the robot kinematics.

Numerical robot calibration techniques do not use any modeling of the errors.[8] The particular actual robot pose is measured. Numerical values of the world (Cartesian) coordinates of the actual robot pose are compared to the calculated nominal pose. A numerical transformation between them is calculated.[9] As all kinds of the errors are taken into consideration in this transformation, the accuracy improvement of the robot is large and depends only on the accuracy and repeatability of the applied measurement system. Numerical calibration is correct only for the particular measured pose.[9] Different interpolating methods are used for the calibration of the robot at poses that are not previously measured.[8]

To apply a numerical calibration method to a particular robot task all poses that are expected in the robot program must be considered. Hence, the methods are appropriate only in simple robot tasks with all the poses known in advance. For the complex operations in which the entire robot workspace is used and the robot poses are changing during the task, a six-dimensional discrete error function of the complete workspace must be obtained. A system for the actual robot poses measurement becomes complicated as in the case of the analytic calibration methods. Enormous memory capacities are required to store the error-data of the whole robot workspace. The application of such a method is rather questionable.

Even if the robot is well calibrated, the particular assembly operation may not be accomplished successfully. When the robot touches its environment, a closed kinematic chain structure is formed. The first branch of the chain, the robot, is accurate but the second branch, the robot periphery, may deviate significantly from the theoretically defined pose. When calibrating the complete assembly robot cell, the calibration of the robot peripheral devices must be taken into account. Usually, an additional computer vision system is used to calibrate the robot periphery, which may decrease the cost effectiveness.

The aim of our research was to develop an efficient, simple, fast, and low-cost calibration method for a robot assembly cell used for placing SMT electronic components onto hybrid circuits. Numerical, relative-based robot calibration method was chosen. Two calibration procedures were developed. The first was used for the calibration of the robot manipulator and the second was intended for the calibration of the robot peripheral devices. A *difficulty measure* **D** of the SMT assembly process was introduced. Based on the measure **D**, two important simplifications concerning the complexity of the robot calibration process were implemented. The volume of the calibrated robot workspace and the number of the calibrated axes in the task space coordinate system were reduced.

The proposed simplified calibration method was realized and tested in a real robot assembly cell.

2. BACKGROUND

An assembly process is a combination of *manipulation tasks* and *basic assembly operations* like grasping, screwing, pushing, placing, sticking, etc.

A robot manipulation task is performed in so-called *gross* motion mode. The manipulated object has all six degrees of freedom relatively unlimited with respect to the absolute coordinate system and other workpieces. To perform the manipulation task only an approximate trajectory is specified with two or more significant points. The accuracy of trajectory tracking during the manipulation task is relatively low.

When the workpiece, held by the robot, comes close enough to the required, preprogrammed pose, collision with other workpieces or the robot periphery is possible. The particular basic assembly operation with a higher accuracy of movement is then accomplished, and the robot is said to be operating in *fine* motion mode.

By the transition from the manipulation task to the basic assembly operation some dof of the manipulated workpiece are "lost." It is convenient to describe the fine motion in a local, i.e., task (Cartesian) coordinate system, which is attached to the workpiece. The origin and the orientation of the task coordinate system (in the absolute coordinate system) is defined with the workpiece geometry and assembly scene. In general, it is an arbitrary pose.

We introduced a special difficulty measure **D** of an assembly operation. It typifies the particular basic assembly operation for calibration purposes. **D** is defined with a level of difficulty L_D and a set of directions $\{\hat{D}_D\}$ of lost dof during the particular basic assembly operation:

$$\mathbf{D} = (L_D, \{\hat{D}_D\}) \tag{1}$$

The level L_D equals the number of dof in fine motion while the directions $\{\hat{D}_D\}$ are defined with the fine motion axes in the task coordinate system of the particular basic assembly operation. The two basic assembly operations shown in Figure 1 have the following difficulties: the placement of the SMT component onto the layer is described by $\mathbf{D}_1 = (2, \{x_1, y_1\})$ and the "peg-in-hole" insertion operation by $\mathbf{D}_2 = (4, \{x_2, y_2, \alpha_2, \beta_2\})$. This means that the fine motion movements had to be more precise along the axes x_1 and y_1 of region 1 as well as along and around the axes x_2 and y_2 of region 2 if the assembly task in Figure 1 is to be accomplished successfully. In Figure 1 the axes in which the movements need not be more precise are depicted with dashed lines and the fine motion regions with the shadowed boxes.

The reason for introducing the difficulty measure **D** was simplification of the calibration procedure for the robot assembly cell.

The following simplification rules were used in the proposed calibration methodology:

1. Robot calibration need to be performed only inside the regions of the workspace where the basic assembly operations take place, i.e., *active workspace*.
2. The calibration procedure is accomplished in the task space of the particular basic assembly operation.
3. The axes in the task space that are calibrated are defined according to the difficulty measure **D** of the particular basic assembly operation.
4. A relative-based numerical calibration approach is chosen as more appropriate than an analytic one when applying the rules 1, 2, and 3.

