Proceedings of the 2015
IEEE Conference on Robotics and Biomimetics
Zhuhai, China, December 6-9, 2015

Base Frame Calibration for Multi-robot Coordinated Systems

Huajian Deng, Hongmin Wu, Cao Yang, Yisheng Guan* , Hong Zhang and Jianling Liu

***Abstract*— It is well-known that industrial robots are not very accurate. Robot calibration, which is one of the key techniques in robot off-line programming (OLP) as well as in robotics, is very helpful to increase the accuracy of robot motion. To solve the problem of base frame calibration for coordinated multi-robot systems, this paper proposes a simple and practical method, which is improved by three points calibration. It determines the base frame relationship for multi-robot systems. With laser sensors and a buzzer, the degree of accuracy has been enhanced. In order to integrate the process and the algorithm of the calibration method, a software has been developed. Experiment results have verified the validity and effectiveness of the proposed method.**

I. INTRODUCTION

Nowadays, industrial robots are becoming more and more widely used in different fields. Modern production needs more complex process, which makes great challenge for traditional single robot system. Therefore multi-robot manufacturing systems are on the way. Using multi-robot systems can increase efficiency, flexibility and capacity.

However, the coordination of multi-robot systems hinders its development. It is important to find out the base frame relationship between different robots, so that the coordination can be finished.

Base frame calibration, which is to determine the relative translation and rotation between base frames of coordinated robots, is a challenging and fundamental problem for coordinated multi-robot systems [1]. A direct measurement is unaccessible because the origins of the robot base frames are out of reach. Calibrations for an individual robot have already been investigated extensively and many effective methods have been developed [2], [3], [4]. Unfortunately, few studies have been made on this problem. Inspired by the calibration method in [5], [6], [7], [8], in this paper, a new kind of base frame calibration method is to be discussed. This method is evolved by three points calibration, and unlike the already known calibration methods, it needs no external calibration apparatus or elaborate setups. The great advantage of this method is the easy operational procedure and simple calibrating condition, which makes it quite feasible for use in manufacturing field. Fig.1 is a multi-robot systems. The robot on the left is robot A, the right one is robot B, and there is a positioner on the bottom.

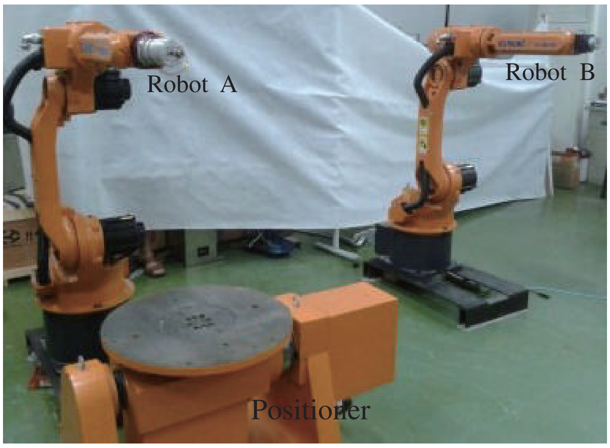


Fig. 1. Multi-robot systems

Details of the calibration method will be discussed in Section 2. Section 3 presents a calibration system. Calibration experiments are carried out in Section 4. The paper ends with concluding remarks in Section 5.

II. CALIBRATION PRINCIPLE

As is known, modeling single robot requires the link parameters, but for coordinated multi-robot systems the base frame relationship is also needed. Base frame calibration, which is a necessary condition for forming a closed kinematic chain, will be discussed in detail in this paper.

It is of importance to find out the relationship of base frame between two robots. This relationship is determined by representing one robot's base frame location and orientation in another robot's coordinate [9]. There are a lot of calibration methods to solve this problem. However, since tool calibration is expensive, this paper proposes a practical calibration method that is based on self-calibration. Some low-price tools are made to promote the accuracy of the calibration, and the process of the calibration is programmed so that it is convenient to use.

