An Iterative Learning Strategy of Robot Manipulators with Spatial Perception

Chao. Cheng-Chuan, and Tsai. Ming-Hau

***Abstract*—Industrial robots that perform faithfully fixed trajectories or standard path commands are not enough to solve the problems caused by the deviations of workpiece size. For high positional accuracy, the development of robot manipulators with spatial perception is one of the achievable solutions. In order to make the robot manipulators sense spatial information, it needs to integrate proper sensors, such as a laser tracker that can accurately measure distances. Therefore, an iterative learning strategy of a robot manipulator with a laser tracker is described in this article. The proposed strategy is experimentally implemented on a six degree-of-freedom industrial robot manipulator. Experiment results show the effectiveness and functionality of the proposed method.**

***Index Terms*—Robot manipulator, Spatial perception, Laser tracker**

I. Introduction

NOWADAYS, the manufacture of industrial equipment is gradually going towards intelligence. Robot manipulators are widely used because of its flexibility. The robot applications include drilling, winding, grinding, polishing and other advanced machining processes. The path accuracy of the robot is a key factor to the applications mentioned above when robot manipulators execute a monotonous and repetitive motion in the manufacturing line. Common industrial robots have a good ability of repeatability about ±0.02 mm to ±0.3 mm. And the accuracy is approximately from 10mm to few millimeters. Fig.1 shows the definitions of accuracy and repeatability. In most of robot machining applications, however, the accuracy is necessary and mandatory. The drilling process is taken as an example, whose accuracy tolerance is usually ±0.25 mm. As for welding operations in automobile assembly, the accuracy requirements are usually within ±1 mm to ±2 mm.

In order to improve the results of robot applications, the accuracy and the tool center point of the robot manipulator both need to be measured and calibrated. The purpose of the accuracy measurement is to find out the positioning error of the robot manipulator. The accuracy is the difference between the command position and the actual position of the robot end effector. For example, if the robot controller sets a command to drive the robot to move 1mm and the robot actually moves 0.9mm, the positioning error is 1-0.9=0.1mm. By multiple position measurement and the optimization algorithm, the accuracy of the robot manipulator could be calibrated for the reduction of the positioning error. Similarly, when mounting a tool with a robot manipulator, the assembly and size of the tool would inevitably affect the accuracy of the robot manipulator in space. The typical approach of tool center point calibration refers to [1].

The calibration methods mentioned above could improve the path accuracy of the robot manipulator. However, in order to obtain the better effect on machining tasks, the robot manipulator needs to get spatial information of the workpiece and itself using sensors. The sensor that is most often used with a robot manipulator is a rotary encoder. The rotary encoder is attached to the motor shaft inside the robot manipulator hardware. The common use of the rotary encoder for positioning of the robot manipulator is to teach specified positions. After moving the robot manipulator to these positions on the workpiece, the robot controller records the position information (pulse number) of the rotary encoder. And then the robot manipulator could move to these specified positions by the command of the robot controller including position information. When performing the position-teaching method, the robot manipulator only faithfully completes the command from the controller. However, the robot manipulator may not be able to successfully complete the task, if the target position is slightly deviated. In the block diagram of the automation control system, the position-teaching method is a control law of the open-loop system, as shown in Fig. 2(a). One of the necessary approaches for the robot manipulator to be intelligent and automatic is to add additional sensors to make the robot manipulator be a closed-loop system, as shown in Fig. 2(b). By adding the sensors, the robot controller could instantly sense the position information of the workpiece during processing, and appropriately correct the machining path of the robot manipulator to cope with a variety of uncertain parameters on the production line, such as the workpiece dimensional deviation and position error of fixtures.

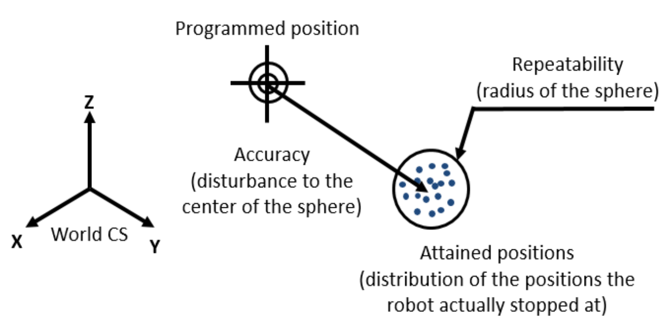

Fig. 1. Accuracy and repeatability.

