A Kinematic Calibration Method for Industrial Robots Using Autonomous Visual Measurement

A. Watanabe[1] (3), S. Sakakibara[1], K. Ban[1], M. Yamada[1], G. Shen[1]
[1] FANUC LTD, Yamanashi, Japan
Submitted by T. Arai (1)

Abstract
Several new methods have been developed to achieve practical accuracy for offline programming of robots and its applicability to the real world. In this paper, a new kinematic calibration method is proposed to automatically improve absolute positioning accuracy of robots. Key points of the method include autonomous measurement and the automatic generation of measuring poses. A new visual feedback motion control method of the robot is proposed to achieve accurate measurement. An algorithm is also proposed to improve the condition of measuring poses automatically. The effectiveness of the proposed methods and algorithm was investigated through experiments with actual robots.

Keywords:
Robot Calibration, Visual Measurement, Positioning Accuracy

1 INTRODUCTION

Offline teaching is now being recognized as a necessity to shorten start-up time of industrial robot systems, and to thus, grow industrial robot applications. It is also well known that, improving absolute positioning accuracy of a robot, and improving detection accuracy of the location of workpieces in a matter of minutes are two very challenging hurdles to putting offline teaching into practical use. The authors have previously developed workpiece position detection methods using autonomous visual measurement in robotic cells [1]. Currently, the improvement of absolute positioning accuracy of an industrial robot with serial mechanisms by kinematic calibration is being studied intensively.

Various methods of kinematic calibration for an industrial robot have been reported [2][3]. However, very few calibration methods have been experimentally confirmed as practical for use on the shop floor. Industrial robot positioning errors observed on the shop floor include those due to varying environmental conditions, such as changes in temperature and load, that are difficult to predict prior to robot shipment. In addition, it is impossible to predict errors due to plastic deformation in robot links resulting from mechanical damage. To decrease these types of errors, a practical kinematic calibration method which cannot only achieve indicated positioning accuracy but also be used easily and fast without changing the set location of the robot, is required.

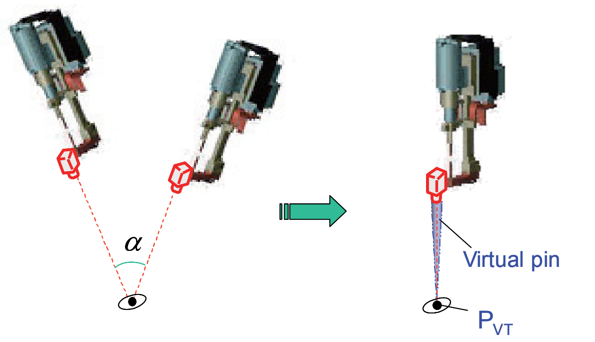
Conventional methods generally used at the shop floor increase the quantity of measurements to improve accuracy of calibration. Thus, a large amount of time is required to achieve high accuracy. To balance accuracy with time, measuring data, measuring accuracy and an error model must be comprehensively considered in determining a measuring device, a setting method for the measuring device and an identification algorithm for the model. It is also necessary to develop an algorithm for generating measuring poses and an automatic calibration process for realizing efficient measurement, to assure that the result can be stably obtained. In addition to the above, because industrial robots were previously only used in playback processes, improving their absolute positioning accuracy has been neglected for a long period of time. As a result of this awareness, most researchers in kinematic calibration focus their objectives on machine tools and positioning devices for which absolute positioning accuracy is given priority over other performance characteristics. In these circumstances, there is not a practical calibration method which can satisfy not only indicated positioning accuracy but also low cost, short operating time and narrow working spaces.

The authors have been conducting research to develop a practical offline teaching method using a CCD camera as a measuring device, because of the advantages of its wide range of view, high repeatability and low cost. In this paper, an automatic robot calibration method is proposed as a result of this research. This method works with a camera that can be easily mounted on a robot without setting camera-intrinsic parameters. For improving accuracy of calibration and shortening measuring time, an autonomous visual measurement based on 3D measuring data, and an algorithm for determining a set of measuring poses are also proposed. The effectiveness of the proposed methods was evaluated with experiments.

