The Repeatability Analysis of Industrial Robot under Loaded Conditions and Various Distances

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Abstract—The increasing usage of robots in manufacturing operations is due to its flexibility and its ability to be reprogrammed easily when the old task changes. The main obstacle in the robotics applications is to minimize the positional errors when it is under real working conditions. This implies that robots have to perform accurately under loaded conditions at any location within the working envelope. The aim of this research is to evaluate the performance of industrial robot under payload and various distances within the working envelope. Relationship between the location and payload versus repeatability are to be obtained. The experimental work and statistical analysis was performed in order to achieve the desired objective of the research. The study of linear performance has been carried out and the results show that the FANUC Robot Arc Mate 100i under the study has the linear repeatability of 2.125 mm. The repeatability value obtained was not the same compare to the manufacturer specification due to various factors that cannot be avoided. Statistical analysis shows that the distance from robot center has significantly affects the repeatability performance of the robot.

Keywords—Performance, Robot, repeatability, Correlation, Regression Analysis

1. Introduction

Robotics is one of the branches of modern technology, which applies a combination of a few different engineering fields. It is a science-based technology, which relates to the theory and application of robotic systems [1]. The utilization of robots in the industries is due to a few factors, among them; firstly, robots are used to increase the productivity levels of production. This fact has been proven as productivity levels have reached up to 67\% compared to before the implementation of robots [2].

The production levels have also been constant even in the second and third working shifts. Quality levels are also known to have increased with the use of industrial robots. This is because the characteristic of a robot is such that once has been ‘taught’ to perform a certain task, it will be able to perform that task at a consistent rate repeatedly. This character however is absent amongst the humans. Robotic applications are also gaining popularity because of its flexibility in the terms of usage as robots can be reprogrammed should there be any changes in the job scope or if the robot has to perform other tasks. In other words, robots can perform a variety of job functions with ease. Robotic hardware’s such as grippers are also easily exchangeable as it only takes a short time to remove and reinstall. It’s precision and repeatability is another factor, which makes it desirable in the industry. Robots are able to move easily at high speeds besides being accurate in placing hardware.

The performance of an industrial robot could be defined by a few vital factors such as:[3]
\begin{itemize}
  \item resolution
  \item accuracy
  \item repeatability
  \item operational speed
  \item payload ability
  \item positional error.
\end{itemize}

The repeatability of the robot depends strictly on to the resolution of instructions and repeatability of the input itself. Figure 1 shows the relationship among the
resolution, repeatability and repeatability of a robotic arm.

Resolution is determined by the control system of the robot. It is related to the smallest increment of movement, which can be done by the robot. It is also one of the smallest segments, which it may be divided from the work envelope. The resolution programming is the smallest increment allowed by the robotic program of instructions. The resolution control is the smallest possible change in movement that can be detected by the feedback device.

Repeatability is referred to as the ability of each robot to place its end tip on any targeted point within its work envelope and can be defined in the resolution of space. The repeatability performance of a robot can be defined as half the value of the space resolution, which represents the movement of the tools fitted to the robot’s arms. Repeatability can also be defined as the ability of a robot to move precisely in a three dimensional plane. The velocity of movement and the payload greatly influences the repeatability of a robot [4]. Any increment of speed will cause the decrease in the repeatability. The robotic arm speed should be reduced to avoid it to overshoot from the given position.

Repeatability is one of the statistical terms which is relates closely with repeatability. It represents how a repeated action happens at any one point. For instance, if a robot is programmed to move to a certain point, repeatability means how close the robot can move and reach that particular point. In other words, repeatability is the measurement of the robot’s ability to move its tip of the arm to a predefined point within its work envelope. This is because every time a robot moves back to the predefined point after a completed cycle, there will be a miniscule of difference in position [5].

Robot operation speed is often referred to as the dynamic performance. Dynamic performance relates to how fast a robot is able to accelerate, decelerate and stop at any given point. Two main factors, which affect the work pace of a robot, are the achievable repeatability and the payload. Other factors to be considered are the configuration of the robot and the location of the tools within its work envelope.