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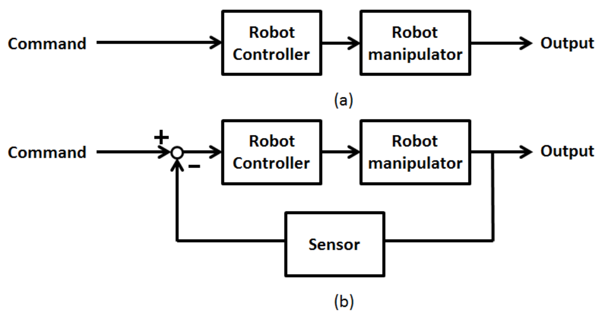

Fig. 2. Open-loop system and close-loop system.

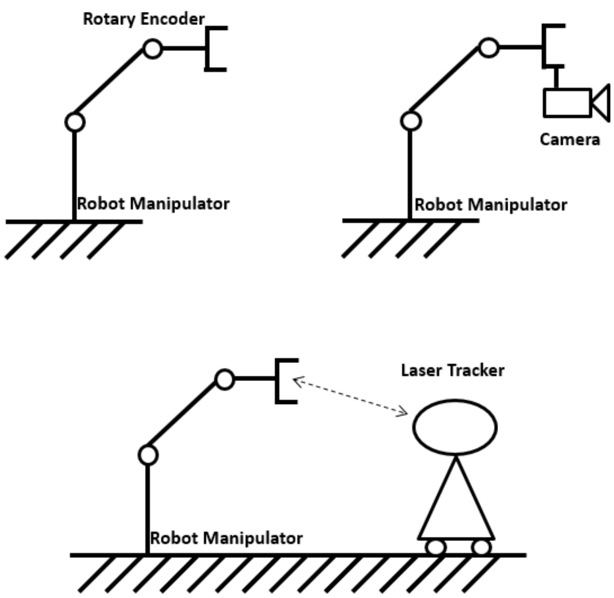

Fig. 3. Robot manipulator and sensors.

The operator on the production line has a variety of sensing capabilities and knows how to make adaptive action corrections in response to minor changes in the production line. Therefore, in order to provide the robot controller with intelligent sensing capabilities, it is possible to select the type of sensor to be additionally installed on the robot manipulator to imitate the operator's motion. Take the plug-in action of the electronic components on the circuit board as an example to illustrate the four sensors with the robot manipulator. Size differences of the circuit boards in different batches could result in inconsistent positions of the plug-in. The skilled plug-in actions of the operator can be easily classified into the following three steps in order. (1) When performing the plug-in action for the same type of electronic component, the plug-in task is completed by repeating the same human arm movement for a long time. (2) When replacing the electronic components of different types, the operator visually observes the general orientation of hole positions on the circuit board, and consciously reflect the angle at which the joints of the arm need to be rotated. The electronic components are intuitively held to be close to the hole on the corresponding circuit board. And then a successful plug-in is made. (3) If the plug-in action fails again and again, the operator observes the hole position at multiple angles and selects a certain direction to achieve plug-in purposes. According to the action characteristics of the above steps, the robot manipulator and the robot controller respectively have the appropriate sensor and the corresponding algorithm, so that the robot manipulator can imitate the operator action mentioned above. If the robot manipulator duplicates the motion of the first step, it only need to install the rotary encoder on the motor shaft of each axis of the robot manipulator, and then to use the position-teaching method to complete the successful insertion of the robot manipulator. After insertion motion, the pulse number of the rotary encoders are recorded. Finally, the robot controller uses a negative feedback algorithm to control each axis to reach the value of the rotary encoder previously recorded for each axis to accomplish the plug-in task. However, a fixed execution path can easily cause plug-in failures due to dimensional variations in circuit boards or electronic components. In order to determine the size difference, adding a camera to the robot manipulator is one of the feasible methods to increase the visual ability of the robot manipulator and to reduce the failure possibility in Step 1 mentioned above. This is the expected result of Step 2. In addition, the conversion relationship between the robot coordinate, the workpiece coordinate, and the camera coordinate is extremely important. The robot controller needs a complete coordinate conversion algorithm in order to correctly perform the positioning of the robot manipulator. However, in the process of coordinate conversion, the occurrence of errors is unavoidable. Even small errors could lead to a decrease in the success rate of precision plug-in motion. The laser tracker can provide multi-directional position measurement and can accurately measure the distance between the assemblies. The laser tracker can solve the shortcomings of the trial-and-error algorithm, long search time, to achieve the idea of Step 3. Fig. 3 shows respectively various relationships between the above three sensors and the robot manipulators. In summary, the robot manipulator needs to integrate multiple sensors for the ability to sense, so that the robot manipulator could simulate the motion of a human operator, such as vision and obtaining spatial information.

