Research on Environment for Industrial Robot Performance Evaluation

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Abstract

In this article, several technologies regarding industrial robot tests are analyzed, and a test environment for industrial robots is developed. Robot test processes and test principles are described. Questions and doubts about the standards are discussed. Accuracy of laser trackers is analyzed. Coordinate system calibration problems are discussed, and solutions are shown. Pose accuracy and pose repeatability test results from the test environment are shown and analyzed. At last, a test software environment is designed.

Keywords: Robot; Performance; Environment Evaluation

1. Introduction

1.1 Industrial Robot

As defined by International Organization for Standardization (ISO), an industrial robot is automatically controlled, reprogrammable, and multipurpose manipulator programmable in three or more axes [1]. Today, industrial robots and robotic systems have already become key components in various industry sectors. According to IFR (International Federation of Robotics) [2], more than 1.1 million industrial robots are implemented over the world.

The first industrial robot 'Unimate' was developed by George Devol and Joseph Engel berger in the company named Unimation. It weighs two tons and was controlled by a program on a magnetic drum. Two years later, the first industrial robot was installed at GM's production line. Soon after the first industrial robot was born, different kinds of industrial robots came to market. Some of the milestones were: in 1973, KUKA, a German company, developed the first robot that with six axes of freedom. In the same year, ABB Robotics (formerly ASEA) introduced IRB 6, the first all-electric micro-processor controlled robot that became commercially available. In 1978, Unimation/Vicarm, USA with support from General Motors, developed Programmable Universal Machine for Assembly (PUMA).

In recent years, huge numbers of industrial robots have been developed. Some of them were developed for special usage, while others were developed for multi-tasks. In 1998, ABB, Sweden, developed FlexPicker, the world's fastest picking robot. In 2004, the first synchronized control system of robot was provided by Motoman, Japan. In 2006, KUKA presented the first Light Weight Robot, the outer structure of the robot was made of aluminum, and the integrated sensors made it ideally suitable to handling and assembly tasks. Recently, developments of machine learning technology started to influence industrial robot sectors. In 2010, FANUC's Learning Vibration Control was introduced, which allowed the robot to learn its vibration characteristics for higher accelerations and speeds which reduce the cycle time of the robot motion by suppressing the vibration of the robot arm. Today, industrial robots and robotic systems have already become the key component of automation. It has been reported that the industrial robotic business is approaching a mature state [3]. One trend of developments is downsizing robots for light industrial usage such as production of small products, sealing and dispensing, quality control, and handling samples in laboratories. Another trend is lower cost and easily programmable robots, which have lower capacity, lower speed and most importantly, lower cost.

1.2 Problem Description

After a new industrial robot model is developed, robot manufactures have the responsibility to test it before the new model hits market. For manufactures, it is essentially important to test different industrial robots with a reliable testing environment. In this article, a testing environment for industrial robots is introduced. The final goal of the article is to develop a functional industrial robot testing environment. The testing environment should be able to provide results, which reflect robot performance characteristics.

A general industrial robot testing international standard is available. ISO 9283 [4] is the latest international standard for industrial robot test. ISO 9283 standard defines performance criteria and related test methods for general industrial robots. The standard assists robot users to understand their robots, and helps robot producers define their products. It specifies performance parameters for robots and how these parameters should be defined, as well as how the parameters shall be tested. The standard describes methods for testing performance characteristics such

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as pose accuracy and pose repeatability, position stabilization time, position overshoot, path accuracies, path repeatability and minimum posing time.

Figure 1: Laser tracker with tested Robot

In our case, to perform industrial robot tests, a measurement instrument is needed. Luckily, a distance measure instrument is available; a laser tracker shown in Figure 1 is a device that can precisely measure the distance between itself and a reflector. The reflector is mounted on the end elector of tested robot arms. Another important character for the laser tracker is that it can not only measure a target but also track the target. If we fix the reflector on the end elector of a robot, with the help of the laser tracker, we will be able to record end elector position of the robot in real time even if end elector is moving.

