Proceedings of the 2017 IEEE
International Conference on Robotics and Biomimetics
December 5-8, 2017, Macau SAR, China

Improving the Local Absolute Accuracy of Robot with Touch Panel

Cheng Li, Hao Gu
ABB Corporate Research Center
Shanghai, China
Email: {cheng.li, hao.gu}@cn.abb.com

***Abstract*—New applications in small part assembly put forward higher requirements on robot's absolute accuracy, which can be effectively improved by robot calibration. However, existing methods are either with expensive equipment such as laser tracker, or time-consuming due to tedious manual operations. In this paper, we present a robot calibration solution using touch panel. It is cost-saving and can quickly improve or recover the robot absolute accuracy in the interested working area. We demonstrate its calibration performance by experiments with ABB Yumi robot.**

***Index Terms*—robot calibration; local absolute accuracy; touch panel**

I. Introduction

With tablets and smart phones getting more and more popular these years, a great opportunity appears for robot application in the automatic manufacturing for 3C (computer, communication, and consumer electronics) industry. Small part assembly is one typical operation in 3C manufacturing, of which the accuracy requirement is much higher than that in the conventional automobile industry. Such sub-millimeter accuracy can hardly be achieved by industrial robots because of the environmental, parametric, measurement and computational factors [1]. Fortunately, we can use robot calibration to improve the accuracy performance.

Various robot calibration approaches are proposed in the literature. In order to identify the kinematic parameters, Hayati model [2] and Veitschegger model [3] were put forward based on the widely used Denavit-Hartenberg (DH) convention [4]. Okamura and Park first employed the product of exponentials (POE) model in robot calibration with an iterative least square algorithm [5]. Later, Chen *et al.* came up with the local POE method using the dyad kinematics [6]. Adjoint error model was proposed based on the POE model and robot's axis configuration space, which was geometrically intuitive, computationally efficient, and can easily handle additional assumptions on joint axes relations [7]. Besides the kinematic parameters, some non-geometric factors are also taken into consideration. Judd and Knasinski analyzed the error sources of structural deformations, gear run-out, gear orientation error and gear tooth error of an Automatix AID-900 robot [8]. Gong *et al.* investigated the effect of link compliance and temperature variation on robot positioning accuracy [9]. Nubiola and Bonev set up the joint stiffness and nonlinearity model for an ABB IRB 1600 robot on top of its kinematic error model to achieve better accuracy performance [10].

No matter which calibration method is used, we need to obtain redundant information about the system by either explicit measurements or constraints. Method of gathering such information largely determines the easiness, efficiency and cost of calibration system. Laser tracker can precisely measure the coordinates of a spherically mounted retro-reflector (SMR), with which we can get the end-effector position [11], or calculate the pose with three or more SMRs [10]. However, the expensive cost of laser tracker limits its applications, in particular for on-site calibration. Coordinate Measurement Machine (CMM) can also obtain the point coordinates, thus be used in calibration [12], [13]. But the whole measurement process is time-consuming since we usually need to touch the target points manually by probe. Driels and Swayze proposed to use wire potentiometer to measure only partial pose information [14]. Vision is also one popular perception approach in calibration systems. Camera can be mounted on the robot tool flange [15]–[17] or fixed externally [18] to measure the relative transformation between robot end-effector and the world coordinate frame. In addition to the external measurement devices, manipulator may form a mobile closed chain with the environment, and parameters can be identified from the close-chain constraint equations [19]. Examples include a fixed endpoint, the opening of a door, point contact constraint [20], [21] and the plane constraint [22], [23]. It often takes less cost than the measurement equipment, but on the other hand we need to jog the robot carefully in order to form the right constraint and protect the system from collision.

With the advancement of consumer electronics, devices with touch panel, such as smart phones and tablets, are widely used in our daily life. The touching technology is improved with higher resolution and better sensitivity, yet it is now very cost-efficient comparing with the traditional vision or laser-based sensors. This makes the touch panel suitable for position measuring. In [24] the authors proposed a system with touch panel to calibrate the robot cell coordinate frames. In this paper we take advantage of touch panel to increase robot absolute accuracy. Although the measurement range is limited only to the touch active area on the panel, it would benefit us in system commissioning and recovery in the following aspects. Firstly, most robot tasks with high accuracy requirements concentrate within one or several discrete areas instead of distributing all over the working space, especially for small part assembly applications. Therefore, it is enough to focus on the robot

978-1-5386-3742-5/17/$31.00 © 2017 IEEE

accuracy only in local regions, which is referred to as the *local absolute accuracy* in this paper. Secondly, since robot can actively search for the surface of touch panel, the calibration process can be performed automatically with minimum manual involvement. Moreover, the system can be quickly deployed on site due to its small volume and easy setup. As a consequence, we can use it not only to improve the robot's accuracy after the system is build up, but also to recover its performance once any crash happens. We would show by experiments with Yumi robot that the proposed system can effectively improve the local absolute accuracy.