Based on the concept of the closed-loop system and sensors mentioned above, an iterative learning strategy of a robot manipulator with a laser tracker is described in this article. The proposed method is developed using sensor-based path optimization technology and the mapping function of CAD files and real workpieces for high machining path accuracy. The iterative learning strategy is to repeat the robot to move on the same trajectory. Meanwhile, the difference of the robot position or pose at the same time interval or in the same space is recorded. In the process of repeated robot trajectory, the path commands from the robot controller are corrected by the recorded differences. Therefore, the robot trajectory produced by the corrected controller commands gradually approaches to the initial expected trajectory.

II. ROBOT KINEMATICS AND TOOL CENTER POINT

A. *Robot Kinematics*

The robot manipulator commonly used in the industry is an articulated robot manipulator. The composition is composed of links and joints between links. Taking the n-axis robot manipulator as an example, the conversion relation between the (n)th coordinate and the (n-1)th coordinate is illustrated, as shown in Fig. 4 and (1), where $c = \cos$, $s = \sin$, and θ_i, d_i, a_i, α_i are defined as Denavit-Hartenberg (DH) parameters.

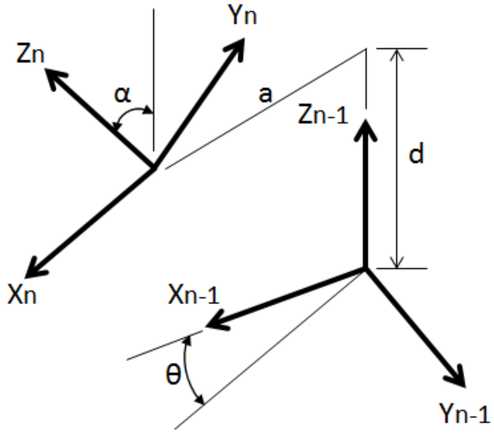

Fig. 4. Robot kinematics[3].

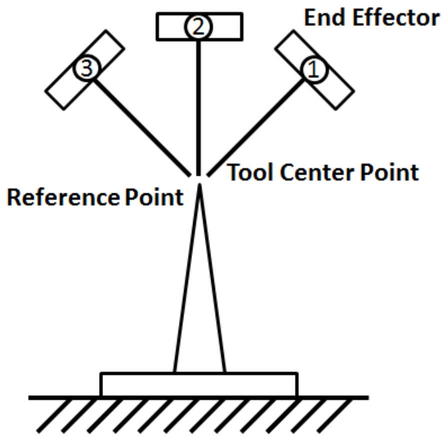

Fig. 5. Tool center point.

Substituting the exact DH parameters into the equation can calculate the precise position and pose of the end effector of the robot manipulator. However, unavoidable factors, such as dimensional tolerance of the mechanical component, geometric deviation of the assembly, and wear of the operation cause the DH parameter to be inaccurately measured. Indirectly, the position and pose of the robot manipulator are affected by the calculation result. The DH parameter calibration method is provided in [2].

$$A_i = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i s\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}, \; i = 1, \ldots, n \quad (1)$$

