Repeatability and Accuracy of an Industrial Robot: Laboratory Experience for a Design of Experiments Course

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Abstract

This paper outlines the incorporation of an experiment designed to evaluate the accuracy and repeatability of an articulated industrial robot into the laboratory component of a "Design of Experiments" course. Six factors found to affect repeatability in the literature have been tested on a Fanuc M16iL robot by a 2^{6-2} fractional factorial experiment. The planning, execution and analysis stages are described in detail in the paper. Lessons learned on the planning stage and experimental setup, as well as recommendations for robot repeatability studies are presented. The verification of the published accuracy and repeatability for the robot is also discussed.

Introduction

One of the challenges in teaching courses on analytical techniques is to have meaningful learning experiences for students. This is particularly true for courses such as Engineering Statistics and Design of Experiments, in which experimental data are analyzed by using various techniques. Although students become quite proficient in analyzing data, they usually do not receive the same level of experience in identifying projects for experiments, how to plan for, design and conduct the experiments. It is however well known that successful industrial experiments require sound planning, design and execution [1], after which statistical analysis is usually straightforward.

The Engineering program at Robert Morris University (Moon Township, PA) has recently implemented laboratory sessions for every engineering course to prepare students for challenges of tomorrow. The laboratory experiences aim to foster (i) strong analytical skills, (ii) practical ingenuity, (iii) creativity, and (iv) technical communication, which are listed among the attributes of Engineers in 2020 by the National Academy of Engineering [2]. This paper outlines one such laboratory experience in which students were given the responsibility to develop, design and conduct an experiment of their choice. This paper outlines the complete experience undertaken by the students.

Background

Industrial robots are used in applications that require high levels of accuracy and repeatability. Repeatability is a measure of the ability of the robot to consistently reach a specified point. Accuracy is a measure of the distance error associated with the desired point and achieved point. These two factors are interrelated and most commonly used among all performance characteristics [3]. Although repeatability and accuracy of industrial robots are usually provided by the equipment manufacturers, environmental conditions, calibration issues and machine wear may influence repeatability and accuracy. Therefore, it is important to determine the repeatability and accuracy of industrial robots when considering them for specific applications.

There are two standards to determine the accuracy and repeatability of industrial robots: ISO 9283 and ANSI/RIA R15.05. ISO 9283 has the scope of conductance of specified tests to develop and verify individual robot specifications, prototype or acceptance testing [4]. The standard has a Pose Performance Analysis component where pose accuracy and repeatability, overshoot, settling time, compliance, and warm-up drift can be measured. The Path Performance Analysis deals with path accuracy and repeatability, velocity and cornering issues. The ANSI/RIA R15.05 standard is written by the RIA (Robotics Industries Association) and consists of two volumes [4]. The volume 1 – ANSI/RIA R15.05-1 covers the point-to-point and static performance characteristics. The performance measures used by R15.05-1 are accuracy, repeatability, cycle time, overshoot, settling time and compliance. The R15.05-2 defines the fundamental path-related and dynamic performance characteristics including loading [4].

The repeatability of industrial robots has been investigated by many researchers. Goswami et al. [5] studied the accuracy of the robot and its relation to repeatability. The authors made an important contribution by establishing the relationship and distinction between accuracy and repeatability. The authors stated that gear backlash, sensor and servo precision are some of the factors influencing robot repeatability while the most important factor for accuracy is the kinematic model of the robot. Moreover Goswami et al. applied the two performance characteristics to actual applications. Pick-and-place, spray painting or welding may be highly dependent of repeatability while robotic orthopedic surgery may only be done under high accuracy.

Brethe et al. [6] investigated the repeatability of a KUKA industrial robot and the distributions of the angular positions of the joints. The authors showed that these distributions can be taken as Gaussian. They also computed repeatability at different locations within the work-volume of the robot using the experimental angular covariance matrix and the stochastic ellipsoid modeling. A high variability was observed in the measured data. The authors used a method of drawing the distribution of the 30 sample repeatability index to compare the computed and measured repeatability. They concluded that the modeling yielded matching results.