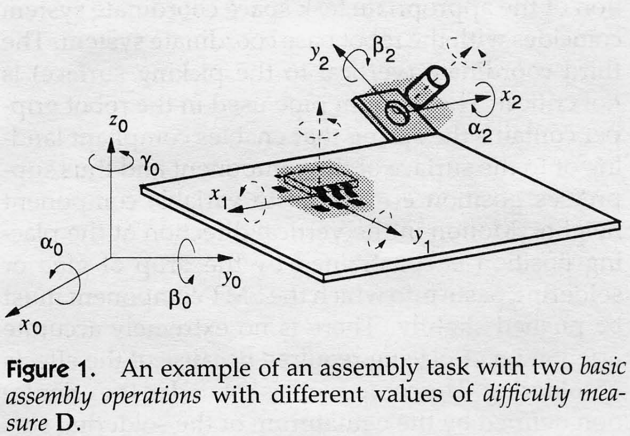

Figure 1. An example of an assembly task with two *basic assembly operations* with different values of *difficulty measure* **D**.

5. The proposed assembly cell calibration methodology requires the robot calibration procedure as well the procedure for the robot periphery calibration.

3. IMPLEMENTATION OF A SIMPLIFIED CALIBRATION PROCEDURE—A CASE STUDY

3.1. The Robot Cell Description

The proposed simplified calibration methodology was developed for the robot assembly cell for surface mounting of miniature SMT electronic components onto hybrid circuit ceramic layers.[10] A SEIKO D-TRAN XY-2000 Cartesian robot with 4 dof was used as a pick-and-place machine together with automatic flexible mechanical periphery for transporting and fixing of ceramic layers. SMT components are supplied by the feeding system. Three layers of standard dimensions, 50.8 × 50.8 mm, are processed at the same time. The smallest component is approximately 1.0 × 1.0 × 2.0 mm, the dimensions of the biggest manipulated component are approximately 6.0 × 8.0 × 1.5 mm. The placement-process cycle time depends on the amount of the SMT components per layer. The average capacity of the cell is 2500 components per hour.

There are two regions inside the robot active workspace that need to be calibrated. The first is the region where the SMT components are supplied to the robot with the feeding system and the second is the region of component placement onto the layers.

In both regions the same difficulty measure $\mathbf{D} = (2, \{x_0, y_0\})$ was found. The basic assembly operation of picking or placing requires two accurate coordinates to specify the picking (placing) position. Required accuracy is approx. ±0.1 mm. The orientation of the appropriate task space coordinate system coincides with the robot base coordinate system. The third coordinate (vertical to the picking surface) is not critical. The vacuum pipe used in the robot gripper contains the spring that enables compliant landing onto the surface of the component and thus suppresses position errors due to variable component heights. Motion in the vertical direction at the placing position is constrained by the drop of glue or soldering paste into which the SMT component must be pushed slightly. There is no extremely accurate orientation of placing required because of the effects of soldering. The component is rotated in the orientation defined by the equilibrium of the soldering surface tension forces.

3.2. A Robot Calibration Procedure

3.2.1. Methodology

According to the number of the calibration regions inside the active workspace and the resulting difficulty measures a relative-based numerical calibration of the robot was taken. The precise robot movements needed to accomplish the basic assembly operations are programmed in the task coordinate system. The task coordinate system is defined by guiding the robot end-point into particular significant poses. This means that the origin and the orientation of the task coordinate system in the absolute coordinate system has the same accuracy as the robot. In this case the robot accuracy improvement in the absolute coordinate system is not important.

The shape and dimensions of the calibration region of the active workspace depend on the particular assembly task. In the general case, a block or a cube around the place where the basic assembly operation is performed would be appropriate. In the case of two-dimensional tasks, part of the workspace degenerates into an appropriate surface section of the robot workspace.

The procedure of robot calibration inside the particular active workspace region contains the following steps:

- **Discretization** of the calibration region.

The region of the active workspace is discretized along those axes of the task space that are needed in the calibration procedure ($\mathbf{D}_{\text{region}}$). The active workspace is essentially cut into incremental boxes. In the general case ($\mathbf{D} = (6, \{x, y, z, \alpha, \beta, \gamma\})$, an additional sphere belongs to each box representing the definition domain for the discretization of the orientation parameters. A discretization interval is chosen in accordance with the tolerance requirements of the assembly task, the specified nominal robot accuracy, and the characteristics of expected predominant error sources in the particular workspace region. As the accuracy error follows a completely unknown function (which we do not need to know, because the numerical calibration is used) no general rule for the interval definition exists. The estimation of the interval size starts with the interval as large as possible and then is decreased until satisfactory results are obtained.

- **Measurement** of robot pose errors.

The robot is programmed to move into the reference pose, which is defined inside the discretized workspace region. Only those kinematic parameters concerning the chosen task space axes are measured, which may represent an important simplification of requirements for the measuring equipment. An error vector pointing from the reference to the actual robot pose then is calculated and stored in the error table. The dimension of the error vector and the complexity of measuring equipment strongly depend on the D_{region} as well on the shape and volume of the particular region.