This paper is organized as follows. We describe the calibration system in Section II and state the calibration problem of local absolute accuracy in Section III. In Section IV, we use experiments to demonstrate that the proposed method can improve and recover robot's accuracy performance. The locality issue is also discussed in this section. Finally, Section V concludes this paper.

II. System Description

The robot calibration system is illustrated in Fig. 1. It consists of the industrial robot, a stylus mounted on robot, and a touch panel. In particular, the touch panel is preferred to be placed in the interested working region. Robot controller communicates with the touch panel to check the touching status and/or coordinates of the touched point, with which the robot can automatically search for the panel. Please refer to [24] for more information about this system.

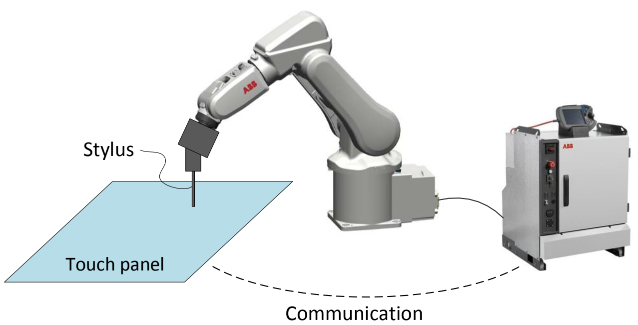

Fig. 1. Calibration system for robot local absolute accuracy.

We attach the tool frame T to the center of robot's end flange (also referred to as the *tool0* frame), as shown in Fig. 2. The relative transformation between frame T and robot base frame S can be described by a homogeneous matrix $\mathbf{g}_{st}$ [25]. Similarly, we set up a work object frame W on the touch panel. Transformation between frame W and S is expressed by matrix $\mathbf{g}_{sw}$. Coordinates of the stylus tip in the tool frame T are the tool center point (TCP) coordinates, denoted as $\mathbf{q}_t$. We can get the position of stylus tip expressed in robot base frame S and work object frame W by

$$\begin{aligned}\tilde{\mathbf{q}}_s &= \mathbf{g}_{st} \cdot \tilde{\mathbf{q}}_t \\ \tilde{\mathbf{q}}_w &= \mathbf{g}_{sw}^{-1} \cdot \mathbf{g}_{st} \cdot \tilde{\mathbf{q}}_t,\end{aligned} \tag{1}$$

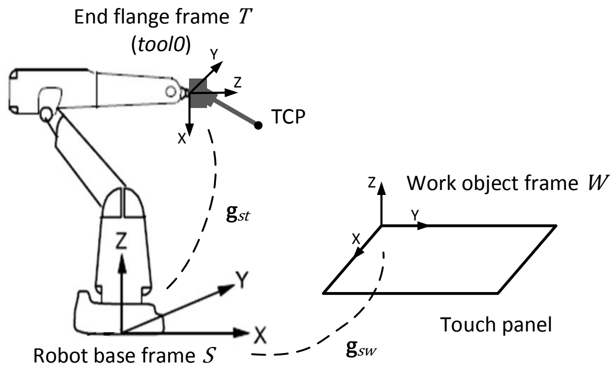

Fig. 2. Robot coordinate frames.

where $\tilde{\mathbf{q}} \triangleq (\mathbf{q}^{\mathrm{T}}, 1)^{\mathrm{T}} \in \mathbb{R}^4$ represents the homogeneous coordinates of $\mathbf{q} \in \mathbb{R}^3$.

The *forward kinematics* of a n degree-of-freedom industrial robot maps its joint positions $\mathbf{\Theta} = (\theta_1, \cdots, \theta_n)^{\mathrm{T}}$ to the tool frame displacement $\mathbf{g}_{st}$:

$$\mathbf{g}_{st} = f(\mathbf{\Theta}). \tag{2}$$

When robot touches the panel by the probe tip, we have

$$\tilde{\mathbf{p}} = \mathbf{g}_{sw}^{-1} \cdot f(\mathbf{\Theta}) \cdot \tilde{\mathbf{q}}_t, \tag{3}$$

where $\mathbf{p}$ is the coordinates of touching point in work object frame W.