B. Tool Center Point, TCP

When considering practical industrial applications, the tool is mounted on the flange interface of the robot manipulator and the tool coordinate is defined. The origin of the tool coordinate is the end point of the tool and the point is also called the tool center point. It is inevitable that there would be size errors when tools are manufactured and assembled. In high-precision applications, such as precision manufacturing and surgical robots, the conversion between tool coordinate and flange coordinate needs to be calibrated. The common calibration techniques such as multi-point TCP calibration are shown in Fig. 5. The calibration method is to select a reference point in a space, and then the tool center point is controlled to touch the reference point in different robot pose, and the measurement data at different times of contact is recorded. The relationship between the TCP and the flange can be transformed to be an optimization issue. The corresponding parameters are further solved by the optimization. In actual engineering operations, since the reference point in the TCP method is determined by the human eye, the error will be made by the uncertainty of the human vision or the unobvious reference point. To avoid the error, the camera and the laser tracker could replace human vision. Using two cameras to establish stereo vision, the relative position of the TCP and the reference point can be calculated, and then the two points are contacted by the visual servo method to reduce the error. The installation of the cameras and the robot manipulator will be discussed in the next.

III. Robot Manipulators with Spatial Perception

Robot manipulators are widely used in the industry, for an example, the workpiece on the conveyor belt is picked and placed. The accuracy of the robot manipulator can be improved by DH parameter and TCP calibrations. The robot controller also needs to get the relative position of the end effector and the workpiece by sensors. The following describes the two sensors commonly used in the spatial positioning of the robot manipulator.

A. Image Sensor

The most common application of image sensors is the machine vision system. It integrates optics, electronics, and machinery to capture spatial images and uses computer algorithms to analyze image information. When the image sensor and the robot manipulator are integrated, more applications can be realized. The image can be captured by the camera and image processing methods can be performed to generate a variety of motion paths of the robot manipulator. In general, the configuration of the camera and robot manipulator can be divided into two modes: eye-in-hand and eye-to-hand. The eye-in-hand structure is to mount the camera on the flange of the robot manipulator, as shown in Fig. 6. The approach can greatly reduce the dependence on the workspace. The eye-to-hand mode is to place the camera in the working space, as shown in Fig. 6. If tasks require high-precision demands to accomplish, the conversion between the camera coordinate and the robot coordinate needs to be considered.

The eye-to-hand mode is to calibrate the camera and the robot coordinate. The other mode, eye-in-hand, is to calibrate the camera coordinate and the flange coordinate. The two coordinate conversion relationships mentioned above do not change, once the camera is fixed. The origin of the camera coordinates is usually on the camera's internal lens and the robot manipulator also has a slight size error during assembly. For the above reasons, the conversion between the two coordinates could be acquired using the hand-eye calibration method. Some studies of the hand-eye calibration can be referred to [4-7]. In the project of ITRI, the robot manipulator is equipped with a camera to perform machine vision positioning technology and to complete the automatic operations for loading and unloading workpiece, as shown in Fig. 7.

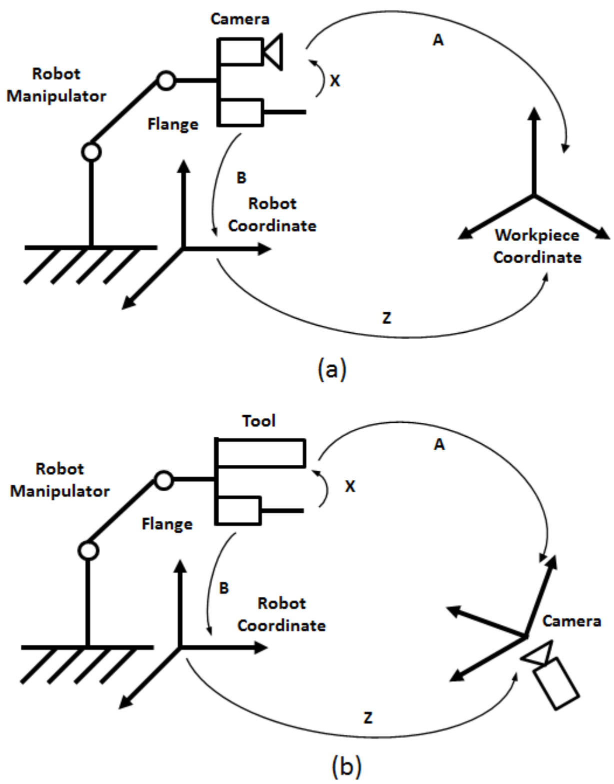

Fig. 6. Eye-in-hand structure and eye-to-hand structure.

Fig. 7. Machine vision and robot.