- **Estimation** of actual robot pose.

The pose error tables contain information on how the robot actually moves when directed into a particular discrete pose. This numerical correction of an inaccurate direct robot kinematic model is exact only at the discrete poses that were measured. All kinds of errors are incorporated in the correction transformation and the accuracy depends only on the measurement equipment.

For an arbitrary pose between the discretized ones, linearization of the error function is applied. The inaccurate direct kinematic model is used to calculate the inaccurate pose ($\mathbf{NOMINAL}_{inaccurate}$) to which the linearized value of the pose error, obtained from the error tables, is added (see Eq. 2).

$$\mathbf{ACTUAL} = \mathbf{NOMINAL}_{inaccurate} + \Delta_{error\ table} \quad (2)$$

The linearization of the error between the particular (measured) points inside the error tables in general can not yield the correct results. It strongly depends on the nature of the error sources provoking the robot inaccuracy. The proposed operation is permitted in cases where the pose errors do not change sign between the measured points. (This may occur with repeatability errors that are not under the scope of the calibration procedures.)

3.2.2. Realization

According to the difficulty measures found in the SMT robot assembly cell, special measuring equipment for the automatic measuring of the relative robot accuracy was developed. It consists of a steel precise measuring plate with precise grooves, a pair of linear displacement transducers (LDT), an additional microprocessor data acquisition board, and a host computer that is a part of the robot cell (Fig. 2).

On the surface of the measuring plate there is a rectangular grid of 11 × 11 precise grooves that are 1.8 mm wide, 1.0 mm deep, and 5 mm apart. The plate was fabricated on an NC grinding machine and

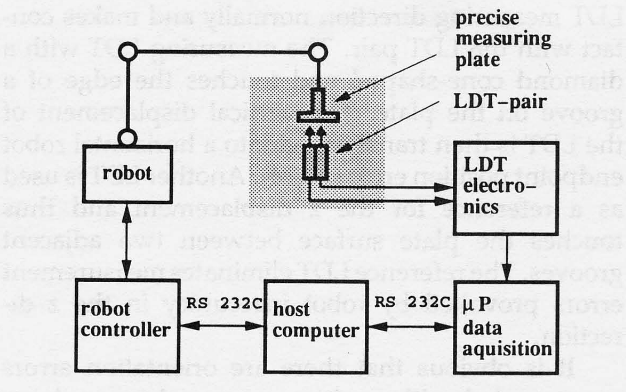

Figure 2. The configuration of the automatic measurement system for measuring the relative robot accuracy.

was justified with a dedicated coordinate measuring system (Mitotoyo, type 231-B), which has an accuracy of ±0.002 mm. During the robot calibration process the plate, which has approximately the same weight as the gripper, is attached to the robot in place of the gripper (Fig. 3). A pair of contact-type linear displacement transducers with a resolution of 0.001 mm are fixed into the calibrated active workspace region. This makes it possible to measure the displacement along the *z* axis of the task coordinate system of the particular active workspace region. The robot with the measuring plate approaches the

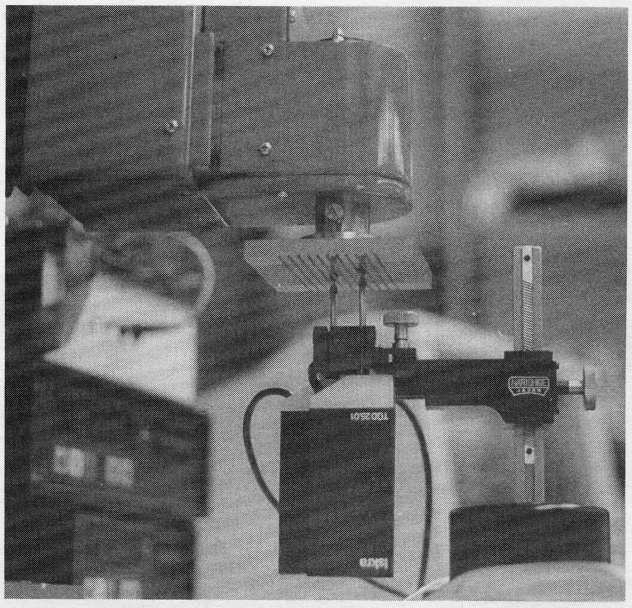

Figure 3. In place of the gripper the measuring plate is attached to the robot; a pair of Linear Displacement Transducers (LDT) are fixed in the calibration region of the robot workspace.

LDT measuring direction normally and makes contact with the LDT pair. The measuring LDT with a diamond cone-shaped end touches the edge of a groove on the plate. The vertical displacement of the LDT is then transformed into a horizontal robot endpoint position error (Fig. 4). Another LDT is used as a reference for the z displacement and thus touches the plate surface between two adjacent grooves. The reference LDT eliminates measurement errors provoked by robot inaccuracy in the z direction.