The location and orientation of a sub-coordinate can be expressed by the pose transformation matrix in its base frame. To determine the pose transformation matrix, the origin of the sub-coordinate and the directional cosines of its three axes need to be known. As is shown in Fig.2, the location of point O_1 has to be acquired to build the pose

All authors are with the School of Mechanical and Electrical Engineering, Guangdong University of Technology, Guangzhou, China, 510006. Y. Guan is the corresponding author, Email: ysguan@gdut.edu.cn. H. Zhang is also with the Department of Computing Science, University of Alberta, Edmonton, AB, Canada, T6G 2E8. J. Lin is with Guangdong Inspection and Quarantine Technology Center, China.

*The work in this paper is supported by the National Natural Science Foundation of China (Grant No. 51375095), the NSFC-Guangdong Joint Fund (Grant No. U1401240), the Natural Science Foundation of Guangdong Province (Grant No. S2013020012797, 2015A030308011), the State International Science and Technology Cooperation Special Items (Grant No. 2015DFA11700), the Frontier and Key Technology Innovation Special Funds of Guangdong Province (Grant No. 2014B090919002, 2015B010917003), and the State General Administration for Quality Supervision, Inspection and Quarantine (Grant No. 2014IK186).

978-1-4673-9675-2/15/$31.00 © 2015 IEEE

transformation matrix, but it is impossible to measure the exact location if point O_1 is in the rotational axis which is generally inside a robot. However, it is a fact that three points determine a circle. Suppose there is a circle centered on point O_1, the location of point O_1 is easy to calculate if we can get the coordinates of at least three points on the circle.

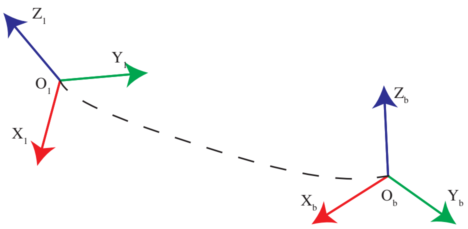


Fig. 2. Frame orientation

As for industrial robot, the coordinate of the end-effector can be attained from the teach pendant. So driving the end-effector to three different points on the circle and reading out their coordinates, then the center point is able to be solved. For the convenience of the robot, it is better to choose those special points to touch, such as the center point on the plate of a positioner, or some screw holes.

A. Positioner Calibration

To calibrate the location of a positioner, the first thing to do is to determine where the origin of the positioner's coordinate is and the directional cosines of its axes within the robot's base frame. Fig.3 shows the coordinate of the positioner. Coinciding the base frame of the positioner and that of the robot, which means connecting the robot's base frame with the positioner's first axis using the ground and the base of the positioner, makes it easy for calibration. Therefore, to get the location and orientation of the positioner, one only needs to figure out the relationship between the coordinate of the positioner's first axis and the robot's base frame.

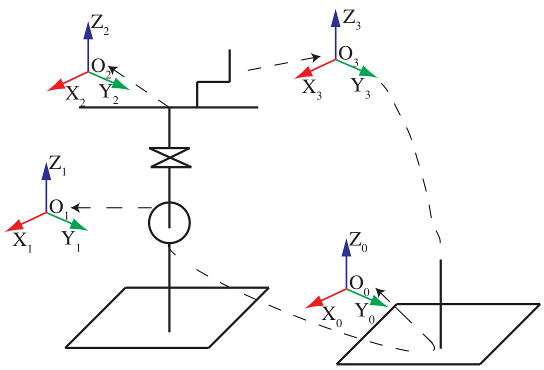


Fig. 3. Positioner coordinate

If the robot's tool center point (TCP) can be moved to the origin of the first axis of the positioner, then its location will be directly attained from the teach pendant. In fact, the origin of the coordinate is inside the positioner which is a solid body, so that it's impossible to touch that point by the robot's TCP. In that case, the location of the origin can only be attained indirectly.

