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Evaluation of influence of target location on robot repeatability

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SUMMARY
This paper evaluates the influence of target location on robot repeatability. An experiment was set up to analyze the effect of the three-dimensional target location on robot repeatability. An error-analysis model to determine repeatability based on the robot's kinematic model and known robot parameters was developed. Experimental results indicated that there was a significant statistical difference between repeatability at different locations in the workspace and that the height of the target point influenced repeatability. Experimental results tended to those derived from the error-analysis kinematic model. Hence, to determine the optimal target location, there is no need for extensive experimentation; instead, only a few target points can be sampled and compared to an error-analysis model.

KEYWORDS: Robot performance; Repeatability; Target location; Error-analysis model.

1. INTRODUCTION

Manufacturers supply robot parameters, but their specifications are not well defined.[1] For example, repeatability and accuracy are not defined with respect to other specified parameters such as velocity and payload. Thus, the user does not know under what operating conditions the specifications were obtained.

The complexity of robot evaluation and selection is further complicated by the many interrelated parameters involved and the difficulties in assessing the trade-off in the choice of the parameters.[2] It is therefore important to determine the effect of different parameters on performance. Moreover, a robot's capabilities are not uniform across the work-volume of the robotic arm and are a function of the robot's controller inverse kinematics algorithms and dynamic characteristics. In the design of a robotic cell, the layout of peripheral equipment (feeders, tools), as well as the position of the robot relative to other elements in the process, are determined[3] and should be set up at optimal locations.

The repeatability of a robot is the precision in which its endpoint achieves a particular pose (end point position and orientation) under repeated commands to the same set of joint angles.[4,5] High repeatability is important for a variety of robot applications, such as pick and place, assembly and spot welding. Repeatability (Rp) is defined as:[6]

$$Rp = \bar{L} + 3S_1$$

where:

$$Li = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2 + (z_i - \bar{z})^2}$$

Xi, Yi, Zi: coordinates of the i-th measurement

X, Y, Z, L: average values

S: standard deviation of L.

Robot repeatability is affected by: a) design variables such as link dimensions, gear backlash;[4] b) environmental parameters such as heat and humidity;[7] c) speed, weight and distance.[8] In order to evaluate these errors, different robot positions for various robot poses within the workspace must be evaluated.[4] In previous research[9] we developed a three-dimensional statistical evaluation framework to predict repeatablity by relating repeatability to the Maxwell distribution function. This model proved to simplify the evaluation of robotic systems within a known economic framework. The research indicated the influence of target location on repeatability but did not compare that between the different points. A theoretical model for repeatability prediction based on the robots kinematics was developed.[10] However, this model was not experimentally validated. Furthermore, the model requires calculation of the error caused by each joint using the matrix transform and therefore is difficult to implement. It has been noted experimentally that the bin position relative to the robot base affects accuracy[3] and repeatability.[9]

The objective of this research is to investigate the influence of the target's location on repeatability and to develop an analytical model, which could enable one to predict repeatability based on the target's location without requiring extensive experimentation or complicated analysis. The model relates only to the robot kinematics and to three-dimensional location of a target point (it does not consider orientation).

2. EXPERIMENTAL DESIGN

The experimental procedure (Figure 1) was similar to that in reference 9 and based on the International Standards for measuring robot performance of industrial robots (ISO9283).[6] The robot was equipped with a special 3D cube that was attached to its gripper and was programmed to approach each target point 30 times. The three-dimensional measurement system consisted of three dial gauges, each equipped with a capacitive Sylvac patented measuring system[11] with a resolution of 0.00125 mm, accuracy of 0.005 mm and repeatability of 0.002 mm. A CRS A255