By monitoring the touching status, robot can go and reach the touch panel all by itself, thus little manual effort is involved in the calibration process. In particular, since the stylus tip would always touch the surface of panel, this calibration system offers 2 dimensional active measurement by sensing the $\mathbf{x}$ and $\mathbf{y}$ coordinates of touched point in the work object frame, and 1 dimension of constraint by forcing $\mathbf{z}$ coordinate to be 0. All these 3 dimensions of information would be used as we state the calibration problem formulation and method in the next section.

III. Calibration Problem of Local Absolute Accuracy

With the proposed calibration system as in Fig. 1, we want to improve or recover robot's absolute accuracy in a local area, which is the neighborhood of touch panel. Robot calibration can be classified into 3 levels [26]: joint level calibration, robot geometric calibration, and non-geometric calibration. Since only the local absolute accuracy we are interested in, effect of some non-geometric factors, such as joint and link compliance, can be viewed as constants. As a consequence, we can attribute the error caused by robot compliance to its kinematic errors. In other words, these non-geometric factors are linearized around the working point. Therefore in this paper, we treat the calibration problem of local absolute accuracy as kinematics calibration that is conducted in the local area.

We consider the *generalized forward kinematics* which views the kinematic parameters $\mathbf{k}$ also as variables

$$\mathbf{g}_{st} = f(\mathbf{\Theta}, \mathbf{k}). \tag{4}$$

We may use different robot kinematic models. For DH convention [4], $\mathbf{k}$ contains the DH parameters describing the relative location of each link coordinate frame iteratively; we can also adopt the POE model [25], in which case $\mathbf{k}$ consists of the robot's joint twists and initial tool frame offset.

The actual kinematic parameters $\mathbf{k}^{\mathrm{a}}$, TCP coordinates $\mathbf{q}_t^{\mathrm{a}}$ and the work object coordinates $\mathbf{g}_{sw}^{\mathrm{a}}$ would always deviate from their nominal values $\mathbf{k}^{\mathrm{n}}$, $\mathbf{q}_t^{\mathrm{n}}$ and $\mathbf{g}_{sw}^{\mathrm{n}}$ in practice. Such deviations would affect the system accuracy, which is reflected by the error between the nominal (or expected) and actual coordinates of touched point in our calibration system

$$\begin{aligned} \tilde{\mathbf{p}}^{\mathrm{a}} &= (\mathbf{g}_{sw}^{\mathrm{a}})^{-1} \cdot f(\mathbf{\Theta}, \mathbf{k}^{\mathrm{a}}) \cdot \tilde{\mathbf{q}}_t^{\mathrm{a}} \\ \neq \tilde{\mathbf{p}}^{\mathrm{n}} &= (\mathbf{g}_{sw}^{\mathrm{n}})^{-1} \cdot f(\mathbf{\Theta}, \mathbf{k}^{\mathrm{n}}) \cdot \tilde{\mathbf{q}}_t^{\mathrm{n}}. \end{aligned} \tag{5}$$

We try to find the best parameters to minimize the measurement errors with N touches. Therefore, this calibration problem can be formulated as

$$\min_{\mathbf{k}^{\mathrm{a}}, \mathbf{q}_t^{\mathrm{a}}, \mathbf{g}_{sw}^{\mathrm{a}}} \sum_{i=1}^{N} \|\tilde{\mathbf{p}}_i - (\mathbf{g}_{sw}^{\mathrm{a}})^{-1} \cdot f(\mathbf{\Theta}_i, \mathbf{k}^{\mathrm{a}}) \cdot \tilde{\mathbf{q}}_t^{\mathrm{a}}\|^2, \tag{6}$$

where $\mathbf{p}_i$ and $\mathbf{\Theta}_i$ are the touching point coordinates and joint positions of the i-th sample, respectively.

As we can see, this is a nonlinear least square problem. We can solve it by iterative linearization approach, or any other available nonlinear optimization solver. In our experiments we explicitly take advantage of the *lsqnonlin* function in Matlab to solve this problem. Identifiability issue is not discussed in this paper, of which readers may refer to [7].