B. Laser tracker and robot calibration

Laser tracker is a high-precision coordinate measuring machine, consist of 5 components: retro reflectors, laser beam steering systems, laser interferometer systems, mechanical bodies, and control consoles, as shown in Fig. 8. Before the measurement, operator need to attach one retro reflector at the end-effector of the robot manipulator. Once the measurement start, laser source of the tracker emits a laser beam into the retro reflector. Later laser beam is reflected back to the tracker. The laser interferometer system accurately calculates the spatial position of the retro reflector. The detail operation of the laser tracker is provided in [1-2].

Laser trackerLeica AT901 is used in this paper, with its specification listed in Table I. As other measuring machine, the overall accuracy of the tracker depends on the working distance, with minimum range equal to 1 meter. The measurement error increases 5 um per 1-meter distance. The best measuring distance between robot manipulator and laser tracker is 1 ~ 2 meters longer than the working range of the robot manipulator.

Robot calibration is a must for high accuracy productions. It is necessary to understand the physical characteristics of the robot manipulator, such as robot arm length and payload before the calibration. Laser tracker is further introduced in the calibration procedure. Lots of motions are performed by the robot manipulator while each spatial position is recorded by the laser tracker. The ITRI robot controller performs an optimization analysis of the spatial data from laser tracker and the position commands of the robot, results in a set of robot parameters. Updating the robot parameters in the ITRI robot controller improves the accuracy of the robot manipulator. The operation method can be referred to [1-2]. With three robot manipulators with different lengths, Table II provides the calibration result.

IV. Close-Loop Strategy

Even with the improved absolute accuracy (positioning accuracy), deviations occur due to various reasons when the robot manipulator runs on different trajectories. To solve this issue, in this paper we collect errors in the position error generated when the robot manipulator runs the processing path, and establishes a closed-loop model for learning and compensation.

A. Introduction of iterative learning control

Iterative learning is a method of tracking strategy that work in a repetitive motion. The tracking accuracy is improved form repetition to repetition, by requiring the input data to track the reference exactly. The process uses information from the previous repetitions to correct the current control signal. The process is finished once the result meets the required condition.

As for robot manipulator, one trajectory is performed repetitively, at the same time record the coordinates of the end-effector via spatial perception. Modify the command in the repeated execution, so that the actual behavior fits the ideal trajectory. In this paper, the iterative learning strategy is refined in the processing path of the robot manipulator, as shown in Fig.9 below. The planning steps are as follows.

Step 1. Robot manipulator moves according to the specified trajectory, with laser reflector attached to the end-effector.

Step 2. Laser tracker continuously records the trajectory with 1 kHz sampling rate.

Step 3. Perform spatial comparison analysis with the specified path, calculate the pre-corrected node and offset.

Step 4. Adjust the motion commands for the pre-corrected nodes, and continuously measure the specified movement of the robot manipulator again

Repeat steps (1) ~ (4) until the error meets the conditions.

B. *Flow chart*

To reduce the position error of the robot manipulator under the required processing paths, error collection and compensation are carried out to solve the accuracy issue. Fig.10 is the architecture used in this paper. The DH parameters and TCP parameters of the robot are initialized in the step numbered 1 in the figure, using the algorithm mentioned in previous section.

Fig. 8. Laser tracker and robot.

TABLE I
SPECIFICATION OF LASER TRACKER

Item	Description
Brand	Leica
Type	AT901B
Resolution of Interferometer	0.32um
Accuracy of Interferometer	±0.5 um/m
Measuring Accuracy	Uxyz (MPE): ≦ ±10um+5um/m(in 2.5 x 5 x 10 m volume)
Measuring distance	distance:1-80m Horizontal angle: 360° Vertical angle: ±45°

TABLE II
COMPARISON OF ACCURACY BEFORE AND AFTER CALIBRATION [2]

Arm Length (mm)	Before Calibration (RMS error, mm)	After Calibration (RMS error, mm)	Verification Range (XYZ, mm)
650	0.69	0.10	1000 × 400 × 600
1500	12.89	0.10	2200 × 500 × 600
2000	4.55	0.37	2500 × 1500 × 1500

Sensor-Based path optimization technology repeatedly corrects the path in the step numbered 2 in the figure to minimize errors between ideal path and actual trajectory.