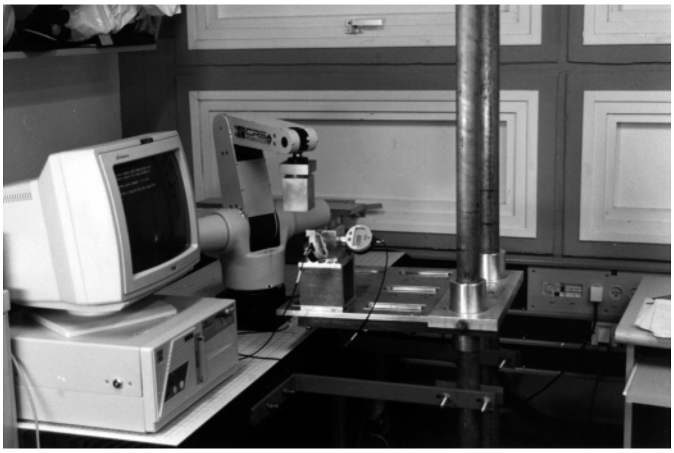


Fig. 1. Photograph of the experimental system setup.

vertical articulated five degrees of freedom robot was employed. The repeatability of the robot, as specified in the product literature, is 0.05 mm with maximum payload of 2 kg and linear speed of 0.508 m/s.

Previous research indicated an influence of the manipulator's speed and payload on repeatability.[1,9] Therefore, a preliminary experiment was set up to determine the best parameters for the extensive experiment. A preliminary experiment (Table I) evaluated five different combinations of speed and payload (corresponding to ISO9283 specifications: 50% and 100% of maximum speed and payload, and for 80% of maximum speed) while approaching the central target point. Based on this experiment, the preferred operational conditions were selected as: payload −2 kg, 80% maximum speed that is the maximum speed allowed by the manufacturer for this payload.

Nine different locations (Figure 2) at three different heights (Figure 3) were selected as target points. The target points were selected at 10% of the work envelope borders corresponding to ISO9283 specifications. Since a large amount of experimentation is required, only the following 15 locations were actually selected for the experiment as follows: H0A1, H0A3, H0A5, H0A7, H0A9. H1A1, H1A3, H1A5, H1A7, H1A9, H2A1, H2A3, H2A5, H2A7, H2A9.

The robot was programmed to pass through several preprogrammed points to enter the measuring system at 45 degrees, so all sensors could be measured without colliding into the sensors. Each experiment was repeated 30 times (resulting in 900 readings for each point). To evaluate the statistical difference between repeatability at the different points Friedman's a-parametric analysis was employed. A comparison of identical points (with same X and Y positions) at different heights was made using the *t*-test (two sample tests assuming unequal variances).

3. ERROR ANALYSIS MODEL

The error-analysis model[12] is an analytical model that determines repeatability for a given position considering only the geometric parameters of the robot's movement. It combines possible errors in each direction by applying partial derivatives to the robot's forward kinematic model to obtain the total error (Er) at a given location (X, Y, Z):

Statistical error model	Absolute model (maximum error)
$Er = (Ex^2 + Ey^2 + Ez^2)^{0.5}$	$Er = abs(Ex) + abs(Ey) + abs(Ez)$

where

$$E_s = \sqrt{\left(\Delta\varphi_1 \frac{dp_s}{d\varphi_1}\right)^2 + \left(\Delta\varphi_2 \frac{dp_s}{d\varphi_2}\right)^2 + \left(\Delta\varphi_3 \frac{dp_s}{d\varphi_3}\right)^2 + \ldots + \left(\Delta\varphi_n \frac{dp_s}{d\varphi_n}\right)^2}$$

s—axis x, y *or* z

p_s—location of the robot on s axis for $s = x, y, z$

φ_i—robot joint angles.

To calculate this error both φ and $\frac{dp_s}{d\varphi_i}$ must be determined.