2 CAMERA-BASED CALIBRATION METHOD FOR ROBOT KINEMATIC PARAMETERS

2.1. Autonomous Measurement Method for Calibration

An example of conventional methods for moving a robot according to images taken with a camera mounted on the robot utilizes visual feedback control [4][5][6]. With this method, the robot is moved in a way such that the image captured with the camera will match a predetermined target image. The authors have proposed a method for controlling robot poses in a way such that a predefined point on the target will always be on a given view line; that is, to be always captured with a prescribed pixel, thereby making it unnecessary to calibrate camera-intrinsic parameters. Obtaining the 3D position of the target according to 2D view line information, however, requires obtaining the target position as the intersection of more than one view line as shown in Figure 1 (a). If the relative angle made by the view lines is small, this method still has a problem in that a target's position error in depth along a view line is affected largely by measurement errors of the camera. If the relative angle is made bigger on the other hand, the robot requires larger working spaces. To achieve high accuracy with smaller working spaces in the identification calculation for kinematics calibration, the authors propose herein a measurement method shown in Figure 1 (b). This method can obtain information about the position along a view line using a target size as well as conventional measurement data, while using only a single measuring pose. In this paper, this method is referred to as the visual touch-up method, since what is done with this method amounts to making the tip, P_{VT}, of a virtual pin touch up the measuring point. The visual touch-up makes it possible to prevent the relatively small angle made by the view lines from affecting calibration, thus achieving more measurement information from the same number of measuring poses.



(a) Stereo measurement measuring data (V,H,α) (b) Visual touch-up measuring data (V,H,s)

Figure 1: 3D measuring method using camera.

In this paper, two measurements are made on a target whose contour is a perfect circle. The first is defined as the center of the circular target contour on a camera-taken image which is designated as, P_M, (hereafter called a measuring point). The second is the long axis (diameter) length of the contour which is referred to as the size of the target. Camera-intrinsic parameters are not identified in this case, however, distortion in the lens may affect calculations of the center and the long axis length on the image. Suppressing this effect requires using a target having an appropriate size and using an image plane around the optical axis where the distortion in the lens is less. In this paper, the center of a CCD image plane is assumed as pixels used for measurement, because the optical axis of off-the-shelf CCD cameras generally passes at or around the center of the image plane.

From a geometric relation shown in Figure 2, the size, s, of the target image is obtained using the following expression:

$$s = \frac{f}{d_T} s_T \tag{1}$$

where d_T is the distance between the measuring point and the lens center in the D direction in the Σ_I. In expression (1), s is proportional to the reciprocal number of d_T, because f and s_T are constant. For the sake of calculation, geometrical characteristic data obtained from the target image used in measurement for the calibration is represented with the position (V,H) of the target measuring point on the image plane and the reciprocal number, $s_{inv}=1/s$, of the target size (hereafter called measuring data). The measurement result is represented with a pose of the robot for which the measuring data matches a designated value; that is, the target measuring point and the image plane have a designated relationship.

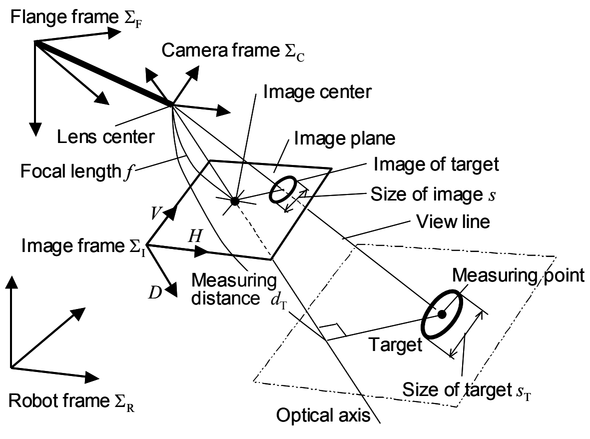


Figure 2: Camera model.

The relationship between the target measuring point and the image plane is intended to match a designated value. That is, the intersection of the view line passing through the measuring point and the image plane is made to match the center of the image plane, and the target size s on the image plane is made to match a size s_0, corresponding to the designated relationship, P_{VT0}. The coincidence of the measuring data with the designated value is realized by moving the robot according to an arm tip displacement value $\boldsymbol{p}(dX,dY,dZ)^T$. The arm tip displacement value is obtained by measuring the difference $\boldsymbol{e}_T(dV,dH,ds_{inv})^T$ between the measuring data and the designated value and then making $\boldsymbol{e}_T$ zero in the relationship between the position and size of the target in the image frame and the position of the target in the robot frame as shown in Figure 3. This operation is repeated to control the pose of the robot in such a way that the value $\boldsymbol{e}_T$ becomes lower than or equal to its threshold value.