We shall emphasize again that here we use kinematic calibration to improve robot's local absolute accuracy, of which the performance would be best only in this local region. Generally speaking, the accuracy would go down out of the area, where the non-geometric factors can no longer be viewed as constants. The less influence the non-geometric factors have, the better accuracy performance the robot can achieve outside the calibration region. Luckily for common industrial manipulators, kinematic error accounts for most of the overall end-effector error [27].

IV. Experiments

A. Experiment Setup

We use ABB Yumi robot and touch panel from Wacom to verify the proposed calibration solution. The experiment setup is shown in Fig. 3.

Each arm of Yumi has 7 degrees of freedom with position repeatability 0.02 mm [28]. Here we use its left arm as a redundant manipulator to conduct this experiment. Intuos Pro S of Wacom (type PTH-451) is placed in front of the robot. As in Fig. 3, we attach the Wacom grip pen, the stylus for this touch panel, to the end of arm. Specifications of touch panel with grip pen is summarized as in Table I [29].

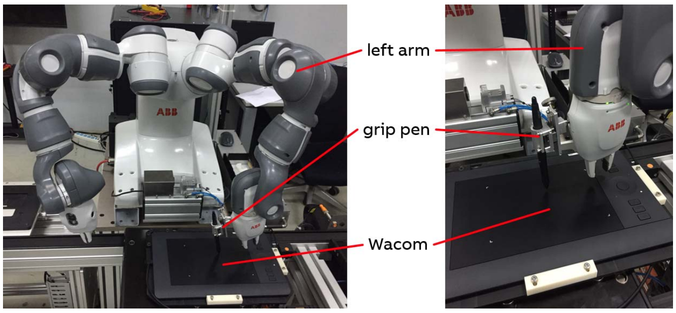

Fig. 3. Experiment setup.

TABLE I
Specifications of Wacom Intuos Pro S with grip pen

Physical size	$320.1 \times 207.8 \times 11.5$ mm
Touch active area	157.48×98.43 mm
Coordinate resolution	200 lines per mm
Coordinate accuracy	± 0.25 mm

Robot cell calibration described in [24] would be performed to locate the touch panel. We then take two sets of samples spread on the panel's surface as illustrated in Fig. 4. The first set is called *calibration sample*, of which data is used for calibration. Starting from the $(30, 30)$ point in work object frame, we let the robot touch an array of spots with 3 rows and 5 columns. Spaces between the rows and columns are 20 mm. On each of these spots, the robot would try to move the stylus tip to the same point in 5 different poses, as illustrated in Fig. 5. In other words, we would have 5 samples with the same nominal robot translation but different orientations on one spot. We also change the angle of joint 7 in the group of 5 samples. Totally 75 samples are taken for calibration.

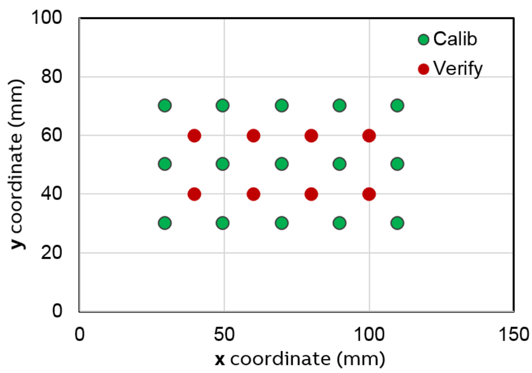

Fig. 4. Calibration and verification sampling spots in work object frame.

Verification samples are taken similarly. 2 rows and 4 columns of spots would be touched starting from $(40, 40)$. On each spot we re-orient the robot end-effector to 5 different poses and vary the angle of joint 7 as well. As a result, we have 40 samples in the verification set. Please note that we take the verification samples on different spots from the calibration

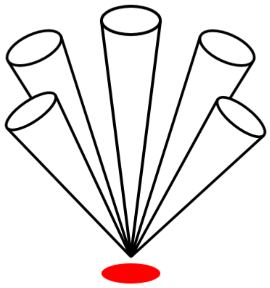

Fig. 5. Five re-orientations at one sampling spot.

set, which can better reflect the calibration performance.

After each touch, the distance between touching point $\mathbf{p}^{\mathrm{a}}$ and the expected point $\mathbf{p}^{\mathrm{n}}$ is viewed as the error in this sample. We evaluate the system accuracy by

$$e = \mathrm{mean}(\|\mathbf{p}_i^{\mathrm{n}} - \mathbf{p}_i^{\mathrm{a}}\|), \tag{7}$$

where i varies from 1 to 75 for calibration samples and to 40 for verification ones. Errors in the robot kinematics, TCP and work object coordinates would all have influence on the system accuracy.