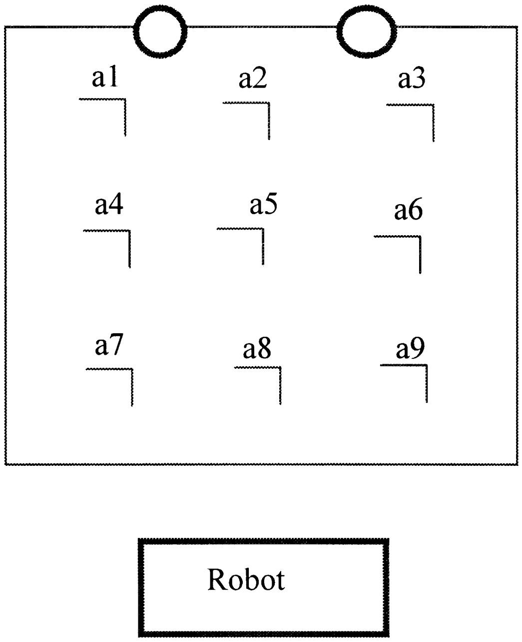


Fig. 2. Determination of nine target points on experimental surface.

Table I. Summaries of experimental results for five different speed and weight conditions.

Experiment conditions (payload_% max.speed)	1 kg_50	1 kg_80	1 kg_100	2 kg_50	2 kg_80
Average (L)	0.0043	0.0078	0.2744	0.00744	0.0199
Standard deviation (Si)	0.0019	0.0048	0.7072	0.00357	0.0203
Repeatability (Rp)	0.0103	0.0224	2.3962	0.01815	0.0809

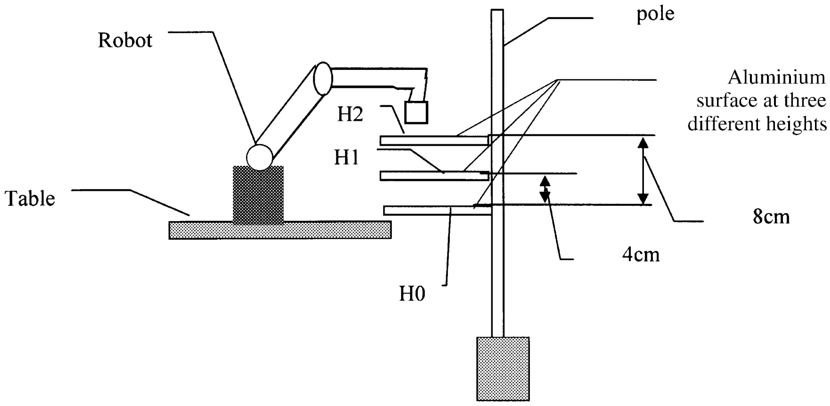


Fig. 3. Platform for setting the height of the experimental point.

φ is derived from the experimental results.

$\frac{dp_s}{d\varphi_i}$ is derived using the angles determined from the inverse kinematic model.

The error analysis model includes the following steps:

(i) Calculate robot angles (φ) corresponding to desired location using the inverse kinematic model
(ii) Derive partial derivatives of the forward kinematic model.
(iii) Substitute experimental results of joints angle error (φ_i) and robot angles (φ_i) into partial derivatives of the forward kinematic model (step 2).
(iv) Calculate statistical and absolute errors.

Using this procedure the complete error analysis model for the CRS robot is detailed in Appendix A. Applying this

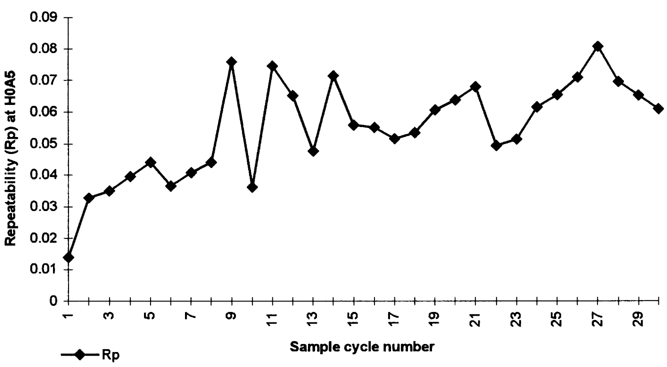
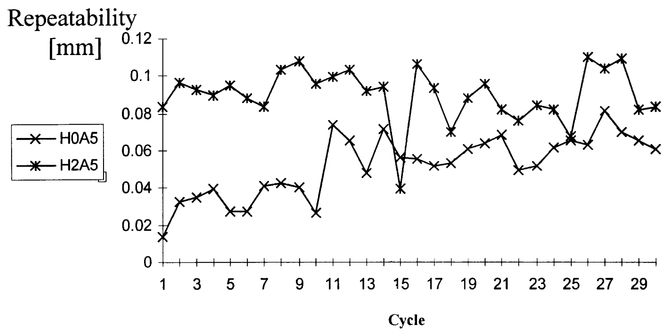