It is obvious that there are orientation errors compounded with position errors when applying the proposed position measurement procedure. Orientation error measurements are relatively difficult and the aims of simple and efficient calibration can be lost when using the proposed set up in the general case. It is supposed by the author that the inverted configuration with the fixed measuring plate and the robot-mounted LDT pair would be a more adequate solution in the general case of robot calibration inside regions with higher values of **D** and higher tolerance requirements.

The geometry of the measuring plate (88.0 mm × 88.0 mm × 9.5 mm) allows measurement of the robot relative accuracy in two positional coordinates inside the rectangular region of 50 mm × 50 mm. The measured area was divided into 121 discrete reference points for each coordinate axis. Separate measurements for each axis were made. Two sets of ten measurements per area and axis were used to eliminate the repeatability errors of the measuring system and the robot. The mean values of the position errors were stored in the error functions $\Delta x(x_{Nx}, y_{Nx})$ and $\Delta y(x_{Ny}, y_{Ny})$ where (x_{Nx}, y_{Nx}) represents the x measuring grid and (x_{Ny}, y_{Ny}) the y measuring grid.

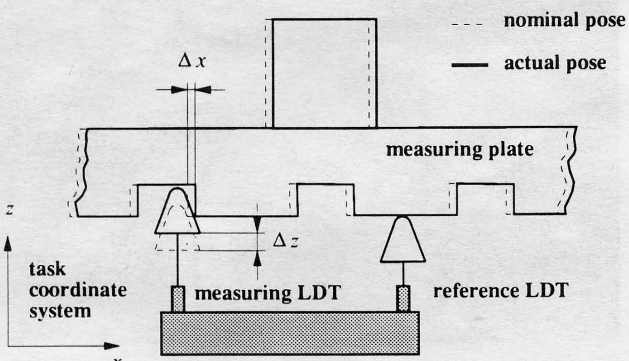

Figure 4. The basic principle of the position error measurement. Vertical displacement Δz is transformed into horizontal displacement Δx.

The resulting error function distributions for both axes inside the first placing region are shown in Figure 5.

The value of the position error between the measured points is obtained with a linear approximation of the error function values of neighboring discrete poses.

3.2.3. Inverse Calibration

In practical robotics the process opposite to the calibration procedure is more important. For an arbitrarily required robot pose inside the calibrated region the theoretical pose must be specified so that the actual pose coincides with the required one. This is the problem of inverse kinematics (inverse calibration), which has no general solution.

The inverse calibration solution of the proposed SMT assembly robot cell is used in the case of an off-line programming mode. The goal of inverse calibration is to specify the appropriate nominal coordinates $\{x_N, y_N\}$ that will guide the robot into the required actual coordinates $\{x_A, y_A\} = \{x_{REQ}, y_{REQ}\}$.

An iterative algorithm for searching the required actual coordinates $\{x_A, y_A\}$ from the error function was constructed. Two discrete functions $x_N(x_N + \Delta x, y_N)$ and $y_N(x_N, y_N + \Delta y)$ are formed at first. The first function represents the nominal values of x at the points of the "grid," which are defined by the actual values of x and the nominal values of y. The second function is analogous for the y direction. (The actual values $x_N + \Delta x$ and $y_N + \Delta y$ are measured values.)

The required x_A is applied in the function $x_N(x_N + \Delta x, y_N)$ and the minimum and maximum nominal values of the corresponding x_N are calculated. In the first step, all possible nominal y_N are used (Fig. 6a). The required y_A is used within the function $y_N(x_N, y_N + \Delta y)$ in the second step, but only the interval $[x_{N\min}, x_{N\max}]$ is considered (Fig. 6b). Just as in first step, the minimum and maximum values of nominal y_N are obtained. Then, the searching process continues in the function $x_N(x_N + \Delta x, y_N)$ within the interval of $[y_{N\min}, y_{N\max}]$ calculated in the previous step (Fig. 6c).

After the first two steps of the searching algorithm (and after each subsequent step) the mean values $\overline{x_N}$ and $\overline{y_N}$, on the intervals $[x_{N\min}, x_{N\max}]$ and $[y_{N\min}, y_{N\max}]$, respectively, are calculated. The calculated nominal position $(\overline{x_N}, \overline{y_N})$ is corrected in the error tables $\Delta x(x_{Nx}, y_{Nx})$ and $\Delta y(x_{Ny}, y_{Ny})$ obtained in the measuring process. The corrected "actual" value is compared with the required actual value. If the difference is less than the required tolerance of