B. Local Absolute Accuracy Improvement

We switch off the ABB absolute accuracy option and try to improve its local absolute accuracy with the proposed system. Initially the mean errors of calibration and verification samples are 0.64 and 0.62 mm, respectively. The touching points are shown in Fig. 6 and 7.

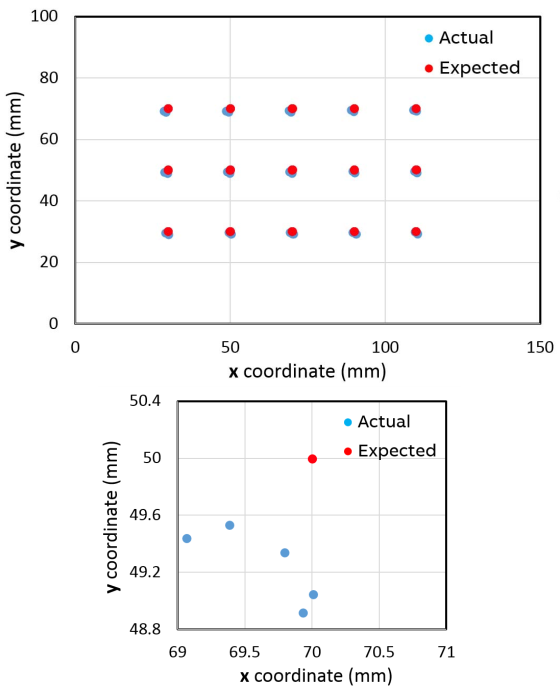

Fig. 6. Robot touching points at calibration samples before calibration and a detailed view around point $(70, 50)$.

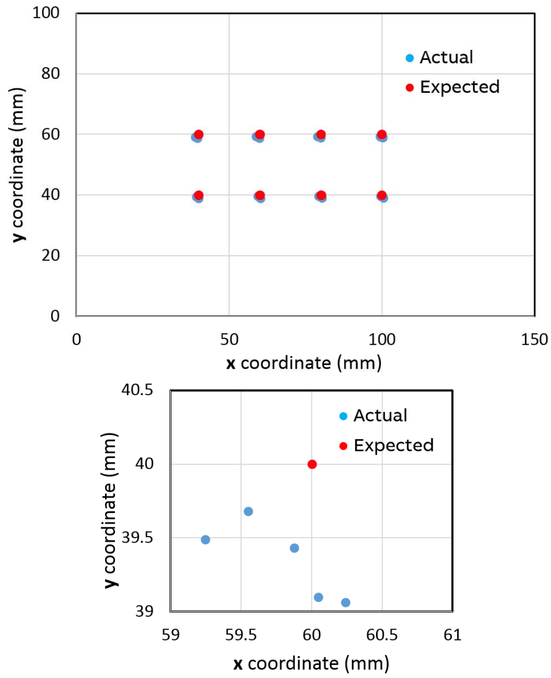

Fig. 7. Robot touching points at verification samples before calibration and a detailed view around point $(60, 40)$.

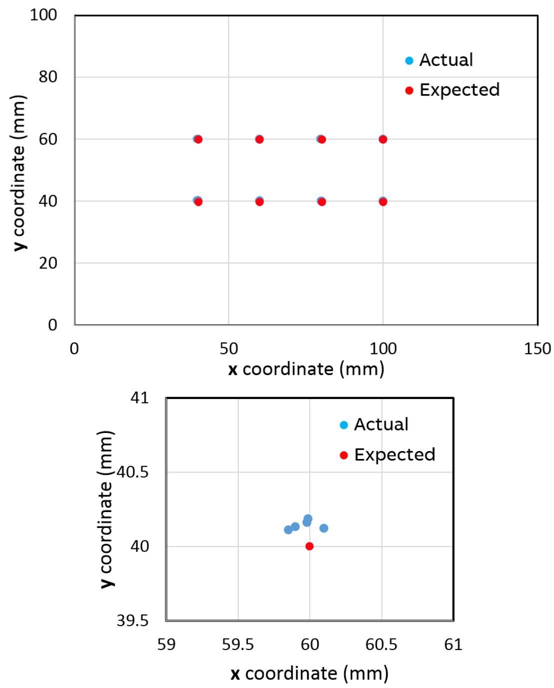

Fig. 8. Robot touching points at verification samples after calibration and a detailed view around point $(60, 40)$.