Reimer and Edan [7] evaluated the impact of target location on robot repeatability. Experimental results showed a significant statistical difference between repeatability at different work-volume locations. Especially the height of the target point was found to be a major factor determining the repeatability of a point within the work-volume.

Mehrez et al. [8] investigated the influence of speed, travel distance, and part loads on the accuracy and repeatability of a PUMA robot. Their study was an extension of previous studies by Offodile et al. [9,10]. The results through an empirical fit indicated that robot repeatability was influenced by the manipulator speed. The accuracy was affected by both the manipulator speed and the part loading. Just like similar robot repeatability and accuracy studies, the results were based on the test robot's structure and levels of the experimental factors utilized. Further statistical analysis was employed in economic decision making in this multi-station assembly operation case conducted by the PUMA robot.

Experimental Details

A Fanuc M16iL robot with six degrees-of-freedom located in the Department of Engineering at Robert Morris University was used in this experiment. M16iL is an articulated robot arm tooled with an EOAT (End-of-Arm-Tooling) exchange device allowing automatic exchange of grippers and other tooling. This 270 kg (594 Ib) robot has the following specifications reported by Fanuc: a payload capacity of 16 kg (35.2 Ib), horizontal reach of 1813 mm (71.378 in), repeatability of ± 0.1 mm (0.003937 in). The robot can be mounted in upright and inverted postures, and on angled surfaces and walls. A large work envelope and load capacity allows M-16iL to be utilized for a wide variety of applications including material handling, assembly, and material removal. Its six axes has a motion range of ± 240° (Joint 2) - ± 900° (Joint6). The joint speeds also vary from 140°/s (2.44 rad/s) (Joint 1) to 450°/s (7.85 rad/s) (Joint 6) [11]. The controller of the robot is the Fanuc's RJ3 and the robot can be programmed through ON-LINE with TP (Teach Pendant) Programming Language or OFF-LINE with the Fanuc's KAREL Language.

The robot used in this study is shown in Figure 1. This robot is the largest of the four available in the department. Larger robots have a tendency to have larger errors associated with them, allowing the error to be measured more accurately with the selected instrumentation [12].

Figure 1. The Fanuc M16iL 6-axis industrial robot used in this study.

Planning for the Experiments

The step-by-step procedure outlined by Coleman and Montgomery [1] was followed during the planning phase of the experiments. As a result of this planning procedure, the control variables, held-constant variables and nuisance factors were determined. The response variables to be analyzed later were selected as accuracy and repeatability of the robot. Both response variables can be determined from the positional data. The control variables, i.e., the factors to be varied during the experiments, were chosen based on the literature survey and working knowledge of the robots by faculty. The control variables varied in the experiments are presented in Table 1 which lists pertinent information considered for each factor. A decision was made to use two-level factorial designs so that "low" and "high" level for each control factor were determined. Robot speed, payload, work envelope location, motion type, the degree of deceleration, and the presence of intermediate points are the six controlled factors, each having a high and a low level, which are listed in Table 1. Note that speed and payload are continuous variables, where as the other four controlled variables are discrete.

Table 1. Control variables determined after the planning procedure.

Control Variable	**Normal Range**	**Measurement Accuracy**	**Setting**	**Predicted Effects**
Speed (S)	0 – 3000 mm/s	Based on robot controller	500 mm/s, 2000 mm/s	Significant
Payload (P)	0 – 16 kg	Scale unit accuracy	0 kg, 4.54 kg (10 lb)	Highly Significant
Work Envelope Location (W)	0 – 1813 mm	Discrete Variable	2 points within work envelope	Questionable Significance
Motion Type (M)	Discrete	Discrete Variable	Joint, Linear	Questionable Significance
Deceleration (D)	Variable	Based on robot controller and devices	Slow, no deceleration	Interaction may be significant
Intermediate points (I)	Two points or many points to create desired path.	Store random points that span entire workspace.	0 points between target location, 20 points between target location	Likely Significant

After control factors were selected, attention was paid to variables which should be "held constant" so that they do not inflate the error in the experimental results. Three factors were selected for this category, which are presented in Table 2.

