The performance analysis of industrial robot under loaded conditions and various distance

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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 accuracy and 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 accuracy and repeatability of 2.125 mm. The accuracy and 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 accuracy and repeatability performance of the robot.

Keywords - *Performance, Robot, Accuracy, Repeatability, Correlation, Regression.*

I. 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 it's 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 accuracy 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]

- resolution
- accuracy
- repeatability
- operational speed
- payload ability
- Positional error.

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

Accuracy and 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 accuracy and 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. Accuracy and

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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 accuracy and repeatability of a robot [4]. Any increment of speed will cause the decrease in the accuracy and 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 accuracy and 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 accuracy and 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].

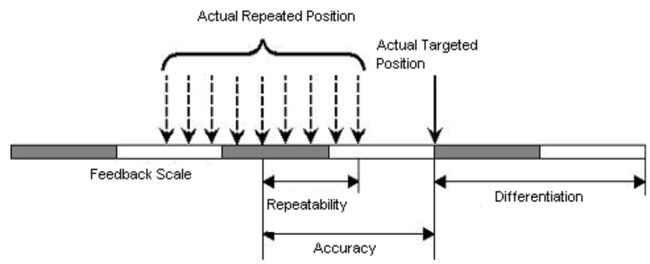


Fig. 1 representative of resolution, accuracy and repeatability of a robotic arm [8]

II. 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 100*i* industrial robot to evaluate its performance in the scope of its robot working envelope. The study involves three main parts:

- To test the accuracy and 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 accuracy 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 accuracy and repeatability of the industrial robot.

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 Fig. 2.

Fig. 2 - attachment held by the gripper and the robot arm

Renishaw Laser Interferometer

The laser interferometer is normally used to determine the accuracy and repeatability of machine tools which require high accuracy and repeatability measurements and calibrations. Fig. 3 shows the laser interferometer equipment while Fig. 4 shows the actual spread-out of experiment. Interferometry is a method of measurement using linear motion whereby distance is measures with accuracy and 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.

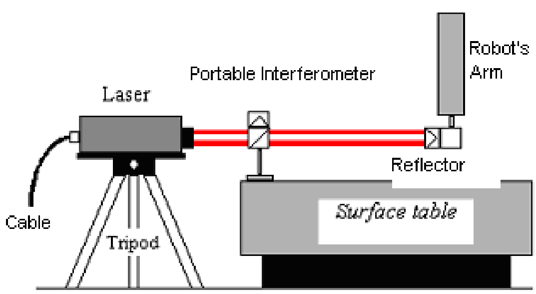


Fig. 3 – laser interferometer fixed to the tripod [10]

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 5.0kg. Robot will be given loads in three stages 0 kg, 2.5 kg and 5.0 kg.

Fig. 4 actual spread-out of experiment

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 accuracy 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.

III. RESULTS AND DISCUSSIONS

From the data collected, all the accuracy and repeatability errors of each point can be calculated by using certain formulas. The analysis will further prove whether this particular robot meets the accuracy and 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 accuracy and 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 accuracy and repeatability are the load and distance from the center of robot. The summary of data for the accuracy and repeatability test is shown on Table 1. The formula to calculate the accuracy and repeatability is shown in Equation (1) and (2).

$$Accuracy = \frac{\sum_{i=1}^{N} \sqrt{\left(x_i - x_{redirect}\right)^2}}{N} \qquad (1)$$

$$\text{Repeatability} = \frac{\sum_{i=1}^{N}\sqrt{\left(x_i - \overline{x}\right)^2}}{N} \quad (2)$$

where x_i is the value obtained from the experiment

Table 1- summary of accuracy (a) and repeatability(b) data for linear motion

Load (kg) / Distance (mm)	0			2.5			5.0			Average
46	0.3150	1.6783	3.7573	0.3017	1.6710	3.2583	0.3180	1.6967	3.2960	1.8103
136	0.7560	1.9757	3.4903	0.7980	2.0247	3.5503	0.8223	2.0547	3.5927	2.1183
226	1.0167	2.3343	4.0030	0.9920	2.3187	4.0037	0.9937	2.3237	4.0260	2.4458
Average		2.1474			2.1020			2.1249		2.1248