After calibration we let Yumi re-visit the verification samples with the identified parameters. Mean error of this re-visit is 0.16 mm, which is smaller than the initial error. We plot the touching points during re-visit in Fig. 8. Comparing Fig. 7 and 8, we can easily visualize the accuracy improvement

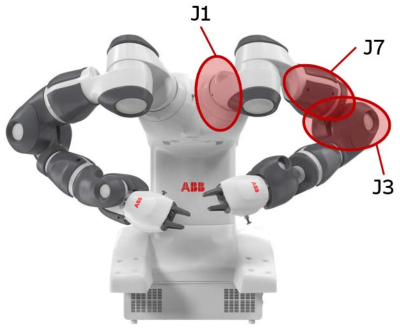

Fig. 9. Joint 1, 3, and 7 of Yumi's left arm.

by calibration. This accuracy level has reached the limit of measurement system (see Table I).

C. Local Absolute Accuracy Recovery

In this case, we intentionally vary the motor zero offsets of Yumi's joint 1, 3 and 7 by $5°$. Position of joint 1, 3 and 7 are highlighted in Fig. 9. By modifying the motor zero offsets we simulate the case after robot crash and try to verify whether we can use the proposed system to recover the local absolute accuracy. Touching points of Yumi after "crash" at the verification samples are plotted in Fig. 10. We can see obviously that the touching points are far away from their expected spots. The average error is about 20 mm.

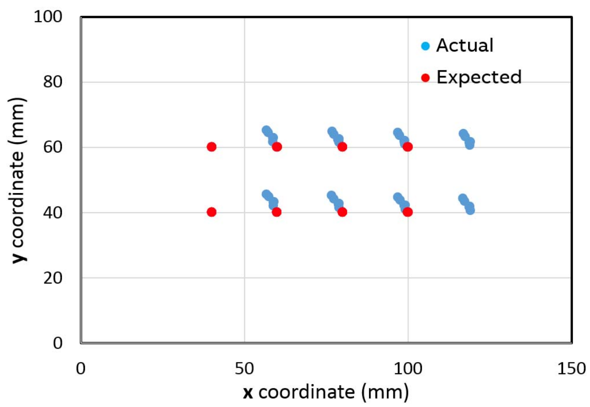

Fig. 10. Robot touching points at verification samples before calibration.

We calibrate the system using data from calibration samples (not plotted), and let the robot re-visit all verification points with identified parameters, which are shown in Fig. 11. The system accuracy after calibration is 0.17 mm, which is at the same level as in the previous experiment. From this experiment we can conclude that, even the robot local absolute accuracy is very bad, it can be recovered by the proposed system quickly and effectively.

D. Locality of Calibration Performance

As discussed in Section III, robot accuracy is best improved in the local area of touch panel using the proposed system. In this subsection, we want to check the accuracy of calibrated Yumi arm at another place beside the calibration location.

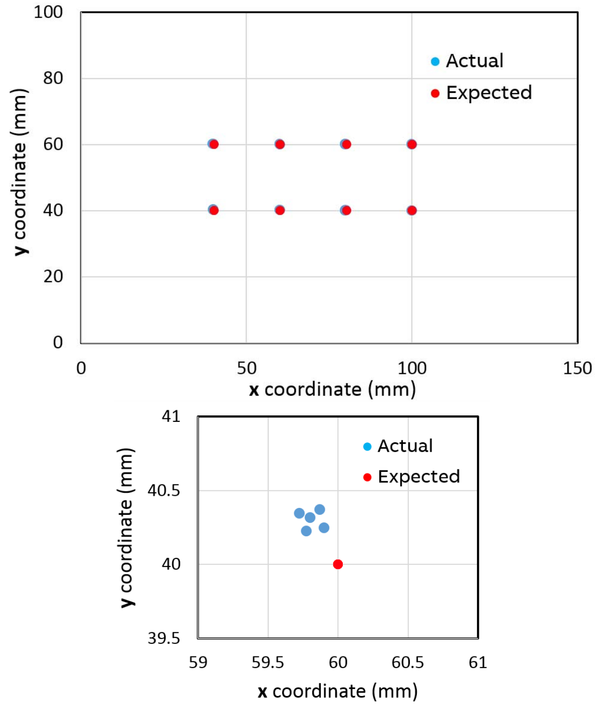

Fig. 11. Robot touching points at verification samples after calibration and a detailed view around point $(60, 40)$.