Apart from the ISO 9283 standard and the laser tracker, this article involves several different kinds of analysis and programming tools. For example, Matlab is used as data analysis tool. Laser tracker SDK that we need to use is available in C++ format. LabVIEW software is chosen as a programming language. For data communication part, a socket communication protocol is used. As a computer science project, different data analysis algorithms are applied in data analysis.

However, with utilities above, several problems are still needed to be solved: Firstly, since the ISO9283 standard is available, a robot test environment should be easy to implement. However, with the growing capacity and diversity of industrial robots, industrial robot test requirements are changing. In this sense, the standard is not perfect.

2. Related Work

Robot manufacturers have responsibility to inform users the capability of the robot. With the growing needs of industrial robots, the requirements for robot testing are growing as well. As we introduced in section 1.2, main three theory related problems need to be solved in this article. Related work will be reviewed in three sections, covering robot test methodologies, measurement tools and coordinate system calibration methods.

2.1 Robot Test Methodologies

There are many robot test methods proposed in literature that have no relation to the ISO standard. Samah provided a general method for robot performance evaluation of mixed operational degrees of freedom robots[5]. In Ken Young's work[6], they assessed static positioning accuracy and static positioning repeatability of an industrial robot. However, they also concluded that measuring straightness errors (different from path accuracy) in an industrial robot have no practical interest. Slamani claimed that the bidirectional positioning performances were never mentioned by the ISO standard[7] The paper gave a description about backlash error measurement and its elect on bidirectional repeatability. Several factors were taken into account, such as degree of polynomial representing, tool center point (TCP) speed, and payload. In Filip's paper [8], instead of using a laser tracker, a vision based monitoring method was used to perform measurement. It used a pattern to provide feedback to a vision system. The paper did not mention the ISO standard, but it still gave the review of a whole measurement methodologies. Measurement methodologies were introduced for robot repeatability tests, backlash tests, drift monitoring, encoder offset identification, and the potential usability in environment calibration. Ahmad evaluated a flexible robot manipulator [9]. The work is based on active vibration control schemes. There are many other papers that discuss robot performance evaluation in different applications [10-17].

ISO standard was used in many proposed solutions. In Kim's paper, they tested robot straightly according to ISO9283 [18]. They explained in detail the test process. The performance criteria they use were: position accuracy and repeat accuracy, position overshoot and stabilization time, multi-direction position accuracy deflection, distance accuracy and distance repeat accuracy, mini pose time. In Hu's paper[19] , the author described the process of developing multi-laser tracker measurement technologies. The measurement was performed according to the ISO9283 standard. A software system was developed to control multi-laser trackers for collaborative measurements by applying tracker-programming-interface (EMSCON). Moreover, this paper gave a clear overview of the working principle of EMSCON system, and even had an error rate analysis of measurements. It was concluded that collaboration of laser trackers would significantly improve the accuracy of measurement results.

Some literature presented tests according to the ISO9283 standard, but they also raised their own questions about this standard. Mohamed performed robot measurement using three different types of equipment on an ABB IRB 1600 industrial robot based on the ISO9283 standard [20]. It was shown that, for repeatability test, since two of the five poses are closer to the workspace boundary, they are naturally better than other poses. They claimed there is almost no information about robot performance evaluation methods except for ISO9283. However, they also found information such as linear path repeatability and linear path accuracy might sometimes be obtained from the robot manufacturer, and also proved to be highly insufficient and impossible to use. Park's paper mentioned the evaluation process of an industrial dual-arm robot [21]. The evaluation process followed exactly the ISO9283 standard. No significant improvement was made, except for the evaluation process. It highlights that in the ISO standard, there is nothing mentioned about payload. In real test cases, measurement always takes the highest payload. It is reasonable that in the test field, the highest payload should be chosen. However, there are requirements for performance evaluation of different payloads, since users will not always use the largest payload. In the article, a robot has two arms, while there is nothing mentioned in ISO standard about how to measure dual-arm robot.

Based on above literature review, we find useful examples of ISO 9283 standard applied in real application. However, we also find questions and doubts about the standard.