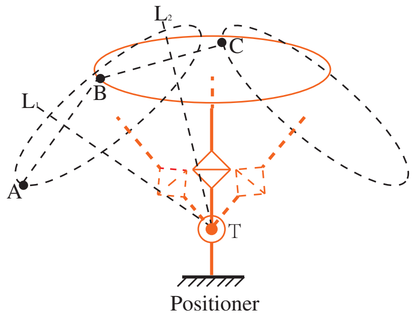


Fig. 4. Calibrate the origin

When the positioner moves, it rotates around its axis. So the origin of the coordinate is definitely on the rotational axis. As previously stated, three points determine a circle. In Fig.4, point B is at the end of the link, let the first axis rotates a certain angle, point B will arrive at a new spot. By this means, point A and point C are created. Since point A, point B and point C are in the same plane, so a circle is able to be made and point O_1, shown in Fig.4, will be its center. Suppose that $P_i(x_i, y_i, z_i)(i = 1, 2, 3)$ are three calibration points. The planar equation is

$$A(x - x_i) + B(y - y_i) + C(z - z_i) = 0 \qquad (1)$$

We can get the coordinates of point A, point B and point C from the teach pendant, and with equation(1) the normal vector $\vec{P}$ can be calculated as

$$\vec{P} = a\vec{i} \times b\vec{j} \times c\vec{k}$$

where $\vec{i}$, $\vec{j}$ and $\vec{k}$ are the unit vectors of the X, Y and Z axes respectively, $a = \frac{A}{\lambda}, b = \frac{B}{\lambda}, c = \frac{C}{\lambda}, \lambda = \sqrt{A^2 + B^2 + C^2}$.

We then attain the equations of line L_1 and line L_2, which are vertical to line AB and line BC respectively. And their intersection point is the center of the circle as well as the origin of the coordinate. After determine the origin, it still need to know the orientation of the X, Y and Z axes. Usually the Z axis is the same as the rotational axis which is written here as $\vec{P}$. Then let $\overrightarrow{O_1B}$ be the X axis. According to the rule of Cartesian coordinate system, $\vec{Y}$ can be calculated as $Y = \vec{P} \times \overrightarrow{O_1B}$. After unitizing $\vec{X}$, $\vec{Y}$ and $\vec{Z}$, we will get the translation and rotation matrix of the first joint coordinate within the base frame, which is

$$A_1^0 = \begin{bmatrix} O_1B_x & Y_1x & P_1x & O_1x \\ O_1B_y & Y_1y & P_1y & O_1y \\ O_1B_z & Y_1z & P_1z & O_1z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

In the same way, the translation and rotation matrix of the second joint coordinate can also be attained as

$$A_2^0 = \begin{bmatrix} O_2B_x & Y_2x & P_2x & O_2x \\ O_2B_y & Y_2y & P_2y & O_2y \\ O_2B_z & Y_2z & P_2z & O_2z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Since A_1^0 and A_2^0 are already known, which are the translation and rotation matrixes of the positioner within the robot base frame, if the translation and rotation matrix of the positioner's TCP can also be known, then the forward kinematics of the positioner is

$$T_3^0 = T_1^0 T_2^1 T_3^2 \tag{3}$$

The difference between T_1^0 and A_1^0 is that A_1^0 is constant and dose not take the joint angle into account. When the original frame rotates around the Z axis by a degree of θ. The relation between the new frame and the old one will be

$$A_\theta^1 = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

so we get

$$T_1^0 = A_1^0 A_\theta^1 \tag{5}$$

For $A_2^0 = A_1^0 A_2^1$, so $A_2^1 = (A_1^0)^{-1} A_2^0$, then we acquire

$$T_2^1 = (A_1^0)^{-1} A_2^0 A_\beta^2 \tag{6}$$

where β represents the angle that the positioner's second joint coordinate rotates.

At last, T_3^2, which represents the translation and rotation relation between the positioner's TCP and its second joint coordinate, needs to be determined. While the robot works with the positioner, their TCPs always touch each other at the same location. Thus we can replace the positioner's TCP with the robot's TCP. It has been mentioned above that the base frames of these two robots are coincident, so their TCPs are quite the same. Inverse the direction of the Z axis, then

$$T_3^2 = (A_2^0)^{-1} T_{TCP}^0 \tag{7}$$

where T_{TCP}^0 represents the orientation of the tool.