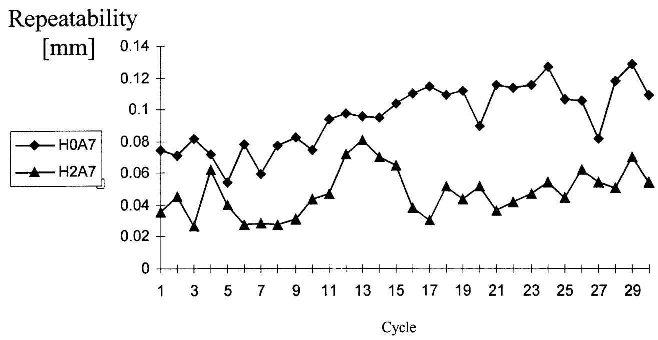
Fig. 4. Repeatability values at point H0A5 (900 samples).

Table II. Average repeatability at different locations.

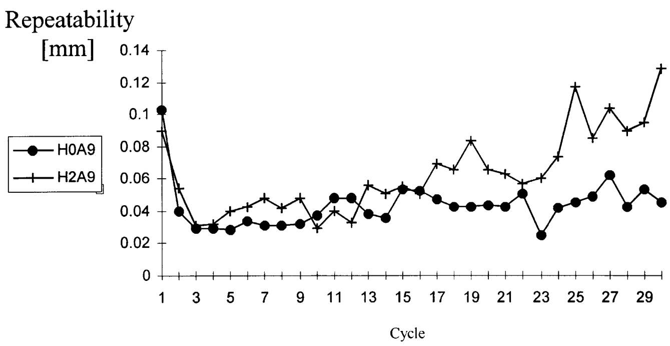
Point Height	A1	A5	A7	A9
H0	0.064257139	0.05201	0.095365	0.043396
H2	0.044302	0.090012	0.047672	0.063131



(a)



(b)



(c)

Fig. 5. Comparison of repeatability at different heights: (a) for location A2; (b) for location A5; (c) for location A9.