2.2 Measurement Tools

There are also many papers regarding applications or analysis of measurement tools. The laser tracker is one of the most accurate measurement tool for robot applications. In Juretzko's work[22], an example of measurements using a laser tracker was shown. The measurement result is contributed by three factors: lateral component, vertical component and longitudinal component. The measurement is simply conducted between two positions, which is considered as a specific case-need test. Ouyang's paper studied how time and temperature affect measuring accuracy of a laser tracker system [23].

Coordinate system calibration

The experiments showed that a tracker system could work well with the highest measuring accuracy just after three hours of warm up. However, the system will be unstable, and accuracy will decrease after 10 hours of work. In this case, they suggested that laser tracker systems should be calibrated and compensated every 10 hours. Their experiments showed that measurement errors can reach up to 0.03 mm when the measure temperature is 30.5 Celsius degrees, while the measurement error will be less than 0.006 mm when temperature is between 20 and 23.8 Celsius degrees. This research provided guidance for applications of laser tracker systems. Herrmann's paper presented experiments and results to determine the position on industrial robots and to evaluate the synchronization of co-operating robots using laser trackers [24]. The emphasis of laser tracker usage here was on collaboration. Effort was given on analyzing data collected from a laser tracker. The application was not fully introduced, but it seems that they did not use the ISO standard, which also was an indication that the standard was not suitable for this application. In Dabao's paper [25], the majority of the work was done on analysis measurement data. The interesting part was about accuracy improvement of laser trackers, which was a good example for later computation. The paper conducted a step-by-step system calibration. An accurate adjustment model was established, and calibration parameters were classified into intrinsic and extrinsic parameters. The measurement model was improved, and an arbitrary position laser plane intrinsic parameters calibration method was studied. Instead of laser tracker, in Hager's approach[26], a stereo vision tracking system was used. The two camera tracking systems track the robot end-elector based on the visual distance between the end-elector and visual features. The results showed that the system was robust with accuracy of several centimeters; while compared with laser trackers, it was still not accurate enough. Chen's paper provides a overview of 3D optical measurement methods including most of the robot measurement method such as laser trackers, stereo cameras, interferometers, time of flight etc[27]. The paper compared different light technologies, optical configurations and data processing methods. Several industrial application examples were presented as well.

Based on above literature review, useful experiences can be learned. Meanwhile, we also find research regarding factors that could influence the accuracy of laser trackers. In order to understand the accuracy of laser trackers, our laser tracker should be tested.

3. ISO Test Principles

As we mentioned above, in the ISO9283 standard [5], the performance criteria and related test methods of manipulating industrial robots are defined. In this section, we will briefly introduce and analyze parts of the ISO standard [4].

3.1Test Environment

In this subsection, the test environment will be described. The ISO test happens within a certain space called ISO cube. The ISO cube is located in the working space and satisfies following requirements:

- ISO cube should be located in the part of working space with the greatest anticipated use.
- The cube should have the maximum volume allowable with the edges parallel to the base coordinate system.

Usually, tests are performed based on five positions. The five test positions are located in a plane (test plane) placed inside a cube (ISO cube) within the robot working space. The test plane is the plane where tests happened on. Usually, the test plane should be pre-defined. Therefore, it is also called selected plane. For example, Figure 2 shows a ISO cube[4]. The five test positions are located on test plane (selected plane) $C_1 - C_2 - C_7 - C_8$.

In Figure 3, we could see that the wrist reference points are located on the selected plane. Usually, we could not perform measurement on selected planes directly. Measurement is performed on measurement planes. We could see from Figure 3 that the measurement plane is parallel to selected planes[4]. Five measurement points are located on the diagonals of the measurement plane. In Figure 4, P_1, P_2, P_3, P_4 and P_5 are the positions for the wrist reference points of the robot[4]. P_1 is the intersection of the diagonals. It is the center of the ISO cube. The points P_2, P_3, P_4 and P_5 are located at the diagonals with (10 ± 2) percent of the length from the ends of the diagonals.