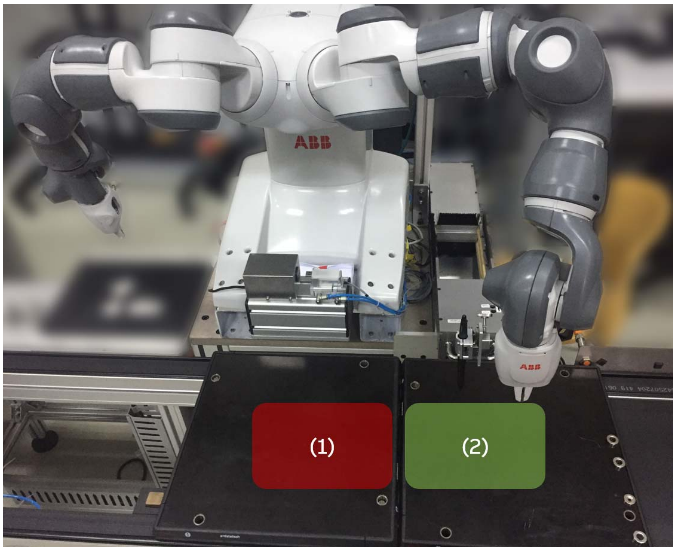

Fig. 12. Two locations to validate the locality.

As shown in Fig. 12, location 1 is where we calibrate Yumi, and location 2 is another place beside. With parameters identified at location 1, we evaluate the robot accuracy at both locations, of which the results are listed in Table II. At location 1, the mean and maximal errors are calculated during verification. As for location 2, we first conduct the robot cell calibration [24] to obtain the work object frame, after which

TABLE II
SPECIFICATIONS OF WACOM INTUOS PRO S WITH GRIP PEN

(in unit of mm)	Location 1	Location 2
Mean error before calibration	0.62	0.73
Max. error before calibration	1.17	1.35
Mean error after calibration	0.16	0.35
Max. error after calibration	0.35	0.73

the verification samples are taken.

Indeed, as we can see from Table II, after calibration the mean and maximal errors at location 2 are higher than those at location 1. This coincides with our argument about locality of calibration performance. At the same time, errors are smaller than those with initial parameters at each location, which implies that even though we target for the local absolute accuracy, the proposed calibration method can benefit places around the touch panel's location.

V. CONCLUSION AND DISCUSSION

In this paper, we propose to use touch panel as a cost-efficient measurement device to improve the robot's local absolute accuracy. The calibration system is described, and the problem of local absolute accuracy is properly formulated.

We carefully examine the system performance through experiments using Yumi robot. By the first case we show that Yumi's accuracy is increased with identified kinematic parameters than the nominal ones; in the second case, accuracy recovery from crash is demonstrated. Furthermore, by comparing the mean and maximal errors at the calibration location and another location beside, we discuss the locality issue of the proposed system. It can be concluded from the experiments that robot calibration with touch panel can effectively improve the local absolute accuracy.

REFERENCES

[1] B. Karan and M. Vukobratović. Calibration and accuracy of manipulation robot models - an overview. *Mech. Mach. Theory*, 29(3):479–500, 1994.

[2] S. Hayati and M. Mirmirani. Improving the absolute positioning accuracy of robot manipulators. *Journal of Robotic Systems*, 2(4):397–413, 1985.

[3] W. Veitschegger and C-H. Wu. Robot accuracy analysis based on kinematics. *Robotics and Automation, IEEE Journal of*, 2(3):171–179, 1986.

[4] R.P. Paul. *Robot Manipulators: Mathematics, Programming, and Control*. MIT Press, 1981.

[5] K. Okamura and F.C. Park. Kinematic calibration using the product of exponentials formula. *Robotica*, 14:415–422, 1996.

[6] I.M. Chen, G.L. Yang, C.T. Tan, and S.H. Yeo. Local POE model for robot kinematic calibration. *Mech. Mach. Theory*, 36(11-12):1215–1239, 2001.

[7] C. Li, Y. Wu, H. Lwe, and Z.X. Li. Poe-based robot kinematic calibration using axis configuration space and the adjoint error model. *IEEE Transactions on Robotics*, 32(5):1264–1279, 2016.

[8] R.P. Judd and A.B. Knasinski. A technique to calibrate industrial robots with experimental verification. *Robotics and Automation, IEEE Transactions on*, 6(1):20–30, 1990.