Table 2. Held-constant variables determined after the planning procedure.

Factor	**Desired Experimental Level**	**Measurement Accuracy**	**How to control**	**Expected Effects**
Temperature	20 – 25º C	Ambient (Based on the room temp.)	Keep doors closed & monitor room temp.	Could affect robot performance
End Effectors	Gripper	N/A	Secure to robot and maintain same tooling	Change in weight distribution
Dial Indicator	0.0127mm graduations	Can measure 0.0254 mm accurately	Secure to table and/or robot base	Discrepancy in reading the response

Finally "nuisance factors", i.e., those that cannot be held constant but should be monitored for unexpected results and/or excessive error, were determined. These factors are presented in Table 3.

Table 3. Nuisance factors determined after the planning procedure.

Nuisance	**Measurement**	**Strategy**	**Anticipated Effects**
Friction	Dial Indicator	Approach point offset (Perpendicular to dial displacement)	Difference
Operator Bias	Visual	Same person to read measurements	Discrepancy in reading the response
Stability of Dial Indicator	Visual	Mount to rigid structure (i.e. robot base) avoid interfering with mounting location	Slight Difference
Warm-Up Period	Measure total time to run experiment, begin with warm up period.	Run continuous experiment and detect effects in run order vs. residual plot.	Residuals may be affected.

Designing the Experiments

Two response variables were chosen to be measured: positional accuracy (A_P) and positioning repeatability (R_P) based on the ISO 9283 standard [13]. The positional accuracy is calculated as;

$$A_P = \sqrt{(\bar{x} - x_c)^2} \qquad (1)$$

where, i is the index representing each attempt of execution to reach a commanded (programmed) position, $\bar{x}$ is the mean of positions attained in the x-direction (x_a) and x_c is the commanded position. To calculate positioning repeatability, the following calculations are necessary:

$$l_i = \sqrt{(x_{ai} - x_c)^2} \qquad (2)$$

$$\bar{l} = \frac{1}{n}\sum_{i=1}^{n} l_i \qquad (3)$$

where $\bar{l}$ is mean positional repeatability according to ANSI/RIA R15.05 standard [14]. The standard deviation for l_i, S_l, is calculated as

$$S_l = \sum_{i=1}^{n}\sqrt{\frac{(l_i - \bar{l})}{n-1}} \qquad (4)$$

where n is the number of times that the robot was taken to the same position under the same conditions. Finally, the positioning repeatability was calculated as;

$$R_P = \bar{l} + 3S_l \qquad (5)$$

The experimental parameters, restrictions, and assumptions led to the selection of a ¼ fraction of a full factorial design with six controlled variables. Hence a 2^{6-2} fractional factorial design with resolution IV was implemented (the reader is advised to refer to a "Design of Experiments" textbook for the notation and resolution). This design provided an acceptable compromise between the number of runs (2^4=16) and resolution needed to estimate the main effects and the two-factor interactions.

Experimental Setup

A dial indicator with 0.0127mm (0.0005in) graduations was used to measure the position of the robot. The magnetic base was securely mounted to rigid steel tables, as shown in Figure 2. For each run, the robot controller adjusted motion parameters to meet the experimental conditions. A single program was created to run a continuous experiment with the addition of delays to adjust manually modified controlled factors. The controlled factors that required manual adjustment were the payload and work volume location as the experiment demanded changes between randomized runs. Dial indicators were positioned in two different areas in the work volume, which was a controlled factor in the experiment. Intermediate points, approach points, and taught (programmed) points were stored in the controller to maintain the same exact path during the entire experiment. The taught points were stored when the dial indicator was slightly compressed. Dial indicators were calibrated after each run.