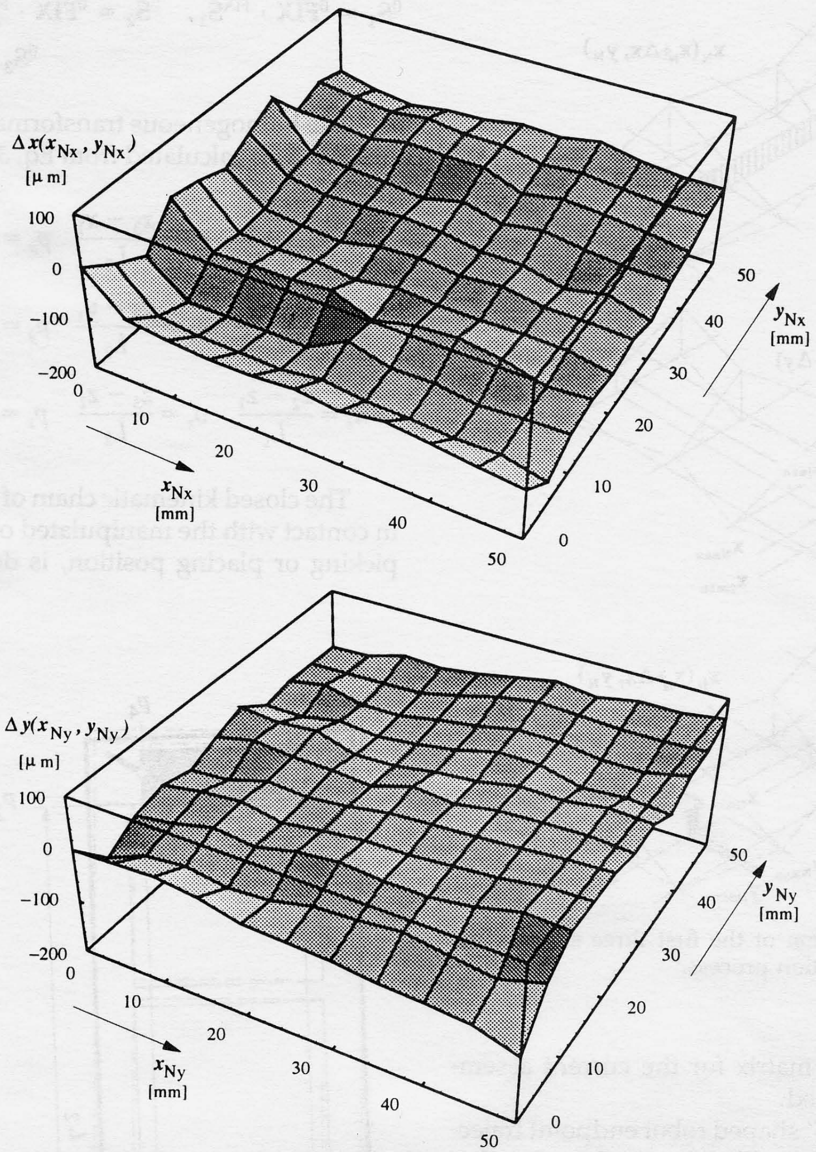

Figure 5. The results of the measurement are presented as the position-error distribution functions $\Delta x(x_{Nx}, y_{Nx})$ and $\Delta y(x_{Ny}, y_{Ny})$ inside the calibration region.

the basic assembly operation, the iteration algorithm stops. The last pair ($\overline{x_N}$, $\overline{y_N}$) is assumed to be the appropriate "fault" nominal position, which yields the required actual one.

3.3. Calibration of the Robot Periphery

For the robot assembly cell in the case study the transport/fixture system provoked the main accuracy errors of the robot periphery. An efficient calibration system for fast redefinition of the position of the transport/fixture system was designed. It consists of specially fabricated calibration markers attached to the main mobile board used for fixing the ceramic layers and the sensory system incorporated into the gripper. With an opto-reflective sensor mounted in the center of the vacuum gripper pipe[10] the relative positions of the two calibration markers are measured. The robot itself is a measuring device, so the measurement of the marker position has the accuracy of the robot. Comparing the new positions with the positions used in the previous assembling

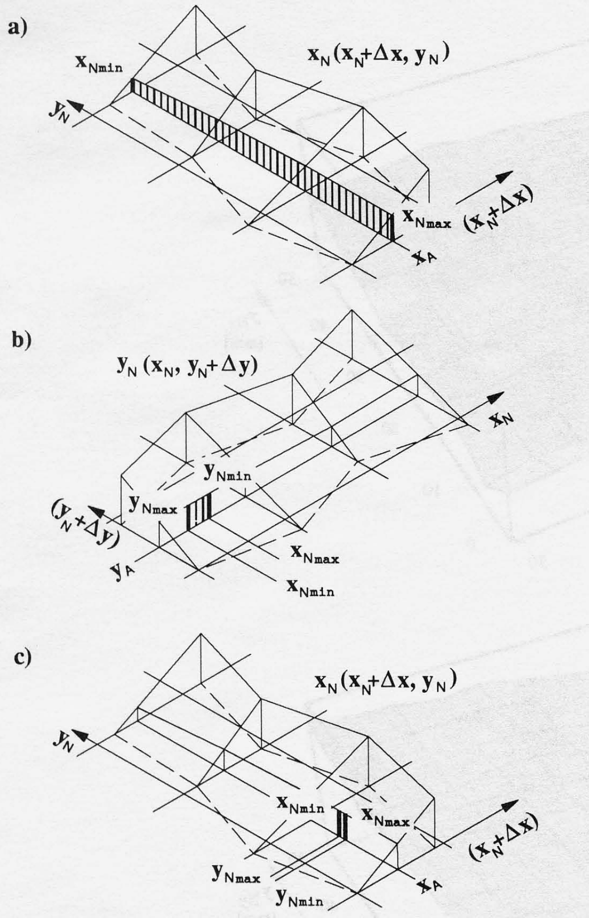

Figure 6. The illustration of the first three steps of the iterative inverse calibration process.

cycle, the correction matrix for the current assembling cycle is calculated.