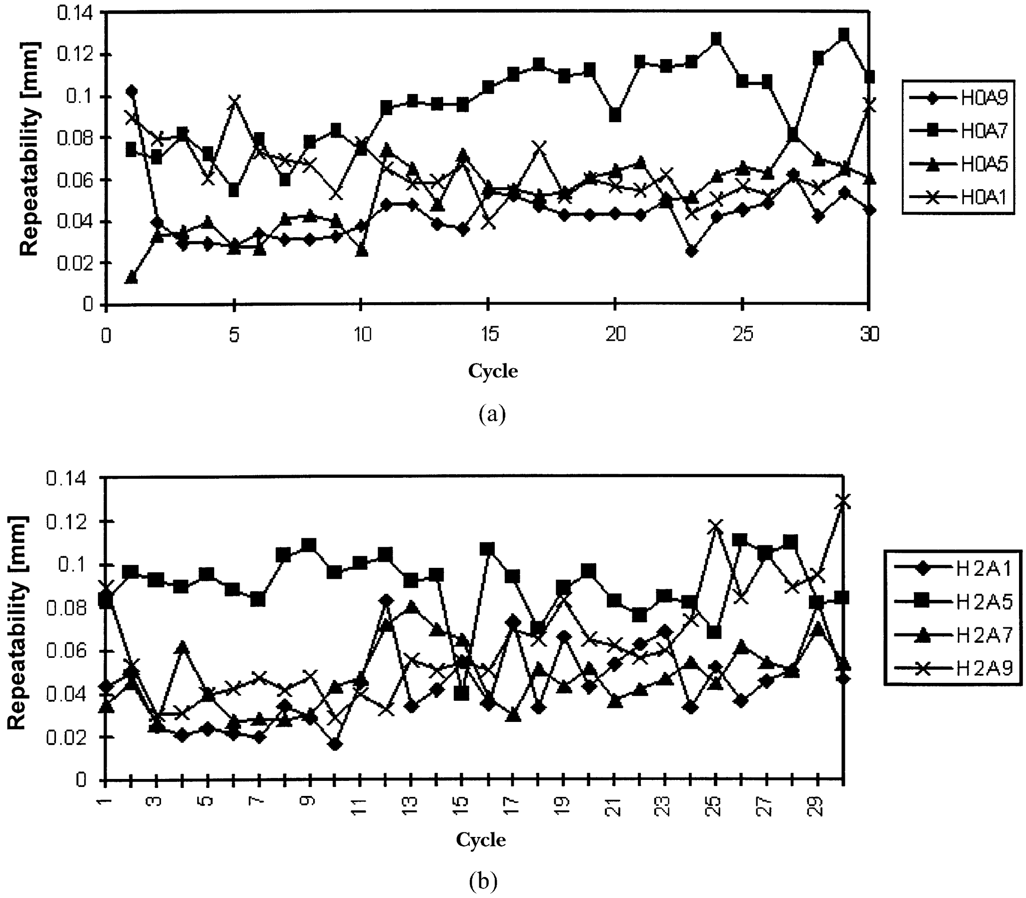


Fig. 6. Comparison of repeatability at different locations: (a) for height H0; (b) for height H2.

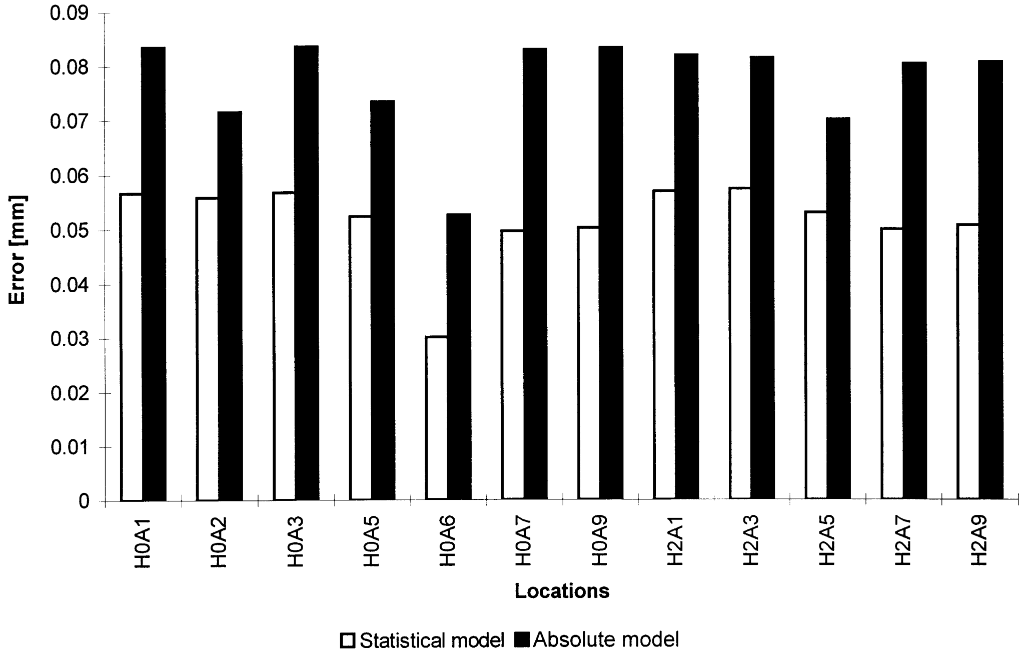


Fig. 7. Comparing results of the absolute model maximum error to the statistical model.