Another important characteristic of robots is the ability to vary its payload capacity. Most robots have better ability to hold and lift higher loads when moving at full speed during its swinging motion. The shape and surface of the object also plays a very important part in determining the abilities of the robots in action. It can achieve a very much higher capacity while working close to its base compared to when the robot arms are fully extended.

Positional error that normally happens to industrial robots is normally due to imperfections to the precision of the robots [6]. This phenomenon can seriously affect the tolerance limits and thus damage the jigs and fittings. Positional precision can be pre-determined by running a series of measurement differentiation between the original position and the preprogrammed location [7]. The positional error on robots depends on kinematics, type of drive, stiffness, thermal stability and other factors [6].

2. Methodology

The methodology will explained the equipment used and the method of experimental work done in order to achieve the objective of this study. The choice of the right devices, instruments and the procedure of experiment are the most important factors in order to obtain the best possible results. A few series of different experiments will be conducted to the FANUC Robot Arc Mate 100i industrial robot to evaluate its performance in the scope of its robot working envelope. The study involves three main parts:

- To test the repeatability of the industrial robot with different loads at different locations
- To perform a statistical analysis based on the results obtained from the experiment to check the relationship between load and repeatability to determine the performance of the industrial robot.
- To perform a statistical analysis based on the results obtained from the experiment to check the relationship between the difference in the location and the repeatability of the industrial robot.

2.1 Robot Attachments

The robot attachment is made from 3 mild steel plates with a thickness of 5mm and 2 screws, which are welded together. This attachment is mounted between the end of the robot arm (on the J6 axis) and the gripper using the screws. The attachment enables the weight to be hung at the end of the arm as shown in Figure 2.
2.2 Renishaw Laser Interferometer
The laser interferometer is normally used to determine the repeatability of machine tools which require high repeatability measurements and calibrations. Figure 3 shows the laser interferometer equipment while Figure 4 shows the actual spread-out of experiment. Interferometry is a method of measurement using linear motion whereby distance is measured with repeatability of one micron and the laser tracking system used is one of the most accurate in the robotic metrological field [9]. Any target, which is held by the gripper, will be tracked automatically by a laser beam, which is projected by the mirror.

2.3 Loads of 0.5kg, 1.0kg and 2 kg
The experiment was conducted using loads of 0.5, 1 and 2 kg so that weights will be able to give a combined load of 2.5 and 5.0 kg. Robot will be given loads in three stages 0 kg, 2.5 kg and 5.0 kg.

2.4 Microsoft Excel Software for Statistical Analysis
Microsoft Excel software is used in to determine the performance of the industrial robot by analyzing the relationship between load and repeatability under the different locations. The regression analysis can only be done after ascertaining the existence of a linear relationship between the performance specifications and factors by using the ‘Correlation’ tool, which is placed under the ‘Data Analysis’. The positive value of the correlations indicates the existence of a linear relationship between the performance specifications and the factor. The regression analysis is done to further prove the relationships existence based on certain hypothesis.

3. Results and Discussions
From the data collected, all the repeatability errors of each point can be calculated by using certain formulas. The analysis will further prove whether this particular robot meets the repeatability and specification, which has been provided in the technical specifications provided by the manufacturer of this robot. The correlations of the load factor and the difference in location or linear distance with the repeatability and specifications will be determined. The hypothesis regarding the relationship will be assumed and tested by methods of statistical analysis.

As stated before, the two factors that can influence the repeatability are the load and distance from the center of robot. The summary of data for the repeatability test is shown on Table 1. The formula to calculate the repeatability is shown in Equation (1).

\[
\text{Repeatability} = \frac{\sum_{i=1}^{N} \sqrt{(x_i - \bar{x})^2}}{N}
\]

(1)
where $x_i$ is the value obtained from the experiment.