There are two "V" shaped robot endpoint trajectories specified over the calibration markers (see Fig. 7). Passing over the calibration markers with the opto-reflective sensor, the points $\mathbf{T}_1$ to $\mathbf{T}_8$ are detected. Their Cartesian coordinates, expressed in the robot base coordinate system, are used to calculate the lines p_1 to p_4. Crossing points ${}^0\mathbf{S}_1(x_1, y_1, z_1, 1)^T$, ${}^0\mathbf{S}_2(x_2, y_2, z_2, 1)^T$, and ${}^0\mathbf{S}_3(x_3, y_3, z_3, 1)^T$ are then derived. These points are defined in the robot base coordinate system but are used to define the fixture coordinate system **FIX** in which they are described with the following vectors: ${}^{FIX}\mathbf{S}_1(0, 0, 0, 1)^T$, ${}^{FIX}\mathbf{S}_2(L_1, 0, 0, 1)^T$, and ${}^{FIX}\mathbf{S}_3(0, L_2, 0, 1)^T$. The values of L_1 and L_2 are precisely measured by the fabrication of a mobile fixture board. The relation between the crossing points expressed in the robot base coordinate system (${}^0\mathbf{S}_i$) and the crossing points expressed in fixture coordinate system (${}^{Fix}\mathbf{S}_i$) are as follows:

$$ {}^0\mathbf{S}_1 = {}^0\mathbf{FIX} \cdot {}^{FIX}\mathbf{S}_1, \quad {}^0\mathbf{S}_2 = {}^0\mathbf{FIX} \cdot {}^{FIX}\mathbf{S}_2, \quad {}^0\mathbf{S}_3 = {}^0\mathbf{FIX} \cdot {}^{FIX}\mathbf{S}_3 \qquad (3) $$

The homogeneous transformation matrix ${}^0\mathbf{FIX} = [\vec{\underline{n}}, \vec{\underline{o}}, \vec{\underline{a}}, \vec{\underline{p}}]$ is calculated from Eq. 3 as shown in Eq. 4:

$$ n_x = \frac{x_2 - x_1}{L_1} \quad o_x = \frac{x_3 - x_1}{L_2} \quad p_x = x_1 $$

$$ n_y = \frac{y_2 - y_1}{L_1} \quad o_y = \frac{y_3 - y_1}{L_2} \quad p_y = y_1 $$

$$ n_z = \frac{z_2 - z_1}{L_1} \quad o_z = \frac{z_3 - z_1}{L_2} \quad p_z = z_1 \quad \vec{\underline{a}} = \vec{\underline{n}} \times \vec{\underline{o}} \qquad (4) $$

The closed kinematic chain of the robot, which is in contact with the manipulated object at the desired picking or placing position, is described by matrix

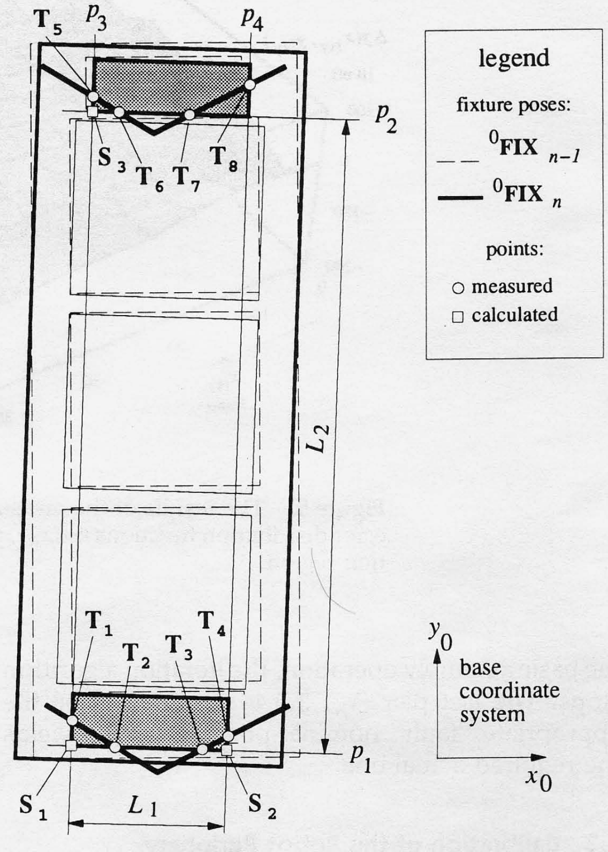

Figure 7. A schematic description of the main mobile board of the transport/fixture system with "V" shaped robot end-point trajectories over the calibration markers (shadowed rectangles). The three squares in the middle represent the ceramic layers attached to the board.