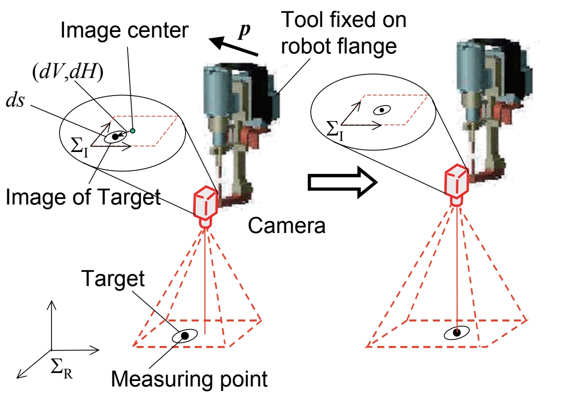


Figure 3: Visual touch-up control.

In Figure 2, the relationship among the robot flange frame Σ_F, the camera frame Σ_C and the image frame Σ_I is invariable because the camera is attached to the tip of the robot arm. The relationship between the robot flange frame Σ_F and the robot frame Σ_R is obtained from information about the current position of the robot. In this paper, therefore, the relationship between the robot frame Σ_R and the image frame Σ_I is represented using the pose of the Σ_I in the flange frame Σ_F.

The pose of the Σ_I in the Σ_F is obtained as follows: First, the robot arm tip is shifted by a very small value ΔX_F, ΔY_F, ΔZ_F in each direction separately. Changes of the measuring data of the measuring point in the Σ_I, $\Delta \boldsymbol{e}_{T,XF}(\Delta V_{XF}, \Delta H_{XF}, \Delta s_{XF,inv})^T$, $\Delta \boldsymbol{e}_{T,XF}(\Delta V_{XF}, \Delta H_{XF}, \Delta s_{XF,inv})^T$, $\Delta \boldsymbol{e}_{T,ZF}(\Delta V_{ZF}, \Delta H_{ZF}, \Delta s_{ZF,inv})^T$ are measured respectively. The Jacobean matrix $\boldsymbol{J}$ is obtained as shown in the following expression:

$$\boldsymbol{J} = \begin{bmatrix} \frac{\Delta V_{XF}}{\Delta X_F}\frac{s}{s_0} & \frac{\Delta V_{YF}}{\Delta Y_F}\frac{s}{s_0} & \frac{\Delta V_{ZF}}{\Delta Z_F} \\ \frac{\Delta H_{XF}}{\Delta X_F}\frac{s}{s_0} & \frac{\Delta H_{YF}}{\Delta Y_F}\frac{s}{s_0} & \frac{\Delta H_{ZF}}{\Delta Z_F} \\ \frac{\Delta s_{XF,inv}}{\Delta X_F} & \frac{\Delta s_{YF,inv}}{\Delta Y_F} & \frac{\Delta s_{ZF,inv}}{\Delta Z_F} \end{bmatrix} \tag{2}$$

In the visual touch-up operation, first, $\boldsymbol{e}_T$ on the image plane is measured, and the shift value $\boldsymbol{p}$ of the arm tip is obtained as shown in the following expression.

$$\boldsymbol{p} = \boldsymbol{J}^{-1}\boldsymbol{e}_T \tag{3}$$

Implementing a control algorithm as shown in Figure 4 a robot can be enabled to perform visual touch-up autonomously. However, the control algorithm should also consider suppressing the effect of lost motion in robot reducers including backlash while executing autonomous visual touch-up.

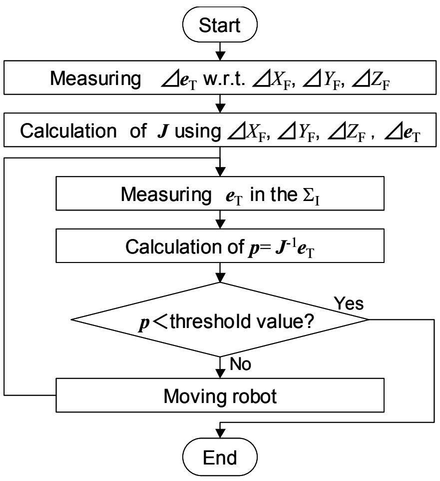


Figure 4: Algorithm of visual touch-up.

2.2. Algorithm for Identifying Kinematic Parameter Error

This paper uses errors in n_p kinematic parameters $\boldsymbol{p}_k=[P_{k,1}, P_{k,2}, \ldots, P_{k,np}]^T$, the position $\boldsymbol{p}_{VT}=[X_{VT}, Y_{VT}, Z_{VT}]^T$ of the virtual pin tip P_{VT} in the Σ_F and the position $\boldsymbol{p}_M=[X_M, Y_M, Z_M]^T$ of the measuring point P_M in the Σ_R as identifying parameters $\boldsymbol{p}_{ID}=[\Delta\boldsymbol{p}_k{}^T, \Delta\boldsymbol{p}_{VT}{}^T, \Delta\boldsymbol{p}_M{}^T]^T$. Under an ideal condition, the position $\boldsymbol{p}_i$ of the point P_{VT} in the Σ_R at the *i*th pose of the robot obtained in visual touch-up will match the position $\boldsymbol{p}_M$ of the measuring point P_M. However, the error $\boldsymbol{p}_{ID}$ containing kinematic parameter errors will yield the following positional error, $\boldsymbol{e}_i$, between $\boldsymbol{p}_i$ and $\boldsymbol{p}_M$:

$$\boldsymbol{e}_i = \boldsymbol{p}_i - \boldsymbol{p}_M \tag{4}$$

As seen from the geometric relation, $\boldsymbol{p}_i$ is a function of $\boldsymbol{p}_{ID}$ to be identified if an angular displacement in each robot articulation is constant.

In this paper, the Newton-Raphson method is used to determine $\boldsymbol{p}_{ID}$ in such a way that the errors $\boldsymbol{e}=(\boldsymbol{e}_1{}^T, \boldsymbol{e}_2{}^T, \ldots, \boldsymbol{e}_{ns}{}^T)^T$ between the position of the point P_{VT} in the Σ_R and P_M become the lowest for n_s robot poses obtained in visual touch-up. In the identifying calculation, the differential $\boldsymbol{g}_{i,j}$ is obtained for the *j*th identifying parameter $p_{ID,j}$ of $\boldsymbol{e}_i$ as shown in the following expression.

$$\boldsymbol{g}_{i,j} = \frac{d\boldsymbol{e}_i}{dP_{ID,j}} = \frac{\boldsymbol{e}'_{i,j} - \boldsymbol{e}_i}{\Delta P_{ID,j}} \tag{5}$$

where $\boldsymbol{e}'_{i,j}$ is the positional error in the *i*th pose of the robot obtained by giving a very small error value $\Delta p_{ID,i}$ to $p_{ID,j}$.

2.3. Index for Evaluating Measuring Poses for Calibration

In the identifying calculation described in the previous section, if $\Delta p_{ID,j}$ is very small, the matrix $\boldsymbol{G}$, where $\boldsymbol{g}_j=[\boldsymbol{g}_{1,j}{}^T, \boldsymbol{g}_{2,j}{}^T, \ldots, \boldsymbol{g}_{ns,j}{}^T]^T$ is the *j*th column vector, can be used to represent error relationships in the following linear expressions.

$$\boldsymbol{e} = \boldsymbol{G}\boldsymbol{p}_{ID} \tag{6}$$

Using the following pseudo inverse matrix expression:

$$\boldsymbol{G}^+ = \left(\boldsymbol{G}^T\boldsymbol{G}\right)^{-1}\boldsymbol{G}^T \tag{7}$$

$\boldsymbol{p}_{ID}$ is obtained as follows:

$$\boldsymbol{p}_{ID} = \boldsymbol{G}^+\boldsymbol{e} \tag{8}$$

As seen from expression (8), the error in $\boldsymbol{p}_{ID}$ to be identified is the one magnified under the $\boldsymbol{G}^+$ condition, that is, at a magnifying factor of an error, $\Delta\boldsymbol{e}$ (measurement error and non-modeled error), included in $\boldsymbol{e}$.

Achieving higher calibration accuracy requires using a less error-prone measurement method, a complete model, and measuring poses selected to provide favorable results. Given a predetermined measurement method, the availability of favorable measuring poses determines the accuracy of calibration. Using $\boldsymbol{G}^+$ enables the calibration to be evaluated in advance because its components can be obtained if measuring poses are selected.

Several evaluation indexes have been proposed for the coefficient matrix $\boldsymbol{G}$ for calibration [7][8][9]. This paper uses the condition number based on absolute values of the components as an evaluation index C_G because of its simple calculation [7].

$$C_G = Cond\left(\boldsymbol{G}^T\boldsymbol{G}\right) = \left\|\boldsymbol{G}^T\boldsymbol{G}\right\| \left\|\left(\boldsymbol{G}^T\boldsymbol{G}\right)^{-1}\right\| \tag{9}$$

Where

$$\left\|\boldsymbol{G}^T\boldsymbol{G}\right\| = \max\left\|h_j\right\| \tag{10}$$

$$\left\|h_j\right\| = \Sigma\left|h_{ij}\right| \tag{11}$$

where $h_{i,j}$ is the (i,j) component of the square matrix $(\boldsymbol{G}^T\boldsymbol{G})$. To handle each component of $\boldsymbol{p}_{ID}$ equally, though whose components have different units, $\boldsymbol{G}'$, which has been normalized using the following expression, is used instead of $\boldsymbol{G}$.

$$\boldsymbol{g}'_j = \boldsymbol{g}_j \big/ \max\left|g_{ij}\right| \tag{12}$$

where $g_{i,j}$ is the (i,j) component of $\boldsymbol{G}$, and $\boldsymbol{g}'_j$ is the *j*th column vector of $\boldsymbol{G}'$.