Now the complete forward kinematics of the positioner is

$$T_3^0 = A_1^0 A_\theta^1 (A_1^0)^{-1} A_2^0 A_\beta^2 (A_2^0)^{-1} T_{TCP}^0 \tag{8}$$

B. Dual Robots Calibration

To calibrate two industrial robots, take Fig.1 as an example. Robot A is regarded as a master, robot B is regarded as a slave. Before calibration, the forward kinematics of robot A and robot B, which can be calculated by $D-H$ method [10], are already known. They are

$$T_{A6}^{A0} = T_{A1}^{A0} T_{A2}^{A1} T_{A3}^{A2} T_{A4}^{A3} T_{A5}^{A4} T_{A6}^{A5} \tag{9}$$

$$T_{B6}^{B0} = T_{B1}^{B0} T_{B2}^{B1} T_{B3}^{B2} T_{B4}^{B3} T_{B5}^{B4} T_{B6}^{B5} \tag{10}$$

We can firstly decide the $\overrightarrow{X}$ and $\overrightarrow{Z}$ through an robot off-line programming system made by BIRL Lab [11], then multiply $\overrightarrow{X}$ and $\overrightarrow{Z}$ to get $\overrightarrow{Y}$. Specifically, before calibration, planning an arc path and a straight path along the X axis by off-line programming. As Fig.5 shows, point P_1, point P_2, point P_3 and point P_4, which are on XY plane, are planned by OLP. Let master robot's TCP and slave robot's TCP meet at these four points respectively. After that, read the coordinates of the robots from the teach pendant. From the mentioned above, the center point O_1 can be determined by point P_1, point P_2 and point P_3. The normal vector $\overrightarrow{O_1Z_1}$, which is regarded as Z axis, can also be attained. X axis can be decided by $\overrightarrow{O_1P_4}$, so Y axis is easily determined by multiplying $\overrightarrow{X}$ and $\overrightarrow{Z}$. In the end, the translation and orientation of the base frame for the slave robot is able to be worked out. It is

$$T_{B0}^{A0} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_x \\ n_z & o_z & a_z & p_x \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

where $\overrightarrow{n}$ is $\overrightarrow{O_1P_4}$, $\overrightarrow{o}$ is $\overrightarrow{O_1Y_1}$, $\overrightarrow{a}$ is $\overrightarrow{O_1Z_1}$, $\overrightarrow{p}$ is the distance between the base frames of robot A and robot B.

From equation (10) and equation (11), we attain

$$T_{B6}^{A0} = T_{B0}^{A0} T_{B6}^{B0} \tag{12}$$

which is the translation and rotation matrix for the TCP of robot B within the base frame of robot A. With this we can plan coordination between robot A and robot B.

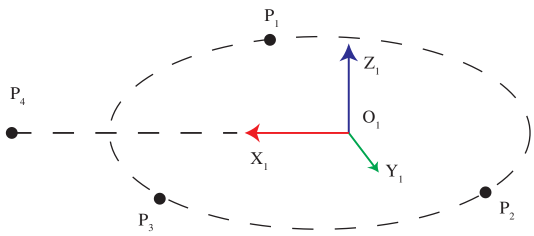


Fig. 5. Dual robots calibration

C. Multi-Robot Calibration

In coordinated multi-robot systems, the base frame relation among different robots plays an important role. So calibration must be done before a coordinated task is performed. To calibrate several robots simultaneously is of difficulty. Therefore we propose that since the base frame relation for dual robots can be solved out through the method mentioned above, we can repeatedly make calibration between two robots. As shown in Fig.6, the base frame relation between robot A and positioner can be solved out as T_p^A, and that between robot

A and robot B is T_B^A, so the base frame relation between robot B and positioner can be calculated as

$$T_p^B = (T_B^A)^{-1} T_p^A \tag{13}$$

According to this method, we can calibrate four, five and even more robots. Each of the different robots base frame can be described in only one coordinate system. After we know T_2^1, T_3^2, T_4^3, $\cdots$, T_{i+1}^i, we can attain

$$T_i^1 = T_2^1 T_3^2 \cdots T_i^{i-1} \tag{14}$$

where 1, 2, $\cdots$, i represents the base frame of robot 1,robot 2, $\cdots$, robot i.