Eq. 5:

$$^{0}\mathbf{ROBOT} = {}^{0}\mathbf{PERIPHERY}$$

$$^{0}\mathbf{T} \cdot {}^{T}\mathbf{TOOL} = {}^{0}\mathbf{FIX} \cdot {}^{FIX}\mathbf{POS} \quad (5)$$

The left side of Eq. 5 represents the kinematics of the robot ($^{0}\mathbf{T}$) with the gripper ($^{T}\mathbf{TOOL}$). The right side is the kinematics of the fixture ($^{0}\mathbf{FIX}$) holding the layer with the specified placing point ($^{FIX}\mathbf{POS}$).

The matrix $^{0}\mathbf{FIX}$ is used in the robot periphery calibration procedure. Two different ways of using the matrix $^{0}\mathbf{FIX}$ are proposed, depending on the robot teaching mode used in the robot cell. In both cases the automatic measurement of fixture pose is accomplished before the particular assembling cycle.

3.3.1. Off-line Robot Programming Mode

The required picking or placing position is specified with the homogeneous transformation $^{FIX}\mathbf{POS}_0$, which is expressed in the fixture frame $^{0}\mathbf{FIX}$. The subscript 0 used with the transformation **POS** indicates the "0th" assembling cycle, which is in fact the off-line teaching phase. The calibration of the periphery for the *n*th assembling cycle is performed with the matrix multiplication (Eq. 6), where $^{0}\mathbf{FIX}_n$ represents the calibration matrix calculated from the values obtained in the measurement at the beginning of the *n*th cycle.

$$^{0}\mathbf{ROBOT}_n = {}^{0}\mathbf{FIX}_n \cdot {}^{FIX}\mathbf{POS}_0 \quad (6)$$

The transformation $^{0}\mathbf{ROBOT}_n$ depicts the particular corrected preprogrammed robot end-effector pose used in the *n*th assembling cycle.

3.3.2. On-line Robot Programming Mode

The working points of the assembly process are defined by the "teaching by guiding" method. Again, the teaching assumes the "0th" assembling cycle ($^{0}\mathbf{ROBOT}_0 = {}^{0}\mathbf{FIX}_0 \cdot {}^{FIX}\mathbf{POS}_0$). The fixture matrix $^{0}\mathbf{FIX}_0$ is calculated before the 0th assembling cycle according to the proposed procedure. The robot endpoint position $^{FIX}\mathbf{POS}_0$ expressed in the $^{0}\mathbf{FIX}_0$ frame is unknown when the on-line programming is used. It is calculated by matrix Eq. 7.

$$^{FIX}\mathbf{POS}_0 = {}^{0}\mathbf{FIX}_0^{-1} \cdot {}^{0}\mathbf{ROBOT}_0 \quad (7)$$

Before the first assembling cycle the transformation $^{0}\mathbf{FIX}_1$ is derived. The on-line specified pose $^{0}\mathbf{ROBOT}_0$ is corrected into $^{0}\mathbf{ROBOT}_1$ according to the following equation.

$$^{0}\mathbf{ROBOT}_1 = {}^{0}\mathbf{FIX}_1 \cdot {}^{0}\mathbf{FIX}_0^{-1} \cdot {}^{0}\mathbf{ROBOT}_0 \quad (8)$$

The same procedure is used before the start of each assembling cycle (see Eq. 9).

$$^{0}\mathbf{ROBOT}_n = {}^{0}\mathbf{FIX}_n \cdot {}^{0}\mathbf{FIX}_{n-1}^{-1} \cdot {}^{0}\mathbf{ROBOT}_{n-1} \quad (9)$$

The transformation $^{0}\mathbf{ROBOT}_{n-1}$ denotes the correct robot pose from the previous cycle and the transformation $^{0}\mathbf{ROBOT}_n$ describes the corrected currently used robot pose.

4. RESULTS AND DISCUSSION

In the case study of an SMT robot assembly cell a robot with relatively good accuracy was used (0.02 mm specified by the producer). The original accuracy was decreased (to approximately 0.25 mm) when the custom designed gripper device was mounted. Fortunately, the original robot repeatability was not changed. The proposed direct robot calibration procedure was then applied and the error tables were prepared.

The tolerance requirements used in the SMT assembly task were about ±0.1 mm. From the results of the measurement we found the following values.

$\Delta x_{Max} = +27\ \mu m$, $\Delta x_{Min} = -153\ \mu m$,

$\Delta x_{mean} = -79\ \mu m$

$\Delta y_{Max} = +62\ \mu m$, $\Delta y_{Min} = -71\ \mu m$, $\Delta y_{mean} = +7\ \mu m$

According to these values the origin of the task coordinate system was shifted to x_{mean} and y_{mean}. The absolute maximum error values were $|\Delta x| = 181\ \mu m$ and $|\Delta y| = 132\ \mu m$. This meant that the robot was accurate enough to fit the tolerance requirements of the task. The robot calibration procedure was performed just as an experiment and the calibration routines were not included as a standard part of the SMT robotic cell software.

