Study of Datum Location Error on the Accuracy of Industrial Robot

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Abstract—Robots are being used in many areas. The robot performance constrains are repeatability and accuracy. Standardised testing and evaluation techniques are needed to examine the process capability of a wide variety of robot. Robot calibration is a term applied to the procedure used in determining actual values which describe the geometric dimensions and mechanical characteristics of a robot. The robot accuracy evaluation method is introduced using ball-link system. To define individual error sources of the robot, is difficult because robots have jointed multi-axes and this can pose severe problems when trying to isolate the individual errors related to one axis. The error sources are determined using one or two axes operation. The datum location error of the axes is evaluated using a simple geometric method. Also the combined datum location error of the robot is evaluated using a ball-bar link system. The errors is analysed by assessment of the shape and error band of circular motion. The datum location error of robot axes is analysed

Keyword-Robot accuracy, Datum location error, Robot calibration, Ball-bar link system

I. INTRODUCTION

Robots are being used in many areas in part assembly, deburring, and welding etc. These operations require performance that was needed on robot system. The robot performance constrains are repeatability and accuracy. The specifications quoted by the manufacturers, are not sufficient to determine the process capability of robot required. Also accuracy is important for offline programming and process planning in robot application. Standardized testing and evaluation techniques are needed to examine the process capability of a wide variety of robot. Robot calibration is a term applied to the procedure used in determining actual values which describe the geometric dimensions and mechanical characteristics of a robot. Many robot calibration methods have been introduced [3,4]. Also robot accuracy evaluation method is introduced using ball-link system and introduced that ball-bar device was used in both a trammeling and circular mode operation [2]. To define individual error sources of the robot, is difficult because robots have jointed multi-axes and this can pose severe problems when trying to isolate the individual errors related to one axis. In this paper, the error sources are determined in a serial procedure using robot axes operation. The datum location error of the axes, which are part of the wrist section of the robot axes, is evaluated using a simple geometric method. Also the combined datum location error of the robot wrist axes is evaluated using a ball-bar link system. The errors in the wrist axes are analyzed by assessment of the shape and error band of circular motion. The datum location error of shoulder axes is analyzed.

II. DATUM LOCATION ERROR OF THE GAMMA AXIS

The perpendicularity of an axis in a milling machine with respect to the cutter spindle is measured by means of the trammel technique [1]. The trammel technique uses the machine bed as the reference plane. However, for robot applications, a reference plane is not readily available in the robot working space and consequently an alternative technique must be adopted [2]. A trammel technique using the ball links was applied to the robot to measure the datum location error of the one of wrist axis [2]. The datum location error of the wrist axis was determined by this technique.

A. *Techniques to establish Gamma axis alignment*

Figure 1 illustrates a consistent algorithm for the industrial robot arm used in the research.

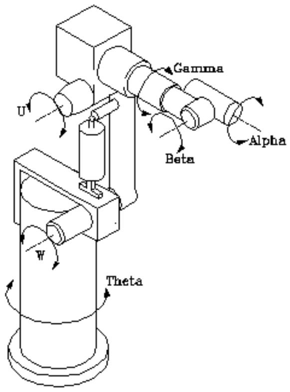


Fig. 1. Link coordination systems for the 6 axes articulated robot

The trammel technique can also be used to find the datum location error of the Gamma axis. The basic technique is shown in figure 2. The small surface plate is located in the robot working space. The sensor is fixed in the robot end effector and set within its range. The difference in reading noted when the Theta axis is rotated on the surface plate. If the plate is perpendicular to the Theta axis, then the deviation of the indicator will be zero. When the Theta axis is rotated at θ and -θ degrees on the plate as shown in figure 2, readings are taken from position 1 to 3. The place of the surface plate is adjusted to coincide with the Theta axis such that the dial gauge gives the same reading at these points. The surface plate is also adjusted with respect to the perpendicular to the Theta axis by correcting the difference in the reading between position 1 and 3.

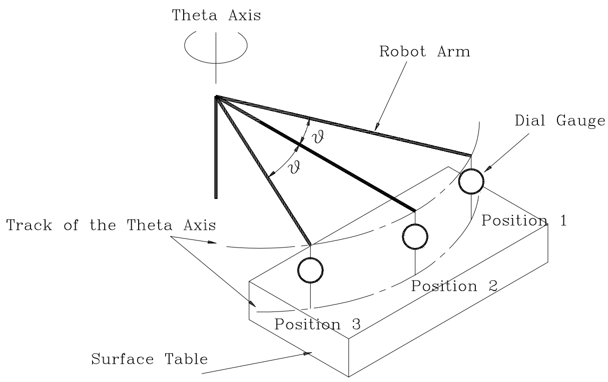


Fig. 2. Setting method of the surface plate using dial gauge

Once the surface plate has been set perpendicular to the Theta axis, the datum location error of the Gamma axis can be established. If the datum location error of the Gamma axis is negligible, the distances d and d' between the endpoint of the robot and the surface plate, should be the same reading when the angular position of the Beta axis is at 90 degrees and -90 degrees. If the distances d and d', are not the same, then their difference will correspond to the datum location error of the Gamma axis as shown figure 4. This error is found with