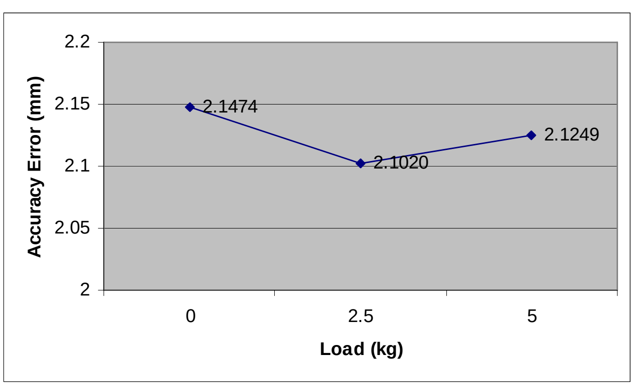
(a)

Loads (kg) / Distance (mm)	0			2.5			5.0			Average
46	0.0020	0.0023	0.0057	0.0033	0.0083	0.0057	0.0020	0.0010	0.0033	0.0037
136	0.0090	0.0077	0.0033	0.0020	0.0017	0.0023	0.0043	0.0050	0.0050	0.0045
226	0.0030	0.0030	0.0033	0.0020	0.0037	0.0030	0.0030	0.0037	0.0033	0.0031
Average		0.0044			0.0036			0.0034		0.0038

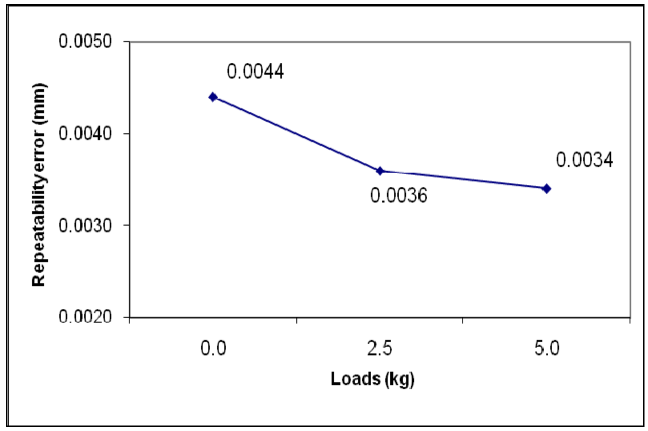
(b)

Linear Accuracy Movement versus Loads for Robot and Repeatability versus Loads

The graph for the load versus different distances is plotted based on the summarized results as shown in Fig. 5. The graph indicate the linear movement accuracy versus loads and repeatability versus loads fitted to the robotic arm.



(a)



(b)

Fig 5 graph for linear accuracy error versus loads (a) and repeatability versus loads (b)

Based on the graph in Fig. 5, it is clear that the loads placed on the tip of robot's arm caused a significant difference on the accuracy and repeatability on the movement of the arm. This difference however, was not consistent. For example, a vast difference of 0.2236 mm with an increase of load from 0 to 2.5 kg and an additional small difference of 0.0229 mm with an increase in load from 2.5 to 5.0 kg. The correlations analysis using Microsoft Excel which is shown in Table 2 proves no existence or relationship between the two factors o. This is due to the negative value which shows no relationship whatsoever between accuracy and repeatability and load factor. This concludes that the variation in load does not influence the accuracy and repeatability of the robot in this study.

Table 2 - analysis of correlations between linear accuracy

Correlations Analysis

	Column 1	***Column 2***
Column 1	1	
Column 2	-0.07074	1

The technical specifications provided by the manufacturer of this robot states an accuracy and repeatability error of less than 1mm, however this experiment concludes that the total accuracy and repeatability of the robot is 2.1248 mm. This could be due to the lack of precision and accuracy and repeatability during the mastering process. Besides on that, an error could have occurred during the programming of the coordinates via the teaching pendant hence the large error to the linear accuracy .