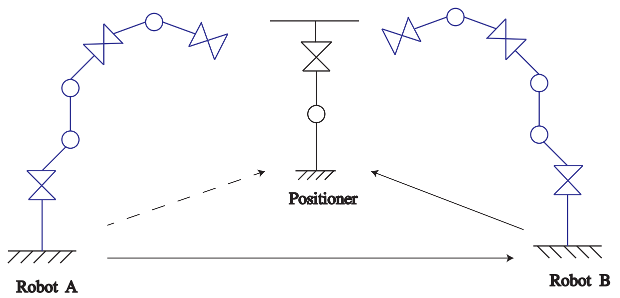


Fig. 6. Multi-robot calibration

This section proposes an improved calibration method for base frame between different robots, which is fundamental as well as necessary to multi-robot coordination. According to the calibration results, we can calculate the forward and inverse kinematics of the robot. By establishing the robot model and forming a closed chain of kinematics, the different robots' TCP can be described in the same coordinate. Based on that, this calibration method can be extended to multiple robots and unify their base frames within the same coordinate system.

III. CALIBRATION SYSTEM

The calibration principle has been discussed in previous section. However, in order to apply the calibration method into practical use, a calibration system is made. It consists of two parts: the hardware system and the software system.

A. Hardware System

When driving the end-effector to the chosen points manually, it is hard to reach the location precisely. A tiny deviation can cause great error. In order to ensure the accuracy, a device is made. It constitutes two parts. One serves as a pin, fixed on the end of the robot. The other serves as a hole, mounted on the plate of the positioner. The measuring device is easy to make, just like the description in Fig.7 shows. With the help of the measuring device, the calibration operation between two coordinated robots can be achieved relatively accurately. However it is still difficult to tell whether the pin is aligned with the hole merely by eye detection. Moreover it is easy to damage the tools when they touch each other too often, which will decrease the accuracy. For the sake of accuracy and intelligence, we improve our device by adding laser sensors and a buzzer. One laser emits and the other receives. As soon as the receiving end receives the laser signal, the buzzer screams, which means the pin is exactly aligned with the hole.

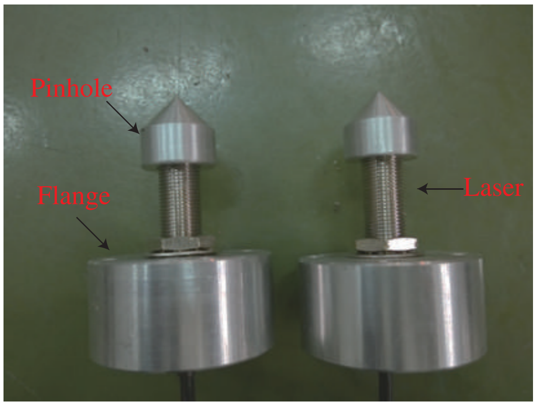
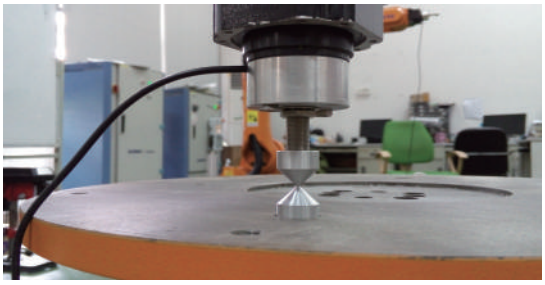
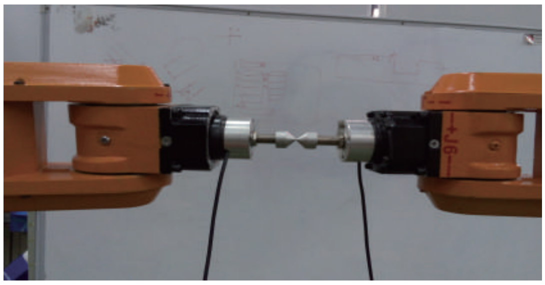


Fig. 7. Calibration device



a. Manipulator and positioner



b. Dual manipulators

Fig. 8. Calibration operation of different platforms

B. Software System

After acquiring the data from the chosen points, solving out the result is complex and hard. Thus the process and the algorithm of the calibration method are programmed into a software developed by Visual Studio 2010, which aims to simplify the calculation and get the answer quickly. The software contains two basic modules. Calibration for the positioner's forward kinematics and the base frame calibration for multi-robot systems. The flow chart will be shown in Fig.9.