C. *Iterative learning strategy*

The iterative learning strategy used in this paper is shown in Fig. 11. Usually it takes more than 3 repetitions to reduce the tracking error. In order to save time, labeling is needed for those nodes that is already under control. Started from the second repetition, if the tracking error is less than the given threshold (0.1 mm), the index of the node will be labeled, thus no more recording of this node will be carried out in the following repetition. Compensation time will decrease after the third round begins.

D. *Result*

The iterative learning strategy in this paper is carried out via a simplified human machine interface. The coordinate transformation setting between the instrument and the work frame is calculated first. After that the iterative learning process begins to start automatically, it will also display the error of the node during the compensation process, as shown in Fig. 12 below.

The following Table III shows the learning results of one given path. Command and corresponding errors of nodes in the path are listed (excerpt). It can be seen that the error of most nodes can be controlled below 0.1 mm.

When the iterative learning strategy is completed, the modified command path will be generated. Once the processing procedure is about to start, the robot manipulator will run the modified command path, instead of the original command path. The error of the processing result depends on the error of the command path, repeatability of the robot manipulator, and the deviation caused by the stress during processing. Generally speaking, the final machining error can be controlled below 0.3 mm.

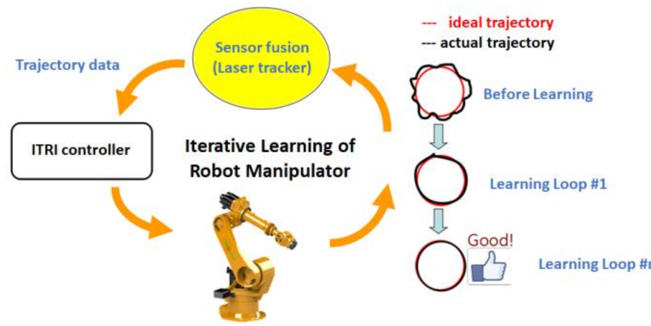

Fig. 9. Iterative learning.

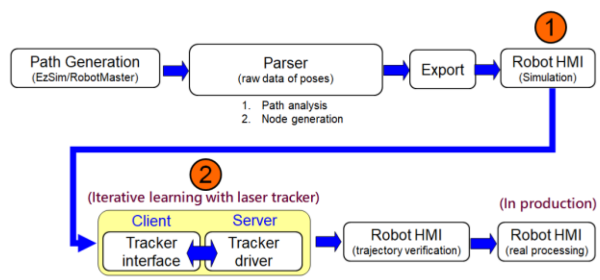

Fig. 10. Flow chart of iterative learning.

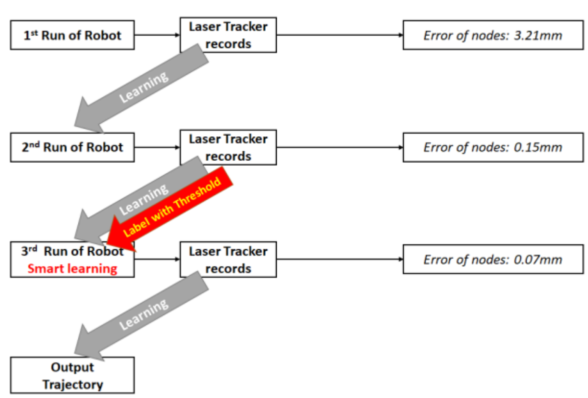

Fig. 11. Iterative learning strategy.

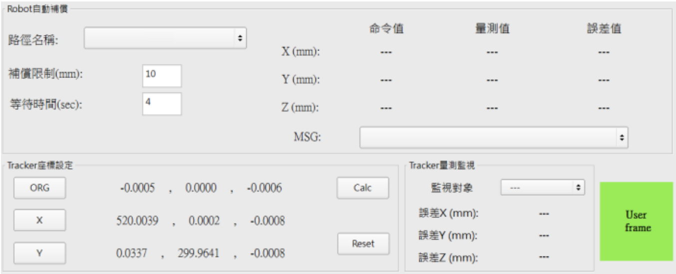

Fig. 12. HMI of iterative learning strategy.