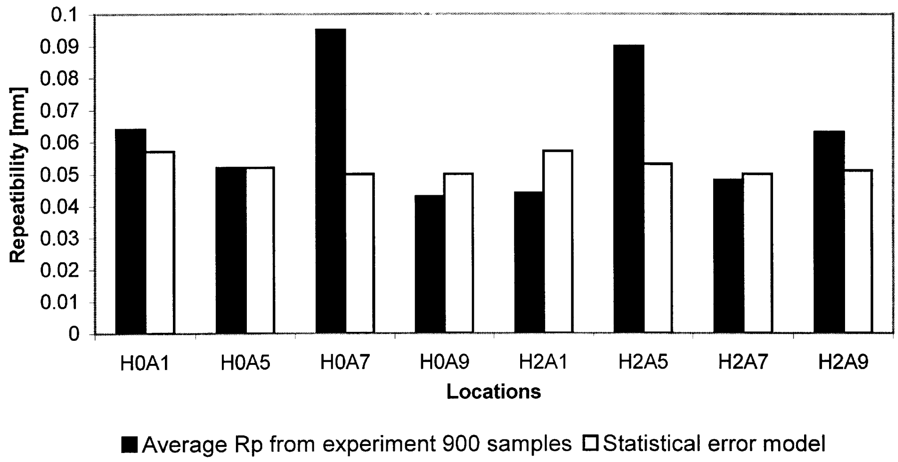


Fig. 8. Comparison between statistical model results and experimental results (900 samples).

model for varying values of X and Y at a constant height yields a three dimensional mapping which describes the change of repeatability; this can be used to determine preferable working points. This mapping was compared to the experimental results.

4. RESULTS AND DISCUSSION

Results indicated that the points could not be compared using an analysis of variance (ANOVA) since:

(i) the values are not normally distributed; repeatability increased along time (Figure 4).

(ii) the variances at the different points are unequal (Cochran's homeostatic test yielded values of 0.268 and 0.468). Hence, Friedman's a-parametric analysis was applied to evaluate the statistical difference between repeatability at the different points. An evaluation of the influence of target location on repeatability (Table II) indicated:

a) significant difference between repeatability at the different target locations ($\alpha < 0.01$, $\chi_r^2 = 146.1$)

b) relative position of the points influences repeatability ($\alpha < 0.01$, $\chi_r^2 = 116.033$)

c) significant difference between repeatability at different target locations of the same height ($\alpha < 0.01$, $\chi_r^2 = 11.3$, Figure 5)

d) height influences repeatability ($\alpha < 0.01$, Figure 6).

As expected, the absolute error model yielded higher errors as compared to the statistical model (Figure 7). The statistical model is more similar to the experimental results (Figure 8). The statistical model yields similar results to the experimental results (containing 900 samples), except for locations H0A7 and H2A5 in which the experimental results are larger. The trends of values are similar (Figure 9). Note that differences of 3 mm between the actual target location and the location entered into the model could have been introduced due to measurement errors in the experimental setup.

The significant differences noted for the different heights and locations correspond to results obtained in previous research[9] and indicate the importance of the proposed experimental evaluation method. Using the error-analysis model, a three-dimensional mapping of repeatability can be