The positioner calibration module provides two ways to input data. One is to enter the data into software point by

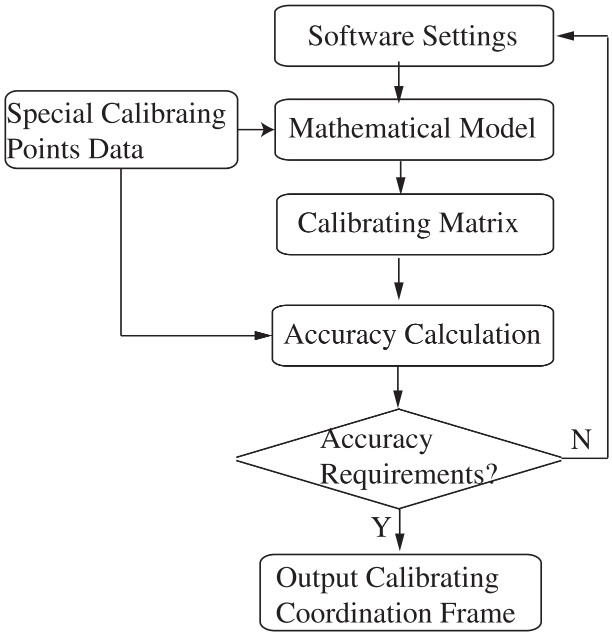


Fig. 9. Software flow chart

point, the other is to load a data file directly. The result will be calculated after one click, which is fast and accurate. The multi-robot calibration module is similar to the positioner calibration module. And the result will be worked out in a few steps.

IV. CALIBRATION EXPERIMENT

In order to verify the validity of the calibration method, a series of experiments are carried out. The devices for the experiment are two RB08 industrial robots and a HBS150 positioner, both of which are provided by Guangzhou CNC Equipment Co. Ltd. (GSK).

A. Positioner Base Frame Calibration

The base frame calibration for the positioner is of great significance. We firstly calibrate the positioner with the pinhole device, then lasers and a buzzer are used to increase the accuracy. In the process, choose some proper points and let the first axis of the positioner rotate -30, 0, 30 and 60 degrees respectively. 0, 80, 160 and 240 degrees are for the second axis rotation. Record the data and then enter into the calibration software. The results are shown as follows.

TABLE I

CALIBRATION WITHOUT LASER

	Origin 1 (mm)	Origin 2 (mm)
Solution 1	(1053.92,144.98,-107.91)	(1052.68,11.64,16.31)
Solution 2	(1053.99,145.96,-106.91)	(1051.86,11.98,16.43)
Solution 3	(1054.23,145.16,-106.58)	(1052.45,10.86,17.13)

Table.I shows the origin of the first and second axes of the positioner. Table.II shows the result attained by adding lasers and a buzzer. However, it is difficult to judge

TABLE II

CALIBRATION WITH LASER

	Origin 1 (mm)	Origin 2 (mm)
Solution 1	(1053.98,145.73,-107.96)	(1052.74,11.62,16.36)
Solution 2	(1053.87,145.94,-107.44)	(1052.49,11.81,16.68)
Solution 3	(1053.92,145.28,-107.66)	(1052.82,11.76,16.60)

TABLE III

RESULT COMPARISON

First link length (mm)	No laser	Laser	Theoretical value
Solution 1	124.22	124.32	
Solution 2	123.34	124.12	
Solution 3	123.71	124.26	
Average	123.75	124.19	125

whether the calibration result is accurate enough. There is no theoretical value of the distance between positioner and the robot, for the positioner can be placed at anywhere. We can calculate the length of the first link of the positioner from the calibration results and compare it with the theoretical value. The deviation in a degree indicates the accuracy. From table.III, we can see that the calculation of the first link length with laser is $124.19mm$, which is closer to the theoretical value than the one without a laser. The precision has improved by 0.36%. From the statistics listed above, we can conclude that the calibration method is feasible. Moreover we increase the accuracy of the calibration method by using laser sensors and a buzzer.