The robot was run thirty five times (n=35) for each combination of levels of controlled variables. In other words, 560 location data (16×35) were collected in this project. Although the ISO 9283 standard requires that n=500, the lower number of 35 still allowed the students to obtain a good estimate of accuracy and repeatability within the time specified for this project.

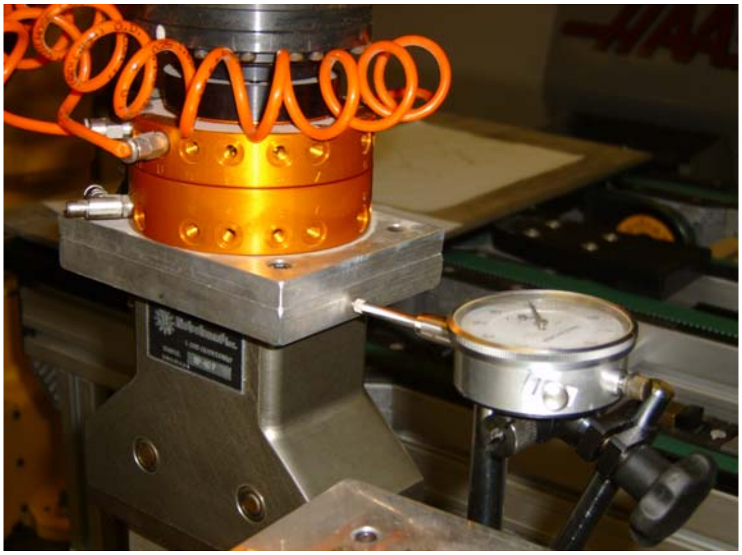

Figure 2. Dial indicator position and robot approach during experiment.

Results and Discussion

The tools used in the analysis of experimental data, namely Daniel's plot [15] and analysis of variance (ANOVA) assume that the data follow the normal distribution. Accuracy, as described in Equation 1, is not expected to follow the normal distribution (a hypothesis which was later confirmed by the analysis of residuals). Hence a logarithmic transformation was performed on the accuracy data to meet the requirement that residuals follow a normal distribution. No transformation was necessary for the repeatability data. Because no replication was made, ANOVA could not be used directly because error cannot be estimated without replication. Consequently, a two step analysis procedure was followed; first Daniel's plot was used to determine those factors that were clearly insignificant. Then the sum of squares (SS) and degrees of freedom (DOF) of those factors were pooled to estimate the mean square (MS) of error so that ANOVA could be applied. The ANOVA tables for accuracy and repeatability results are presented in Tables 4 and 5, respectively. Those factors with p-values lower than 0.05 were taken as significant and are indicated as bold in Tables 4 and 5. These calculations were made by students by using Microsoft Excel software. In Tables 4 and 5, the letters represent the control factors listed in the first column of Table 1.

Table 4. ANOVA results for the accuracy results after the logarithmic transformation of the data.

Source of Variation	SS	DOF	MS	F	p-value
S	2.362	1	2.362	6.970	**0.027**
W	0.150	1	0.150	0.444	0.522
M	6.132	1	6.132	18.096	**0.002**
SW=PD	0.052	1	0.052	0.153	0.705
SM=DI	0.383	1	0.383	1.129	0.316
PI=WM	0.077	1	0.077	0.227	0.645
Error	3.049	9	0.339		
Total	12.205	15			

Table 5. ANOVA results for the repeatability results.