Table 2 - analysis of correlations between linear repeatability and load factor

Correlations Analysis

	Column 1	*Column 2*
Column 1	1	
Column 2	0.121305721	1

Regression Statistics	
Multiple R	0.121306
R Square	0.014715
Adjusted R Square	0.002243
Standard Error	0.032448
Observations	81

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.001242241	0.0012	1.179852788	0.280689256
Residual	79	0.083177342	0.0011		
Total	80	0.084419582			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.002553	0.005700546	0.4479	0.655474986	-0.00879358	0.013899749
X Variable 1	0.001919	0.00176625	1.0862	0.280689256	-0.00159712	0.005434153

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: $\beta_1 = 0$ (No Linear relationship)

H_a : $\beta_1 \neq 0$ (Linear relationship)

Take $\alpha = 0.01$

From table above, $t_{statistic} = 1.08621$

$v = n - 2 = 81 - 2 = 79$

Rejection region for α-Test:

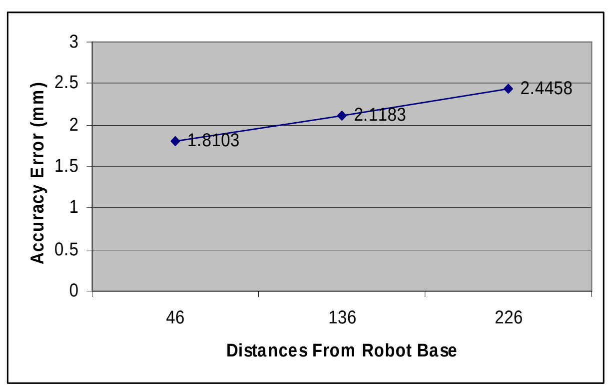
$t_{statistic} \geq t_{\alpha/2,\ n-2}$ or $t_{statistic} \leq t_{\alpha/2,\ n-2}$; therefore

$t_{statistic} \geq 1.6669$ or $t_{statistic} \leq -1.6669$

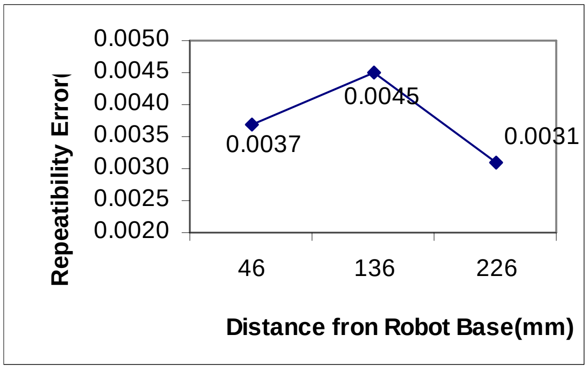
Since $t_{statistic} = 1.08621$ (< 1.6669), therefore H_0 cannot be denied. This proves that there is no linear relationship between repeatability and load factor.

Linear Accuracy versus Distance and Repeatability versus Distance from the Robot Base

Fig. 6 shows the accuracy and repeatability of linear motion versus the distances from the base of the robot. The graph shows the linear relationship between the distances from the center of the robot versus accuracy and repeatability whereby the further the robot's arm is from the center of the robot, the higher the accuracy and repeatability error is. This means that greater accuracy and repeatability can be achieved when the arm is nearer to the base of the robot.



(a)



(b)

Fig. 6 graph for accuracy error versus distance (a) and repeatability versus distance from robot base(b)

Evidence from the regression analysis by using the Microsoft Excel software shows that the distance factor, from the base of the robot plays a vital role in proving the linear relationship with the accuracy and repeatability performance of the robot. It can be concluded that the distance factor relates directly to the accuracy of the robot. The summary of the correlation and regression analysis is presented in the Table 3.