TABLE III
RESULT AFTER ITERATIVE LEARNING

# node	Cmd. x	Cmd. y	Cmd. z	Error of x	Error of y	Error of z	Total Error
0	469.0318	34.1957	-43.3298	0.0328	-0.0602	0.0044	0.0687
1	469.0288	34.232	-119.542	0.0358	-0.0965	0.0165	0.1043
2	467.5507	70.1548	-143.322	0.035	-0.0435	-0.0375	0.0673
3	467.4753	71.8957	-144.52	0.0373	-0.0075	-0.0171	0.0417
4	467.4364	72.7632	-145.095	0.0397	0.0135	-0.0305	0.0518
5	467.3677	74.5467	-146.278	0.0354	0.0069	-0.0244	0.0435
6	467.3007	76.4698	-147.531	0.024	-0.0098	-0.0342	0.0429
7	466.1356	76.4855	-147.367	0.0212	0.0421	-0.0467	0.0663
8	465.0859	76.7674	-146.963	0.045	0.0289	-0.0433	0.0688
9	464.5052	77.0526	-146.568	0.0522	0.0164	-0.0498	0.074
10	464.0109	77.3962	-146.076	0.0523	0.0317	-0.0462	0.0767
11	463.6192	77.9053	-145.427	0.0456	0.0046	-0.0433	0.0631
12	463.397	78.631	-144.484	0.0527	-0.0001	-0.0315	0.0614
13	463.381	79.7188	-143.066	0.0372	-0.0093	-0.0369	0.0532
14	463.3657	80.2312	-142.411	0.0375	-0.0078	-0.019	0.0427
15	463.3373	81.7256	-140.432	0.0223	-0.0117	-0.0472	0.0535
16	463.2493	83.2656	-138.428	0.0252	-0.0179	-0.0402	0.0507
17	463.1308	84.8405	-136.421	0.0555	-0.06	-0.0404	0.0911
18	463.0314	86.358	-134.403	0.0666	-0.0455	-0.0507	0.0952
19	462.9359	87.8809	-132.418	0.0736	-0.0371	-0.0278	0.087
20	462.8601	89.4026	-130.415	0.0606	-0.0265	-0.0228	0.0699
21	462.813	90.6521	-128.716	0.0524	0.0083	-0.0283	0.0601
22	462.786	92.1353	-126.718	0.0346	0.0189	-0.0373	0.0543
23	462.7602	93.4	-125.081	0.0233	-0.0096	-0.0292	0.0386
24	462.7428	94.6117	-123.417	0.0037	0.015	-0.0464	0.0489
25	462.7211	95.8481	-121.781	-0.0115	0.0149	-0.0364	0.041
26	462.67	97.075	-120.14	0.0025	0.0261	-0.0332	0.0423
27	462.6111	98.3228	-118.492	0.024	0.0199	-0.0392	0.0502
28	462.554	99.5528	-116.867	0.0438	0.0315	-0.0215	0.058
29	462.5234	100.7849	-115.219	0.0371	0.041	-0.027	0.0615
30	462.4828	102.016	-113.567	0.0405	0.0516	-0.037	0.0753
31	462.4446	103.2607	-111.924	0.0415	0.0486	-0.0378	0.0743
32	462.4066	104.5146	-110.271	0.0423	0.0369	-0.0482	0.074
33	462.3618	105.7441	-108.648	0.0495	0.0543	-0.0332	0.0807
34	462.3254	107.0149	-107.008	0.0486	0.0307	-0.0342	0.0669
35	462.2973	108.2505	-105.355	0.0403	0.0432	-0.0455	0.0746
36	462.2655	109.4893	-103.719	0.0356	0.0524	-0.0411	0.0755
37	462.2269	110.7328	-102.07	0.0378	0.057	-0.0485	0.0838
38	462.1685	112.0225	-100.451	0.0599	0.0155	-0.026	0.0671
39	462.1237	113.2867	-98.8081	0.068	0.0035	-0.0312	0.0748

V. CONCLUSION

Robot manipulator is the key component to meet the increasing demand for automation devices. To guarantee the yield rate of the production line, absolute accuracy of the robot manipulator and the accuracy of the trajectory need to be improved.

In this paper we briefly introduce the sensors integrated with the robot manipulator. Using laser tracker to acquire the position of the robot manipulator for calibration. Increasing the positioning accuracy first, and further introduce a set of strategy to reduce the trajectory error of a given path. Overall this strategy improves the production yield.

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