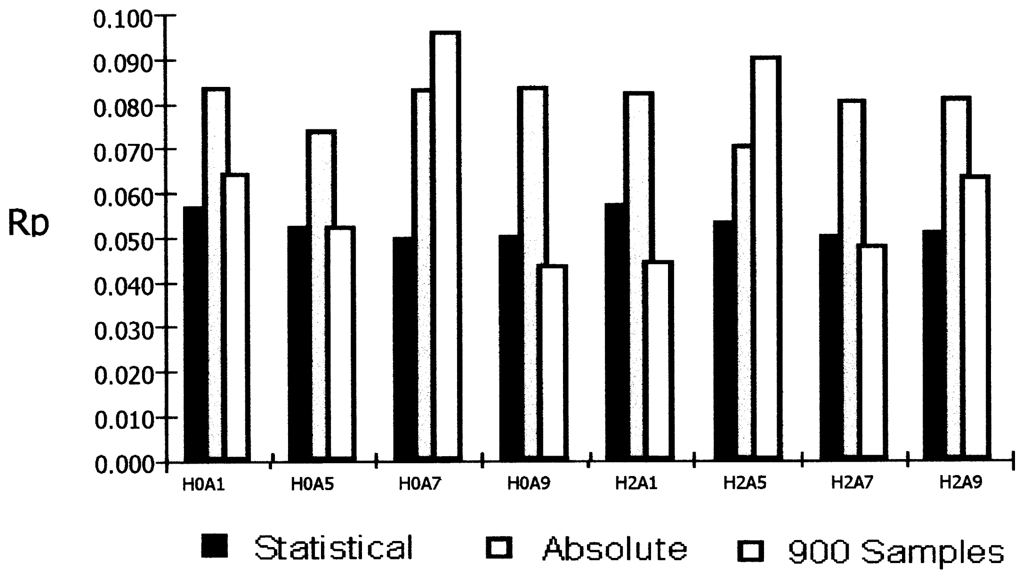


Fig. 9. Comparison of repeatability values of experiment (900 samples), statistical model and absolute model.

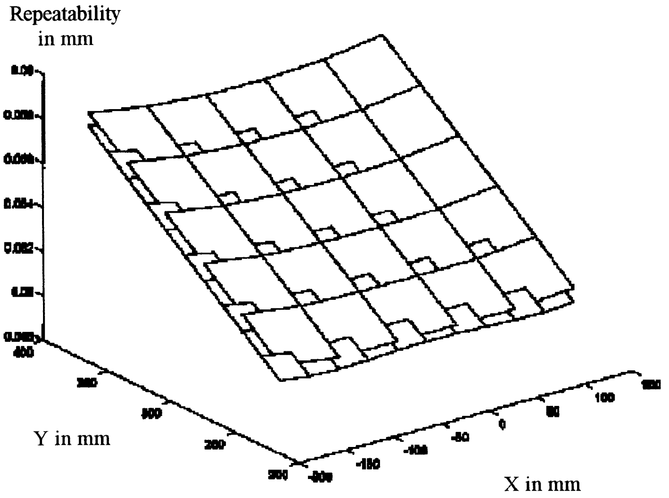


Fig. 10. Error estimation for locations on two surfaces at different heights.

estimated at different heights (Figure 10). This mapping can indicate locations with minimum repeatability without the need for extensive experimentation. Hence, this model is an important tool in robotic cell layout design.

5. CONCLUSIONS

Experimental results indicated that there was a significant statistical difference between repeatability at different locations in the workspace and that the height of the target point influenced repeatability. This indicates the significance in repeatability evaluation in the design of a robotic cell layout. Experimental results tended to those derived from the error analysis kinematic model. This implies that to determine the optimal target location within the robot's workspace, there is no need for extensive experimentation; instead, only a few target points can be sampled and compared to an error-analysis model and thus the best location can be selected.