Source of Variation	SS	DOF	MS	F	p-value
P	0.01545	1	0.01545	0.852	0.383
M	0.10553	1	0.10553	5.821	**0.042**
I	0.01733	1	0.01733	0.956	0.357
SP=WD	0.11126	1	0.11126	6.137	**0.038**
SM=DI	0.04402	1	0.04402	2.428	0.158
SC=PW=MD	0.01580	1	0.01580	0.871	0.378
PM=WI	0.03213	1	0.03213	1.772	0.220
Error	0.14502	8	0.01813		
Total	0.48654	15			

These results indicate that only speed and motion type affect the accuracy of the robot while motion type and a two-factor interaction between either speed and payload, or work envelope location and deceleration are significant. Note that which one of these two factor interactions is significant could not be determined because of the alias structure, as explained by Montgomery [16]. Moreover payload, which was initially expected to be significant (as stated in Table 1) was not found to affect either the accuracy or repeatability of the robot within the experimental range (0-4.54 kg). Hence the empirical equations for accuracy and repeatability can be written as;

$$\log(A_P) = -1.561 - 0.096S - 0.155M \qquad (6)$$

and

$$R_P = 0.1758 - 0.0203M - 0.0208SP \qquad (7)$$

respectively.

A total of 35 data points were collected based on time constraints compared to 500 points as specified by the ISO 9283 standard. The number of points used in the experiment may not have been sufficient in detecting the large positional changes over short number of runs. The ISO standard also measures X, Y, and Y coordinates. This experiment investigated repeatability of only one axis compared to all spatial axes. All of these simplifications were made due to the time constraints for this course project.

This laboratory experience also gave the students an opportunity to learn that there are many factors that contributed to error in the experiment. Some were anticipated and were uncontrollable, as shown in Table 3. During the planning stage, students were also forced to think about the measurement system. The resolution of the measuring device was found to be sufficient to determine slight positional differences of the robot after many cycles. The repeatability measure of 0.1 mm was defined in the robot specifications. The selection of the measurement system and successful execution of the experiment confirmed the repeatability published by the robot manufacturer.

Conclusions

A laboratory experience for a "Design of Experiments" course that involved the programming of a robot to measure its accuracy and repeatability was developed. This experience provided the students with an appreciation of the importance of thorough planning that involves a literature survey, selection of a measurement system that will meet the needs of the experiment and careful execution of the experiment. Most factors that were expected to affect the accuracy and repeatability of the industrial robot were found to be significant. Despite the limitations of the experiment, such as the number of data, measurement in only one coordinate, etc., the results were respectable for being consistent with the findings reported in the literature. Moreover students found it to be most useful for their education because they planned the experiment, built the setup, programmed the robot, ran the experiments and conducted the data analysis, with only some assistance from two professors. Student feedback on the course reflected their appreciation of this learning activity. Similar laboratory experiments for teaching as well as the expansion of this study for research are now planned.

Despite a good effort to study the literature and the familiarity of the students with the robot, it is noteworthy that some of the factors were found to affect neither the accuracy nor the repeatability of the robot. However, this laboratory was found to be an invaluable experience by the students. Careful planning and prior working knowledge are prerequisites to a successful experiment. In this case, the strategy followed produced good results within the constraints of the experiment, which was mainly the time to be invested in execution.

Some improvements can be made in the planning stages of future repeatability experiments. For example, the high level of payload can be above the upper limit of the maximum load specification, 16 kg (35.2 Ib). The high level of speed at the wrist can be close to the maximum limit of the M16iL robot, 3000 mm/s (118.18 ips). In addition to modifying the factor ranges, the layout of the experiment could incorporate multiple dial indicators to measure deviations in three dimensions including the other two axes. Following the specifications of the ISO 9283 standard by obtaining 500 data points for each run may also provide enhanced results.

A revision of the measurement system of the experiment may be the simplest way to get more information out of the experiment. Different methods which are more consistent and able to obtain a higher resolution measurement are also desirable. Some methods that were discovered during the research phase were the use of lasers and mirrors to project small positional differences onto a screen where they are amplified. There are other more accurate methods that involve complex setups and computer assistance, which were deemed unnecessary for this laboratory experience.

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