B. Dual Robots Experiment

The base frame relationship for multi-robot systems can also be acquired by means of the above calibration method. After finishing the calibration for the dual robots, we set up the kinematic model and carried out coupling motion and following motion experiments with dual robots. The experiments are demonstrated in Fig.10 and Fig.11. Fig.10 is dual robots following motion experiment. When a candle is placed on the positioner, the robot with a milling cutter moves as the positioner rotates. Fig.11 is a dual robot coupling motion experiment. The slave robot, with a fixed pen, painted a star onto the box held by the master robot. These experiments have verified the correctness of the base frame calibration for dual robots.

This section proposes a series of experiments to verify the validity and the effectiveness of the calibration method and software. In the positioner calibration experiment, the accuracy of the calibration is analyzed through a comparison between the theoretical value and the results.

V. CONCLUSIONS

In order to make sure the base frame relationship for multi-robot systems forms a closed-loop kinematic chain, this paper has proposed an effective calibration method for an industrial robot. Based on the already known calibration methods, we added laser sensors and a buzzer to improve

Fig. 10. Manipulator and positioner coordinating motion

Fig. 11. Dual manipulators coupling motion

the accuracy of the alignment and enhanced the validity by increasing data processing. This paper has calibrated the base frame relation between two robots, and proved the validity, feasibility and precision through experiments. On this basis, as long as we can calibrate the base frame relationship between two robots, then more robots' base frame relationship will be able to be attained by using the same method on each one.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions and help of Mr. Longxin Chen and Mr. Yihui Li in system set-up and experiments assistance.

REFERENCES

[1] M. D. Zivanovic and M. Vukobratovic, *Multi-arm cooperating robots: dynamics and control*. Springer Science & Business Media, 2006, vol. 30.

[2] I.-C. Ha, "Kinematic parameter calibration method for industrial robot manipulator using the relative position," *Journal of mechanical science and technology*, vol. 22, no. 6, pp. 1084–1090, 2008.

[3] Y. Meng and H. Zhuang, "Autonomous robot calibration using vision technology," *Robotics and Computer-Integrated Manufacturing*, vol. 23, no. 4, pp. 436–446, 2007.

[4] J.-U. Dolinsky, I. Jenkinson, and G. Colquhoun, "Application of genetic programming to the calibration of industrial robots," *Computers in Industry*, vol. 58, no. 3, pp. 255–264, 2007.

[5] J. Song, D. Yao, J. Hu, J. Ma, and J. Wang, "A novel calibration system for a space manipulator," in *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*. IEEE, 2006, pp. 4672–4677.

[6] G. D. van Albada, J. M. Lagerberg, A. Visser, and L. O. Hertzberger, "A low-cost pose-measuring system for robot calibration," *Robotics and Autonomous Systems*, vol. 15, no. 3, pp. 207–227, 1995.

[7] H. Zhuang, Z. S. Roth, and R. Sudhakar, "Simultaneous robot/world and tool/flange calibration by solving homogeneous transformation equations of the form ax= yb," *Robotics and Automation, IEEE Transactions on*, vol. 10, no. 4, pp. 549–554, 1994.

[8] R. G. Bonitz and T. C. Hsia, "Calibrating a multi-manipulator robotic system," *Robotics & Automation Magazine, IEEE*, vol. 4, no. 1, pp. 18–22, 1997.

[9] H. Wu, Z. Bi, M. Su, P. Zhang, Y. He, and Y. Guan, "Coordinated motion planning with calibration and offline programming for a manipulator-positioner system."

[10] J. J. Craig, *Introduction to robotics: mechanics and control*. Pearson Prentice Hall Upper Saddle River, 2005, vol. 3.

[11] Z. Yin and Y. Guan, "Off-line programming of robotic system based on dxf files of 3d models," in *Yinchuan, 2013. ICIA'08. IEEE International Conference on*. IEEE, 2013, pp. 1296–1301.