2.4. Algorithm for Generating and Adjusting Measuring Poses Automatically

Several methods have been proposed which automatically generate candidates of measuring poses and efficiently select the most favorable sets of poses using an evaluation index [7][10]. These methods must calculate the evaluation indices at least one time for all generated measuring poses across the entire parametric space. The calculation period is very extensive. It is well known that larger displacements in articulations of a robot for measuring poses are effectual to produce better calibration results. This paper uses serial link industrial robots to be calibrated, and proposes a method to generate measuring poses with larger angular displacements from a limited motion area. The method consequently evaluates the pairing of measuring poses and optimizes them based on the evaluation index.

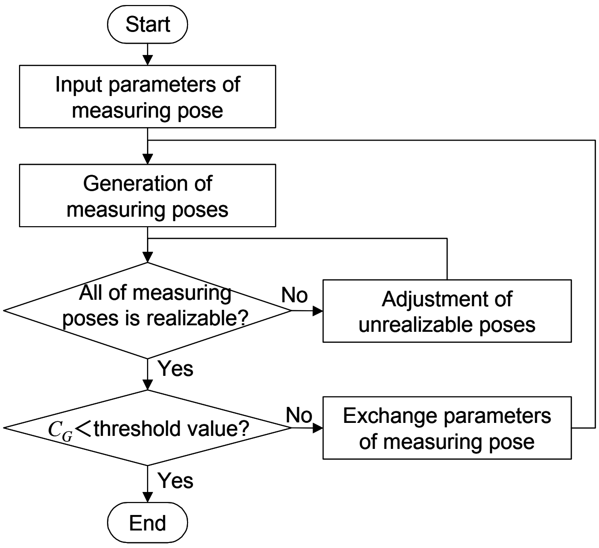


Figure 5: Algorithm for generating poses.

1. Specify parameters for generating initial measuring poses.
2. Generate a candidate set of the initial measuring poses.
3. Check whether the measuring poses in the set are reachable. If all the poses are reachable, skip to Step 5. If any pose is unreachable, go to Step 4.
4. Adjustment of the measuring poses: For unreachable measuring poses, adjust the rotation angles of all axes including the out-of-range ones so that their displacements from those of other measuring poses will become as large as possible to move within the operating range.
5. Evaluation of the pairing of the measuring poses: Complete generating measuring poses if the condition number is lower than predefined threshold value. Otherwise, go to Step 6.
6. Adjust the parameters for generating initial measuring poses by predefined values so that the condition number will decrease, and then go back to Step 2.

2.5. Automatic Calibration Process

As a minimum requirement for autonomous measurement using a CCD camera, the operator must move the camera mounted on the tip of robot arm to a position where the target can be viewed by the camera, and teach the position to the robot as the initial measuring pose. To improve ease of operation and reduce total operating time, a 2-step automatic measuring process is proposed which does not require the specification of initial values for camera mounting and target positions.

1. Inch the robot keeping the target in the view and measure robot poses around the single measuring point using visual touch-up. Then roughly identify the positions of the camera and the target but with enough accuracy to achieve the next measurement for kinematic calibration.
2. Determine a set of measuring poses using the above-mentioned algorithm for generating and adjusting measuring poses. Then obtain robot poses that have the same relative location to the measuring point on the target by using visual touch-up.

After the measurement, the identification algorithm can calculate $\boldsymbol{p}_{\mathrm{ID}}$.

3 EXPERIMENT VERIFICATION

3.1. Experiment Conditions

The following equipment was used in the experiment:

Robot

FANUC Robot R2000*i*A165F (as shown in Figure 6 and 7)

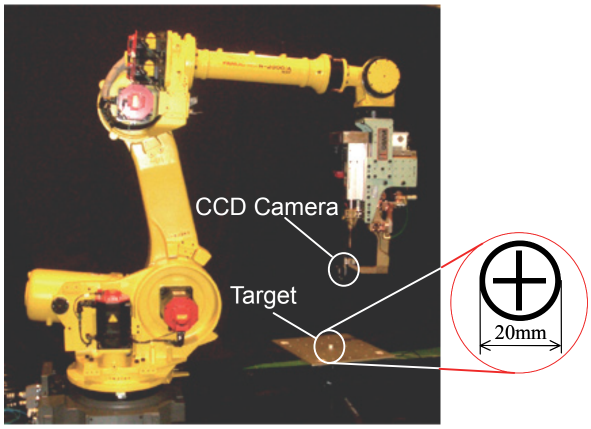
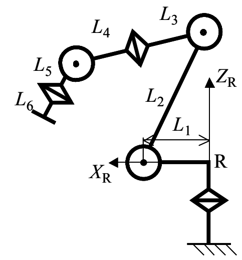


Figure 6: Experimental robot system.