**Table 1 - Summary of Repeatability Data for Linear Motion**

<table>
<thead>
<tr>
<th>Loads (kg)</th>
<th>0</th>
<th>2.5</th>
<th>5.0</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (mm)</td>
<td>46</td>
<td>0.0020</td>
<td>0.0023</td>
<td>0.0057</td>
</tr>
<tr>
<td></td>
<td>136</td>
<td>0.0090</td>
<td>0.0077</td>
<td>0.0033</td>
</tr>
<tr>
<td></td>
<td>226</td>
<td>0.0030</td>
<td>0.0030</td>
<td>0.0033</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.0044</td>
<td>0.0036</td>
<td>0.0034</td>
</tr>
</tbody>
</table>

**Table 2 - Analysis of Correlations between Linear Repeatability and Load Factor**

<table>
<thead>
<tr>
<th>Correlations Analysis</th>
<th>Column 1</th>
<th>Column 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column 1</td>
<td>1</td>
<td>0.121305721</td>
</tr>
<tr>
<td>Column 2</td>
<td>0.121305721</td>
<td>1</td>
</tr>
</tbody>
</table>

**Regression Analysis**

<table>
<thead>
<tr>
<th>Regression Statistics</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple R</td>
<td></td>
<td>0.121306</td>
<td></td>
</tr>
<tr>
<td>R Square</td>
<td></td>
<td>0.014715</td>
<td></td>
</tr>
<tr>
<td>Adjusted R Square</td>
<td></td>
<td>0.002243</td>
<td></td>
</tr>
<tr>
<td>Standard Error</td>
<td></td>
<td>0.032448</td>
<td></td>
</tr>
<tr>
<td>Observations</td>
<td></td>
<td>81</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>1</td>
<td>0.001242241</td>
<td>0.0012</td>
</tr>
<tr>
<td>Residual</td>
<td>79</td>
<td>0.083177342</td>
<td>0.0011</td>
</tr>
<tr>
<td>Total</td>
<td>80</td>
<td>0.084419582</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.002553</td>
<td>0.005700546</td>
</tr>
<tr>
<td>X Variable 1</td>
<td>0.001919</td>
<td>0.00176625</td>
</tr>
</tbody>
</table>

The analysis shows a not very strong bonding in relationship between the repeatability with load, but could be constructed by an equation model.

Model used represents: -

$$\hat{y} = \beta_0 + \beta_1 x$$

From the analysis, the regression line equation is: -

$$\hat{y} = 0.00191851x + 0.002553086$$

Hypothesis: -

Linear relationship exist if $\beta_1 \neq 0$. Therefore, hypothesis testing to be done is: -

$$H_0: \beta_1 = 0 \text{ (No Linear relationship)}$$

$$H_1: \beta_1 \neq 0 \text{ (Linear relationship)}$$

Take $\alpha = 0.01$
From the table above, \( t_{\text{statistic}} = 1.08621 \)
\( v = n - 2 = 81 - 2 = 79 \)

**Rejection region for \( \alpha \)-Test:**

\[
t_{\text{statistic}} \geq t_{\alpha/2, n-2} \quad \text{or} \quad t_{\text{statistic}} \leq t_{\alpha/2, n-2}; \quad \text{therefore}
\]

\[
t_{\text{statistic}} \geq 1.6669 \quad \text{or} \quad t_{\text{statistic}} \leq -1.6669
\]

Since \( t_{\text{statistic}} = 1.08621 \) (< 1.6669), therefore \( H_0 \) cannot be denied. This proves that there is no linear relationship between repeatability and load factor.

### 3.2 Linear Repeatability versus Distance from the Robot Base

Figure 6 shows a graph of repeatability error versus distance from the robot's base. Based on this graph, it is known that there is no linear relationship between repeatability and the distance from the base of the robot.

![Graph for Repeatability Error versus Distance from Robot Base](image)

It is known that there is a good linear repeatability for both distances, near and far; but there is a high level of repeatability error in the middle of the work envelope. However, the overall repeatability factor is considered good as it is still below the specifications of \( \pm 0.1 \) mm.

### 4. Conclusion

From the finding it can be proved that the overall repeatability is 2.125 mm. The experimental results figure did not meet with the technical specifications provided by the manufacturer of the robot, which quoted an repeatability of \( \pm 1 \) mm. The variation in load does not influence the repeatability of the FANUC Robot Arc Mate 100i in this study while there is exists a linear relationship between repeatability and the distance from the robot base. This relationship proved by the representation of equation model \( \hat{y} = 0.00191851x + 0.002553086 \). The environmental noise factors such as vibrations and the instability of room temperature of between 22°C and 24°C also could have played a vital role in the repeatability of the robot.

### References