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APPENDIX A. CRS ERROR ANALYSIS MODEL

1. Forward kinematic model

$$P_X = -d_5\cos(\varphi_1)\sin(-\varphi_4-90)+a_3\cos(\varphi_1)\cos(-\varphi_3)+a_2\cos(\varphi_1)\cos(-\varphi_2)$$

$$P_Z = -d_5\cos(-\varphi_4-90)-a_3\sin(-\varphi_3)-a_2\sin(\varphi_1)+d_1$$

$$P_Y = -d_5\sin(\varphi_1)\sin(-\varphi_4-90)+a_3\sin(\varphi_1)\cos(-\varphi_3)+a_2\sin(\varphi_1)\cos(-\varphi_2)$$

2. Inverse kinematic model

$$\theta_1=\tan^{-1}\left(\frac{P_y}{P_x}\right)$$

$$\theta_2=\tan^{-1}\left(\frac{\alpha(a_3C_3+a_2)-\beta a_3S_3}{\beta(a_3C_3+a_2)+\alpha a_3S_3}\right)$$

$$\theta_3=\cos^{-1}\left(\frac{\alpha^2+\beta^2-a_2^2-a_3^2}{2a_2a_3}\right)$$

$$\theta_4=\cos^{-1}(-a_Z)-\cos^{-1}\left(\frac{\alpha^2+\beta^2-a_2^2-a_3^2}{2a_2a_3}\right)$$

$$-\tan^{-1}\left(\frac{\alpha(a_3C_3+a_2)-\beta a_3S_3}{\beta(a_3C_3+a_2)+\alpha a_3S_3}\right)$$

$$-\theta_5 = \tan^{-1}\left(\frac{-O_Z}{N_Z}\right) = \tan^{-1}\left(\frac{S_{234}S_5}{-S_{234}C_5}\right)$$

if $\theta_2 + \theta_3 + \theta_4 = 0$

then $\theta_1 \pm \theta_5 = \tan^{-1}\left(\frac{O_X}{N_X}\right)$

$\alpha = a_2S_2 + a_3(S_2C_3 + C_2S_3)$

$\beta = a_2C_2 + a_3(C_2C_3 - S_2S_3)$

After finding the robot angles that match the position (X, Y, Z), the angle is substituted into the position in the partial derived equations (before there is a need to convert the model angles to the robot angles since the robot angles are measured relative to world coordinates while the model angles are measured relative to previous links corresponding to Denavit Hartenberg kinematic solution).

$t_i =$ robot angles

$q_i =$ robot angles

$t_1 = q_1$

$t_2 = -q_2$

$t_3 = -(q_2 + q_3)$

$t_4 = q_2 + q_3 + q_4 - pi/2$

After finding the transformation the positional errors are calculated.

3. X Partial derivatives calculation:

$dP_{x_1} = \sin(t_1)(d_5 \sin(-t_4 - pi/2) - a_3 \cos(-t_3) - a_2 \cos(-t_2))$

$dP_{x_2} = -a_2 \cos(t_1) \sin(-t_1)$

$dP_{x_3} = -a_3 \cos(t_1) \sin(t_3)$

$dP_{x_4} = d_5 \cos(t_1) \cos(-t_4 - pi/2)$

4. Y Partial derivatives calculation:

$dP_{y_1} = \cos(t_1)(-d_5 \sin(-t_4 - pi/2) + a_3 \cos(-t_3) + a_2 \cos(-t_2))$

$dP_{y_2} = -a_2 \sin(t_1) \sin(t_2)$

$dP_{y_3} = -a_3 \sin(t_1) \sin(t_3)$

$dP_{y_4} = d_5 \sin(t_1) \cos(-t_4 - pi/2)$

5. Z Partial derivatives calculation:

$dP_{z_1} = -a_2 \cos(t_1)$

$dP_{z_2} = 0$

$dP_{z_3} = a_3 \cos(t_3)$

$dP_{z_4} = -d_5 \sin(-t_4 - pi/2)$

Finally, the total error is calculated.

6. Total error calculation:

$Ex = ((dtdPx_1)^2 + ((dtdPx_2)^2 + (dtdPx_3)^2 + (dtdPx_4)^2)^{0.5}$

$Ey = ((dtdPy_1)^2 + ((dtdPy_2)^2 + (dtdPy_3)^2 + (dtdPy_4)^2)^{0.5}$

$Ez = ((dtdPz_1)^2 + (dtdPz_2)^2 + (dtdPz_3)^2 + (dtdPz_4)^2)^{0.5}$