L_1	479mm
L_2	1075mm
L_3	0mm
L_4	1300mm
L_5	260mm
L_6	0mm

Designed Values of the kinematic parameters

Figure 7: Mechanism of R2000*i*A165F.

End of Arm Tool

106 kg spot welding gun (as shown in Figure 6).

Camera

- Opteon USB camera (1/3" CCD of 640 × 480 pixels).
- Lens f = 12 mm.
- Stand-off = approximately 350 mm.

Target

A cross mark in a circle (as shown in Figure 6).

Generation of measuring poses

Parameters of measuring poses:

- Initial measuring pose $\boldsymbol{p}_{\mathrm{B}} = [X_{\mathrm{B}}, Y_{\mathrm{B}}, Z_{\mathrm{B}}, W_{\mathrm{B}}, P_{\mathrm{B}}, R_{\mathrm{B}}]^T$
- Measuring pose variations D_{W}, D_{P}, and D_{R}

In this paper, roll, pitch and yaw angles are used to express the orientation of robot poses (*WPR*).
Measuring pose generation:
The *i*th measuring pose is obtained using the following expression.

$$\boldsymbol{p}_{i,0} = [X_{\mathrm{B}}, Y_{\mathrm{B}}, Z_{\mathrm{B}}, W_{\mathrm{B}} + i_{\mathrm{W}} D_{\mathrm{W}}, P_{\mathrm{B}} + i_{\mathrm{P}} D_{\mathrm{P}}, R_{\mathrm{B}} + i_{\mathrm{R}} D_{\mathrm{R}}]^T \tag{13}$$

where, i_W, i_P, i_R =-1,0,1.In this case, 27 measuring poses can be generated using preset parameters for measuring poses.

Calculating device for generation

Robot controller

3.2. Error model

The error model for the experimental robot is shown in Figure 8. Since robot links and drive systems have been processed and assembled under strict dimensional control, elastic deformations are assumed as the main cause of absolute positioning inaccuracies at the tip of the robot arm. By considering that elastic deformation occurs mainly in the reducer mounted on each rotation axis, elastic deformations caused by load are defined as a shift in the zero point on the reducer of each rotation axis. Because the relative position among the tip of robot arm, P_{VT} (Tip of virtual pin) and P_M (measuring point on the target) are used in identification, zero point error of J_1 and J_6 are dependent on error of $\boldsymbol{p}_{VT,0}$ and $\boldsymbol{p}_{M,0}$. Therefore, independent zero point errors of J_2, J_3, J_4, and J_5 axes $[\Delta\theta_2,\Delta\theta_3,\Delta\theta_4,\Delta\theta_5]^T$ are defined as kinematic parameters of robot $\boldsymbol{p}_k$, and errors $[\Delta X_{VT},\Delta Y_{VT},\Delta Z_{VT}]^T$ included in $\boldsymbol{p}_{VT}$ are defined as fixture parameters of virtual pin P_{VT}, errors $[\Delta X_M,\Delta Y_M,\Delta Z_M]^T$ included in $\boldsymbol{p}_M$ are defined as fixture parameters of target P_M. In this paper a total of 10 calibration parameters were identified.

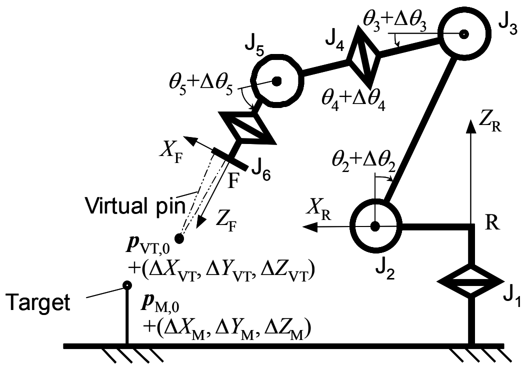


Figure 8: Error model of the measuring system.