For the correlations analysis, the value '1' gives a very strong relationship where else '0' denotes no relationship what so ever. Therefore, the analysis shows minimal connection or relationship between accuracy and the distance from the base of robot. However, it is possible to build an equation model. The representation of equation model is shown in Equation (2).

$$\hat{y} = \beta_0 + \beta_1 x \quad (2)$$

Based on results analyzed, the regression line equation is shown in Equation (3) for accuracy and Equation (4) for repeatability.

$$\hat{y} = 0.0034687x + 1.6493152 \quad (3)$$
$$\hat{y} = 0.00191851x + 0.002553086 \quad (4)$$

Based on the hypothesis, the linear relationship will exist if $\beta_1 \neq 0$. Therefore, hypothesis testing to be done is by following all the 8 steps described just after this paragraph.

1. H_0: $\beta_1 = 0$ (no linear relationship)
2. H_a : $\beta_1 \neq 0$ (linear relationship exist)
3. Take $\alpha = 0.01$
4. From the table above, $t_{statistic} = 1.858248$
5. $v = n - 2 = 81 - 2 = 79$
6. *Rejection region for α-Test*:
7. $t_{statistic} \geq t_{\alpha/2,\ n-2}$ or $t_{statistic} \leq t_{\alpha/2,\ n-2}$; therefore
8. $t_{statistic} \geq 1.6669$ or $t_{statistic} \leq -1.6669$

Since $t_{statistic} = 1.858248$ (> 1.6669) for accuracy, so H_0 can be excluded. Therefore, there is strong evidence that proves the distance factor from the base of the robot influences the accuracy and repeatability of the robot. By using the model $\hat{y} = 0.0034687x + 1.6493152$ for accuracy and model where x is the distance from the base of the robot, the robot user can predict the accuracy and repeatability of every movement made by the robot from its base. The overall accuracy and repeatability value of 2.125 mm obtained from the experiment. Comparing these figures to the actual figures from the technical specifications provided by the manufacturer of accuracy ±1 mm, the results have varied from the initial prediction. This could be due to a few factors including the possibility of wrong set-up procedures, flaws in the robot itself, and not forgetting the environmental factor.

Table 3 correlations and linear regression analysis for linear accuracy and distance factor and

Correlations Analysis

	Column 1	*Column 2*
Column 1	1	
Column 2	0.2046445	1

SUMMARY OUTPUT			
Regression Statistics			
Multiple R	0.20464455		
R Square	0.04187939		
Adjusted R Square	0.02975128		
Standard Error	1.23454104		
Observations	81		
ANOVA			
	df	*SS*	*MS*
Regression	1	5.262817852	5.26281785
Residual	79	120.4032348	1.52409158
Total	80	125.6660527	
	Coefficients	*Standard Error*	*t Stat*
Intercept	1.64931523	0.288555095	5.71577232
X Variable 1	0.00346872	0.001866664	1.85824784

Based on the correlation and regression analysis, the relationship between the specifications (accuracy) with the influential factors (load and distance) only accuracy coupled up with the distance factor is clearly related. It can be expressed with the Equation (1). Therefore, the robot operator can more or less predict the accuracy and repeatability of every distance between the tip of the robot's arm, x to the base of the robot.

IV. CONCLUSION

From the finding it can be proved that the overall accuracy and repeatability is 2.125 mm. The experimental results did not meet with the technical specifications provided by the manufacturer of the robot, which quoted an accuracy and repeatability of ±1 mm. The variation in load does not influence the accuracy and repeatability of the *FANUC Robot Arc Mate 100i* in this study while there is exists a linear relationship between accuracy and repeatability and the distance from the robot base. This relationship proved by the representation of equation model $\hat{y} = 0.0034687x + 1.6493152$. The environmental noise factors such as vibrations and the instability of room temperature of between 22 ^{0}C and 24 ^{0}C also could have played a vital role in the accuracy and repeatability of the robot.

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