[9] C. Gong, J. Yuan, and J. Ni. Nongeometric error identification and compensation for robotic system by inverse calibration. *International Journal of Machine Tools and Manufacture*, 40(14):2119–2137, 2000.

[10] A. Nubiola and I.A. Bonev. Absolute calibration of an abb irb 1600 robot using a laser tracker. *Robotics and Computer-Integrated Manufacturing*, 29(1):236–245, 2013.

[11] G. Alici and B. Shirinzadeh. A systematic technique to estimate positioning errors for robot accuracy improvement using laser interferometry based sensing. *Mechanism and Machine Theory*, 40(8):879–906, 2005.

[12] C. Lightcap, S. Hamner, T. Schmitz, and S. Banks. Improved positioning accuracy of the pa10-6ce robot with geometric and flexibility calibration. *IEEE Transactions on Robotics*, 24(2):452–456, 2008.

[13] S.K. Mustafa, G.L. Yang, S.H. Yeo, and W. Lin. Kinematic calibration of a 7-dof self-calibrated modular cable-driven robotic arm. In *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, pages 1288–1293. IEEE, 2008.

[14] M.R. Driels and W.E. Swayze. Automated partial pose measurement system for manipulator calibration experiments. *Robotics and Automation, IEEE Transactions on*, 10(4):430–440, 1994.

[15] H. Zhuang, K. Wang, and Z.S. Roth. Simultaneous calibration of a robot and a hand-mounted camera. *Robotics and Automation, IEEE Transactions on*, 11(5):649–660, 1995.

[16] P. Rousseau, A. Desrochers, and N. Krouglicof. Machine vision system for the automatic identification of robot kinematic parameters. *Robotics and Automation, IEEE Transactions on*, 17(6):972–978, 2001.

[17] J.M. Motta, G.C. de Carvalho, and R.S. McMaster. Robot calibration using a 3d vision-based measurement system with a single camera. *Robotics and Computer-Integrated Manufacturing*, 17(6):487–497, 2001.

[18] A. Omodei, G. Legnani, and R. Adamini. Three methodologies for the calibration of industrial manipulators: Experimental results on a scara robot. *Journal of Robotic Systems*, 17(6):291–307, 2000.

[19] D.J. Bennett and J.M. Hollerbach. Autonomous calibration of single-loop closed kinematic chains formed by manipulators with passive endpoint constraints. 7(5):597–606, 1991.

[20] M.A. Meggiolaro, G. Scriffignano, and S. Dubowsky. Manipulator calibration using a single endpoint contact constraint. In *Proceedings of ASME Design Engineering Technical Conference, Baltimore, USA*, 2000.

[21] A. Rauf and J. Ryu. Fully autonomous calibration of parallel manipulators by imposing position constraint. In *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, volume 3, pages 2389–2394. IEEE, 2001.

[22] M. Ikits and J.M. Hollerbach. Kinematic calibration using a plane constraint. In *Robotics and Automation, 1997. Proceedings., 1997 IEEE International Conference on*, volume 4, pages 3191–3196. IEEE, 1997.

[23] H.Q. Zhuang, S.H. Motaghedi, and Z.S. Roth. Robot calibration with planar constraints. In *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, volume 1, pages 805–810. IEEE, 1999.

[24] Y. Cai, H. Gu, C. Li, and H. Liu. Easy industrial robot cell coordinates calibration with touch panel. *Robotics and Computer Integrated Manufacturing*. (Under review, available at https://abb-my.sharepoint.com/personal/cheng_li_cn_abb_com/_layouts/15/guestaccess.aspx?docid=078900534fb76468d98bde773d003a111&authkey=AZkGuDAuYFsi1E6FVtthwfo).

[25] R.M. Murray, Z.X. Li, and S.S. Sastry. *A Mathematical Introduction to Robotic Manipulation*. CRC press, 1994.

[26] Z.S. Roth, B. Mooring, and B. Ravani. An overview of robot calibration. 3(5):377–385, 1987.

[27] B.W. Mooring, Z.S. Roth, and M.R. Driels. *Fundamentals of Manipulator Calibration*. Wiley-interscience, 1991.

[28] ABB. *Yumi Data Sheet*. Online available at http://search.abb.com/library/Download.aspx?DocumentID=9AKK106354A3254&LanguageCode=en&DocumentPartId=&Action=Launch.

[29] Wacom. *Important Product Information, Intuos Pro Touch PTH-451, PTH-651, PTH-851*. Online available at http://cdn.wacom.com/f/ipi/0x0315/IPI-EN.pdf.