3.3. Accuracy of visual touch-up

Repeatability in position measurement

1. View line follow-up measurement:
   Table 1 lists variations in 100 stereo measurement results with view line parameters identified in the flange coordinate system Σ_F. The stereo measurement results were obtained from three measuring poses of the robot arm tip by rotating it ±15deg about an initial 0deg measurement position. In this evaluation each measurement pose required about 20 seconds to complete, or approximately 60 seconds for a complete stereo measurement.

	X_R	Y_R	Z_R
3σ	0.02mm	0.04mm	0.16mm

Table 1: Repeatability of view line follow-up control.

2. Visual touch-up:
   Table 2 lists variations in 100 visual touch-up results for the same target with the pose WPR of the Σ_F since the touch-up value was changed every time. Each single visual touch-up operation required about 20 seconds to complete.
   From the results comparison, adding the size information was successful in improving the repeatability in the D direction. Required measurement time was reduced to 1/3 or less of the conventional value while keeping the measurement error at 3/4.

	V	H	D
3σ	0.02mm	0.02mm	0.12mm

Table 2: Repeatability of visual touch-up.

Absolute accuracy in position measurement

The robot poses obtained by visual touch-up and manual touch-up using an actual pin to a single target were also investigated by changing the orientation of the Σ_F. Table 3 shows the differences $\Delta\boldsymbol{p}_F$ between the pose in the Σ_F obtained by the visual touch-up and the pose in the Σ_F obtained by the manual touch-up. When the accuracy in the manual touch-up performed with an actual pin (empirically measured to be about 0.1 mm) is taken into account, it can be considered that visual touch-up can achieve accuracy equivalent to conventional manual pin touch-up.

	ΔX_R	ΔY_R	ΔZ_R
$\Delta\boldsymbol{p}_{F\ (45deg,0,0)}$	0.2mm	0.1mm	-0.1mm
$\Delta\boldsymbol{p}_{F\ (0,45deg,0)}$	-0.1mm	-0.1mm	-0.1mm
$\Delta\boldsymbol{p}_{F\ (0,0,45deg)}$	-0.2mm	-0.1mm	0.1mm

Table 3: Error of visual touch-up.

3.4. Calibration Result

Relationship among variations in identification results, condition number and measuring method

At first, the initial vale of (D_W,D_P,D_R) was set as (5deg,5deg,5deg). With preset thresholds and searching step (each 5deg in *WPR*), several sets of measuring poses were determined by using the proposed algorithm. In this case, time required for generating, adjusting and evaluating a set of measuring poses is approximately 15sec by using the robot controller. To evaluate the effectiveness of condition number the threshold was changed several times and then several sets of measuring poses were obtained. Four sets were selected randomly for the evaluation. In order to evaluate the relationship between variations in the identification results and the condition number, 10 sets of measuring data obtained from each set of measuring poses were used for the identification. Time required for step 1 of the proposed calibration process was approximately 5min, and time required for step 2 was approximately 12min. As a part of the identification results, J_2 zero point error $\Delta\theta_2$ is shown in Figure 8 with respect to the condition number.

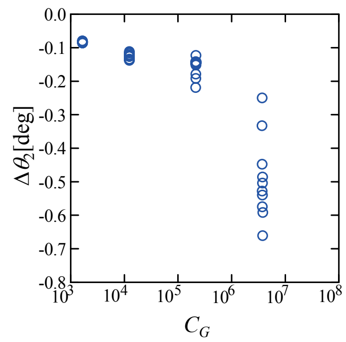


Figure 9: Relationship between identifying accuracy and condition number(Calibration using visual touch-up).

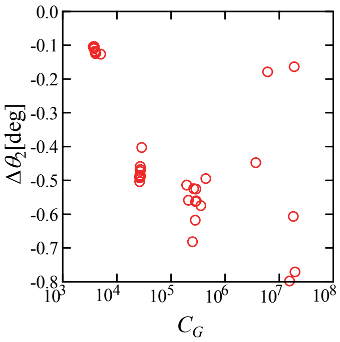


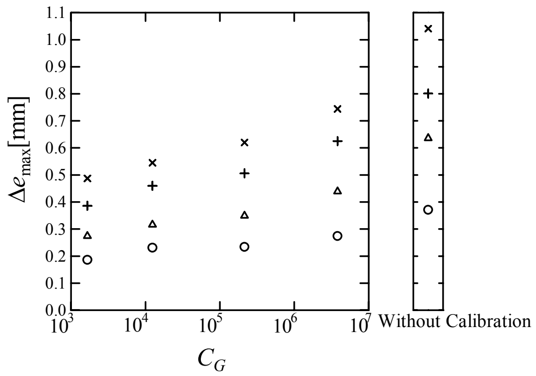
Figure 10: Relationship between identifying accuracy and condition number(Calibration using view line data only).