Pose characteristic tests usually are the essential part of ISO test. The pose characteristic tests include: pose accuracy and pose repeatability, multi-directional pose accuracy variation, distance accuracy and distance repeatability, position stabilization time, position overshoot, drift of pose characteristics, and exchangeability. Among these tests, the most important test is usually pose accuracy and pose repeatability tests. Thus, we will present two tests to demonstrate our test method, where pose accuracy and pose repeatability tests will be introduced in the following subsection.

3.2 Pose Accuracy and Pose Repeatability Test Conditions

Pose accuracy and pose repeatability actually have the same test conditions, but they use different calculation methods.

The test starts from P_1, and the robot end elector successively moves to P_5, P_4 , P_3, P_2, P_1. Each of the positions should be visited with a unidirectional approach. The movement should be repeated 30 times. At the end of the test, for each position, pose accuracy and pose repeatability are calculated.

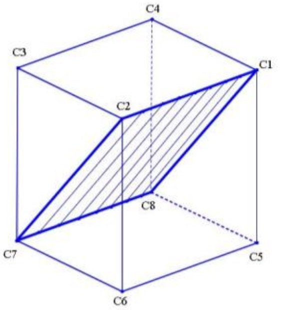

Figure 2: Example of ISO cube

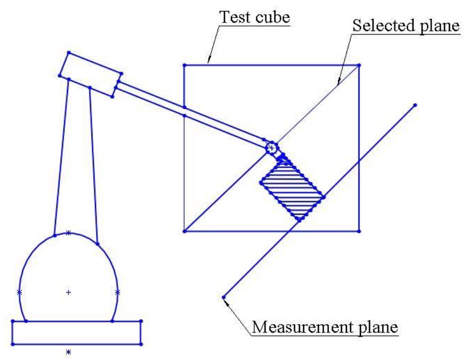

Figure 3: Measurement planes

Data selection

After we understand test conditions, it is important to process raw data; here we will briefly introduce data selection principle.

As we mentioned in above section, the five positions are visited successively and repeated for 30 times. Since our laser tracker measures in a continuous mode, we will get a data sequence as results. The data sequence includes the five positions measurement results and the moving end electors positions between them. However, only the five positions measurement results are useful. Therefore, we need to first remove the moving end elector positions data. Normally, our laser tracker records 100 data points in 1 second. Our robot will stop for 5 seconds in each position. Since the measurement is repeated for 30 times, for each position, we will get 15000 data points. It is crucial to select representative data from the 15000 data points.

Pose Accuracy

Pose accuracy reflects the deviation between commanded poses and the mean of the attained poses when the robot is commanded to approach the commanded poses from the same direction. Pose accuracy includes position accuracy and orientation accuracy, but we only consider position accuracy here.

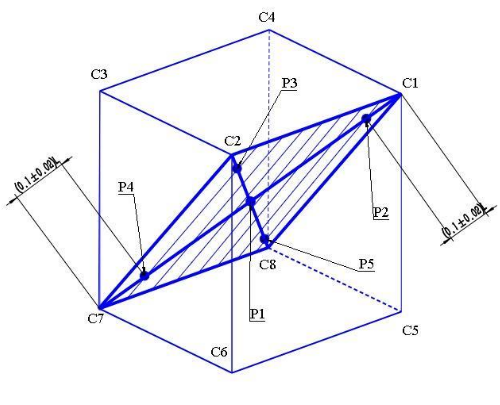

Figure 4: Example of test poses

As we could see from Figure 5, pose accuracy PA_p actually is given by the difference between commanded poses (x_c, y_c, z_c) and averaged attained poses ($\bar{x}$, $\bar{y}$, $\bar{z}$)[4]. (PA_x, PA_y, PA_z) is pose accuracy from x, y, z axis.