The measuring plate was designed to best fit the application requirements. As the ceramic layers had the standard dimensions of 50.8 × 50.8 mm the measuring area was 50 × 50 mm. A measuring interval of 5 mm was chosen to correspond to the estimated placement grid of the electronic components. This was meant to provide a greater likelihood that the components would be placed on the measuring intervals. In such a case, the inverse calibration would be more accurate as the required positions will be closer to the measured points. Of course, the minimum interval is limited by the physical dimensions of the LDT pair configuration.

A linear approximation was used in the direct robot calibration, as well as in the iterative inverse calibration procedures that were developed for the case study, having a level of difficulty $L_D = 2$. With a higher L_D, convergence problems in the inverse calibration are expected and thus different inverse calibration methods would be used.

The author believes that for the SMT placement robot assembly task that was described, a significantly less accurate (and less expensive) robot would be successful. In that case, the proposed robot accuracy procedure would be of greater importance.

On the other hand, the robot periphery was found to be highly inaccurate and unrepeatable. The pose errors of mobile main fixture board were estimated to approx. 0.5 mm. The results of the robot placement process were not acceptable in about 25% of the production and the robot cell effectiveness was low. The robot periphery calibration was found to be the most important. The limits of the robot periphery calibration were defined with the robot repeatability, which was extremely good in the case study (about ±0.005 mm). The real accuracy of the measuring system proposed depends on the sensory system used. The Omron type opto-reflective sensor incorporated in the gripper made an accuracy of ±0.05 mm possible. When utilizing a robot with worse repeatability another, more appropriate sensory system should be used.

The robot periphery calibration procedure was introduced into the software package of the robot cell. It was performed before each particular assembling cycle and took about 5 seconds, which was 2.4% of an average assembling cycle time for 3 layers with 40 SMT components. It was estimated that there were practically no more irregularities in SMT component placement due to the pose displacement of the transport/fixture system after the calibration.

5. CONCLUSION

Task-dependent robot calibration was proposed. Difficulty measure **D** of a basic assembly operation defined the reduction of the volume of the calibration region and the number of calibrated dof in the task space. An original microprocessor-controlled measuring system was developed that enables automatic measurement of the relative robot accuracy in two perpendicular directions on the plane normal to the approach vector of the robot end-effector. The principle of transforming a vertical displacement into a horizontal one ensures high measuring accuracy over a relatively large area compared to the measuring range of the LDT itself. An efficient robot periphery calibration is incorporated in the assembly cell. It assures the simultaneous correction of the mobile transport/fixture system for the ceramic layers. The accuracy of this procedure is limited by the robot repeatability and the resolution of the marker-edge detector. Satisfactory results were achieved when applying the proposed calibration strategy in the SMT robotic assembly cell.

The author is indebted to Prof. Dr. Alojz Kralj, Prof. Dr. Tadej Bajd, and colleagues from the Laboratory for Robotics, Faculty of Electrical and Computer Engineering, University of Ljubljana for their support during the research work.

REFERENCES

1. D. E. Whitney, C. A. Lozinski, and J. M. Rourke, "Industrial robot forward calibration method and results," *Trans. of the ASME, Journal of Dynamic Systems, Measurement, and Control*, **108**, 1–8, 1986.
2. M. R. Driels and U. S. Pathre, "Generalized joint model for robot manipulator kinematic calibration and compensation," *Journal of Robotic Systems*, **4**(1), 77–114, 1987.
3. H. W. Stone and A. C. Sanderson, "A prototype arm signature identification system," *Proc. 1987 IEEE Int. Conf. on Robotics and Automation*, 1987, pp. 175–182.
4. R. N. Vaishnav and E. B. Magrab, "A general procedure to evaluate robot positioning errors," *The International Journal of Robotics Research*, **6**(1), 59–74, 1987.
5. Z. S. Roth, B. W. Mooring, and B. Ravani, "An overview of robot calibration," *IEEE Journal of Robotics and Automation*, **RA-3**(5), 377–385, 1987.
6. H. Weule and B. Reichling, "Optisches meßsystem zur genauigkeitsprüfung von industrierobotem," *Robotersysteme*, **3**, 189–198, 1987.
7. A. Nowrouzi, Y. B. Kavina, H. Kochekali, and R. A. Whitaker, "An overview of robot calibration techniques," *The Industrial Robot*, **15**(4), 229–232, 1988.
8. E. Red, X. Wang, and E. Turner, "Calibration control of robot vertical assembly," *Journal of Robotic Systems*, **6**(1), 19–33, 1989.
9. B. J. Schroer and A. Rezapour, "Calibration of robots used in high precision operation," *Robotics*, **4**, 131–143, 1988.
10. J. Zupančič et al., "Flexible robotic cell for hybrid circuits assembly," *14th Ann. Conf. of IEEE Industrial Electronics Society IECON 88*, Singapore, 1988, pp. 1022–1027.