Figure 9 shows the relationship in the case when visual touch-up was used. Figure 10 shows the relationship in the case when only 2D data of the view line orientation was used in the identification. The figures show that stable identification results can be obtained by using a set of measuring poses with small enough condition number. Comparing Figure 9 with 10, it is also confirmed that accuracy of the identification can be improved by using visual touch-up without increasing the number of measuring poses used.

From these results, it can be concluded that the condition number is an adequate index for evaluating stability of the identification and it is effective to use visual touch-up in calibration.

Positioning accuracy before and after calibration

An evaluation test was conducted using a plate that has 25 (5x5) targets uniformly placed with 100mm pitches on its surface. For the positions of the targets on the plate, designed values were used. The positions can be assumed to have less than 0.1mm accuracy by machining. The positions of all points were measured using visual touch-up after compensating the robot and the measuring system with it based on identified results. Figure 11 shows the relationship between maximum error $\Delta e_{\max}$ in the distance between arbitrary two points in the same row or column measured against the designed value d and the condition number as was evaluated above.



$(\times : d = 400\text{mm}; + : d = 300\text{mm}; \Delta : d = 200\text{mm}; \text{O} : d = 100\text{mm})$

Figure 11: Relationship between distance error and condition number.

As shown in Figure 11, relatively high positioning accuracy was achieved by using the set of measuring poses with a small condition number. It is confirmed that the condition number is also an adequate index for evaluating positioning accuracy after the calibration. Although it is not perfect to represent elastic deformation on the robot arm reducers by the constant zero point error, the distance error $\Delta e_{\max}$ after the calibration using the set of measuring poses with respect to smallest condition number was reduced to below 1/2 of the case without calibration. Considering the time required for the calibration, the ratio between the error after the calibration and the distance (1/600 when d =100mm, 1/800 when d =400mm) and achieved positioning accuracy of the robot (0.5mm when nominal repeatability of the robot is 0.3mm), it can also be concluded that proposed methods are practical.

4 CONCLUSIONS

A new automatic kinematic calibration method using an autonomous measurement and an algorithm for determining measuring poses based on the condition number was proposed and its effectiveness was experimentally investigated. The conclusions are summarized as follows:

1. In order to improve accuracy of the identification and shorten measuring time, a visual touch-up (rather than stereo measurement) was proposed.
2. In order to increase efficiency of the measurement in the calibration, an algorithm was proposed to determine a set of measuring poses based on the condition number and working space of an industrial robot on the shop floor.
3. Using the methods proposed in 1 and 2, an automatic calibration method was proposed.
4. The effectiveness of the proposed methods was evaluated through experiments with an actual industrial robot.

5 REFERENCES

[1] A. Watanabe, S. Sakakibara, K. Ban, M. Yamada and G. Shen, 2005, Autonomous Visual Measurement for Accurate Setting of Work Pieces in Robotic Cells, Annals of the CIRP, 54/1:13-18

[2] X.L. Zhong and J. M. Lewis, 1995, A new method for autonomous robot calibration, Proc. of IEEE Int. Conf. on Robotics and Automation, 1790-1794

[3] S. Toyama, S. Hatae, T. Haga, 1991, Kinematic calibration of SCARA robot with condition number and error map method, Annals of the CIRP, 40/1: 9-12

[4] Y. Shirai, H. Inoue, 1973, Guiding a robot by visual feedback in assembling tasks, Pattern Recognition, 99-108

[5] L. E. Weiss, A.C. Sanderson, and C.P. Newman, 1987, Dynamic sensor-based control of robots with visual feedback, IEEE J. of Robotics and Automation, RA-3/5: 404-417

[6] B. Espiau, F. Chaumette, P. Rives, 1992, A new approach to visual servoing in robotics, IEEE Trans. on Robotics and Automation, RA-8/3:313-326

[7] Y. Takeda, G. Shen, H. Funahashi, 2004, A DBB-Based kinematic Calibration Method for In-Parallel Actuated mechanisms Using a Fourier Series, Trans. of the ASME, J. of Mechanical Design, 126:856-865

[8] A. Nahvi, J. M. Hollerbach, 1996, The noise amplification index for optimal pose selection in robot calibration, Proc. of IEEE Int. Conf. on Robotics and Automation, 647-654

[9] J.H. Borm, C. H. Menq, 1991, Determination of optimal measurement configurations for robot calibration based on observability measure, Int. J. of Robotics Research, 10/1:51-63

[10] D. Daney, 2002, Optimal measurement configuration for Gough platform calibration, Proc. of IEEE Int. Conf. on Robotics and Automation, 147-152