$$PA_P = \sqrt{\left(\bar{x} - x_c\right)^2 + \left(\bar{y} - y_c\right)^2 + \left(\bar{z} - z_c\right)^2} \quad (1)$$

$$PA_x = \left(\bar{x} - x_c\right) \quad (2)$$

$$PA_y = \left(\bar{y} - y_c\right) \quad (3)$$

$$PA_z = \left(\bar{z} - z_c\right) \quad (4)$$

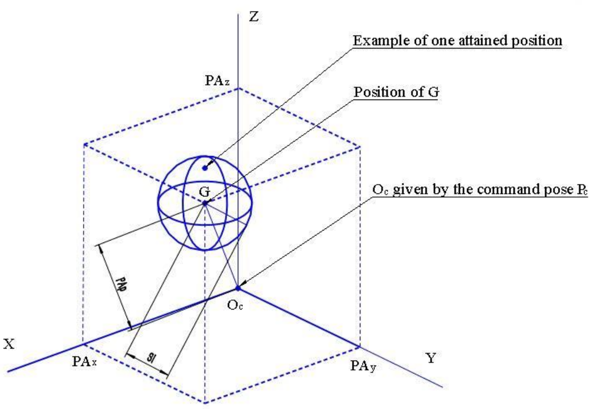

Figure 5: Pose accuracy and pose repeatability

Where the average ($\bar{x}$, $\bar{y}$, $\bar{z}$) is given by the measurements of i-th attained pose (x_i, y_i, z_i).

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (5)$$

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \quad (6)$$

$$\bar{z} = \frac{1}{n}\sum_{i=1}^{n} z_i \quad (7)$$

In order to obtain pose accuracy, we need to collect (x_i, y_i, z_i) (attained poses) and (x_c, y_c, z_c) (commanded poses) from raw data. Attained poses can be collected by the 30 measurements. However, commanded poses are difficult to obtain. In ISO standard, there is no solution provided. A solution is provided from industry. It suggests one more measurement of the five positions, which is separated with the 30 measurements. In this separated measurement, the robot end elector successively moves to P_5 , P_4, P_3, P_2 and P_1 . At each position, the measured value should be recorded as commanded poses. However, this solution is not perfect, since such measurements would not correspond to the true commanded poses. This solution gives ground truth (commanded poses) provided by measurement system itself. Therefore, there is no difference between commanded poses and attained poses. Even with the same setup, we could expect very different pose accuracy results from one trial to the next, depending on what you use as your reference point. We believe this solution is wrong. The pose accuracy test results are useless.

Pose Repeatability

Pose repeatability introduces us the closeness between the attained poses after n repeating visits to the same command poses in the same direction. In Figure 5, we could understand the value of pose repeatability is the radius of sphere whose center is the bar center[4]. Pose repeatability PR_l is defined as follow:

$$PR_l = \bar{l} + 3S_l \quad (8)$$

with averaged deviation l, given by

$$\bar{l} = \frac{1}{n}\sum_{i=1}^{n} l_i \quad (9)$$

Where l_i is the deviation between i-th attained poses and averaged attained poses,

$l_i = (\bar{x} - x_i)^2 + (\bar{y} - y_i)^2 + (\bar{z} - z_i)^2$ (3.40) Here S_l represents standard deviation of l_i.

$$l_i = \sqrt{\left(\bar{x} - x_i\right)^2 + \left(\bar{y} - y_i\right)^2 + \left(\bar{z} - z_i\right)^2} \quad (10)$$

$$S_l = \sqrt{\frac{\sum_{i=1}^{n}\left(l_i - \bar{l}\right)^2}{n-1}} \quad (11)$$

In order to obtain pose repeatability, we only need to collect (x_i, y_i, z_i) (attained poses).

3.3 ISO Test Analysis

As we introduced above, the pose accuracy test represents a mean error between the poses robot attained and the poses users commanded. The pose accuracy calculation method assumes the commanded poses (x_c, y_c , z_c) are known, while in reality, we never get this knowledge. We only have access to sensors separated with robot arms, which will contain a different coordinate system compared to that at the robot arm. In other words, we could only get measured poses, which are different from commanded poses.

3.4 ISO test principles

As we introduced above, ISO standard does not provide a solution, while in industry, a wrong method is applied to obtain commanded poses. The pose accuracy test results are useless. This is a very big problem, which causes lots of problems and confusions. In the future, ISO standard should provide a solution.

Pose repeatability introduces us the closeness between the attained poses after n repeating visits to the same command pose in the same direction. The ISO standard assumes that measured positions are prefect. However, in reality, different measurement methods and data selection methods will largely affect measurement results.

We also have doubts about the general measurement concept of ISO standard. As we introduced, the ISO test is preformed on a test plane. However, in reality, robot arms will not just work on this plane. In fact, robot working space could be bigger than the ISO cube. The ISO test results will help us understand robot performance in the ISO cube. However, in the robot working space other than the ISO cube, robot performance information is unknown. Moreover, different ways of selecting test planes will also affect test results. In fact, there are six different test planes existing in one ISO cube. The ISO standard also does not define how to select test planes.

Another problem is the test instrument. ISO 9283 mentioned nothing about test instrument. The standard just assumes that users have perfect test instruments. However, in reality, different test instruments will have different ways of measurements, so it gives different results. At least, there should have some restrictions on test instruments defined in ISO standard. By doing so, the test confidence level could be ensured.

4. Implementation Work

The goal of implementation work is to build a test software environment. The software environment should include different sub-systems. The most important sub-systems are as follows:

- Communication interface: the communication interface with a laser tracker is implemented. We use an event based structure to control the asynchronous communication. Data translation processes are also developed in this interface.
- Coordinate system calibration: we introduced requirements for coordinate system calibration and calibration methods. We implemented two different calibration methods for the software environment.
- User interface: in Figure 6, we could see the user interface of our software environment. It includes basic commands for robot tests with a 3D visualization method.

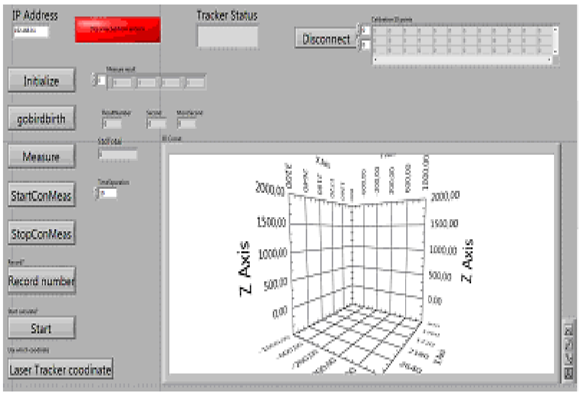

Figure 6: Example of Software Interface

- Movement detector: A movement detector is developed. The movement detector will return real time results of the robot movement detection. This is essential for further implementation of the test environment.

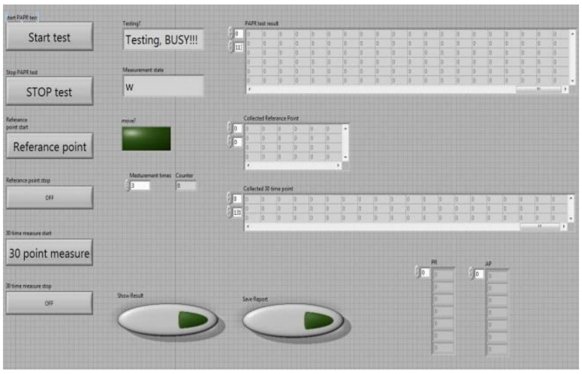

Figure7: Pose accuracy and pose repeatability test interface

- Pose accuracy and pose repeatability test function: we implemented a test example to demonstrate our software environment. The pose accuracy and pose repeatability test and data process algorithm are included. The software interface is given in Figure 7.

Report function: This function allows users to print reports including test results.

5. Conclusions

In this article, the technologies regarding industrial robot tests are discussed. A robot test software system is developed. Conclusions are shown as follow:

- The coordinate system calibration method is introduced.
- ISO 9283 standard is analyzed. Doubts and questions about the standard are discussed. Our test results confirm our assumption about pose accuracy test.

- An accuracy verification study of the laser tracker is carried out. The accuracy of our laser tracker is confirmed.
- A complete software system of pose accuracy and pose repeatability test is developed. The system includes communication interface, coordinate system calibration, movement detector, test function, report function, and user interface.

We will focus on improving ISO standard, implementing other test functions and error source analysis in the future.

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