$$\theta = Sin^{-1}\left((d - d')/t\right)$$

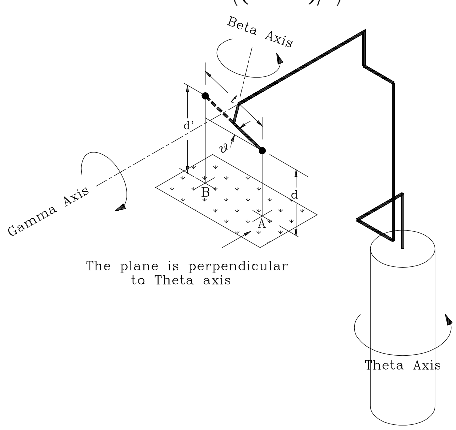


Fig. 3. Principle of the datum location error of the Gamma axis

B. Experimental determination of the datum location error of the Gamma axis of the industrial robot

To set the surface plate, a indicator was used and attached to the end effector of the robot. The surface plate was set to perpendicular to the Theta axis by rotating the Theta axis as shown in figure 3. The remainder of the robot axes were fixed during this rotation. With 90 degrees rotation of the Beta axis, the reading of distance d at point A was measured, and then by rotating the Beta axis through 180° the reading of distance d' at point B was measured at -90 degrees position of the Beta axis. In the experimental, it was found that d was shorter than d'. The distance d and d' were then adjusted until they were equalised by rotating the Gamma angle at 90 and -90 degrees position of Beta axis. A −0.1626° correction was required. This represents the datum location error of the Gamma axis.

III. COMBINED DATUM LOCATION ERROR OF THE WRIST (GAMMA AND BETA) AXES IN THE CIRCLE CONTOURING USING 2 ROBOT AXES OPERATION

A. Combined datum location error of the wrist axes of the industrial robot

A circle was generated by simultaneous movement with 2 axes of robot (i.e. the W and U axes) as shown in figure 4. The Beta axis was rotated to the 90 degrees position to facilitate the generation of the circle using the 2 robot axes. The generated circle plane will be perpendicular to the W and U axes of the robot. The ball was fixed at the centre of robot end effector, and the base ball fixed on a magnetic base was located on the tripod in the robot working space. The kinematic link was located between the base ball and the robot end effector by magnetic force. The base ball was set to the centre of the circle by the reading of the kinematic link on the circle contouring. The radius of this circle was measured during the circle contouring in the clockwise and anticlockwise direction. The process was repeated by rotating the Beta axis through 180 degrees (i.e. -90 degrees position of the Beta axis). The circles generated at the 90 degrees and -90 degrees position of the Beta axis in the figure 4 can be analysed with the shape of the circle contouring. If there is no datum location error of Gamma and Beta axes, these circle shapes are exactly the same.

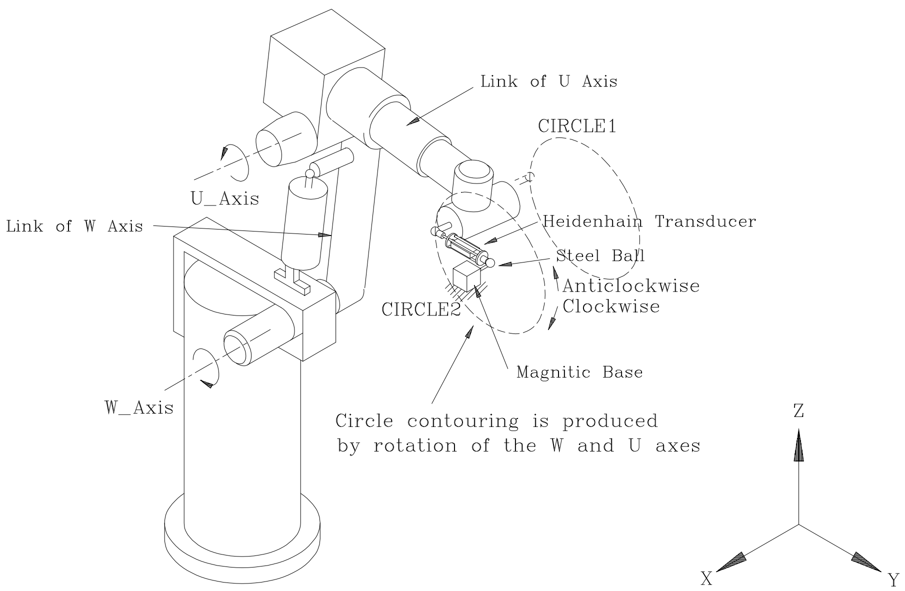
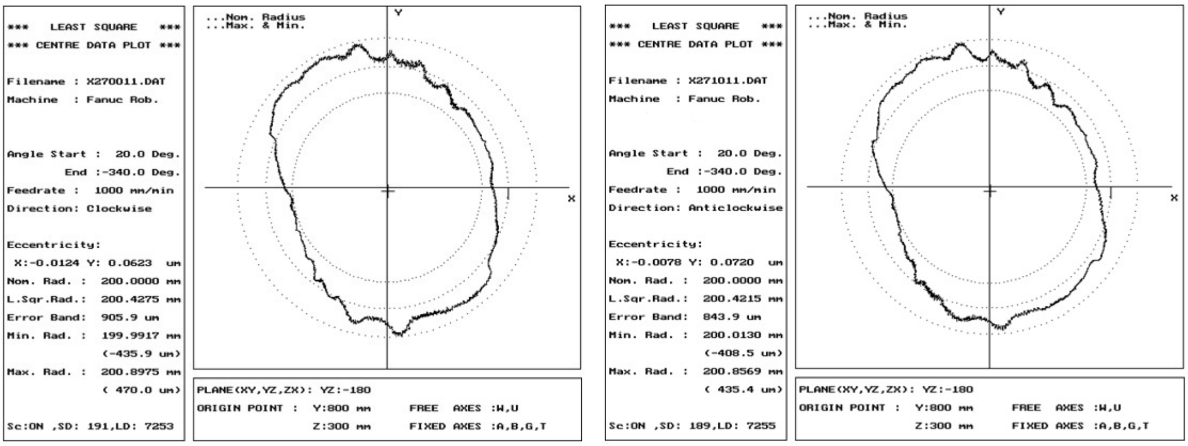


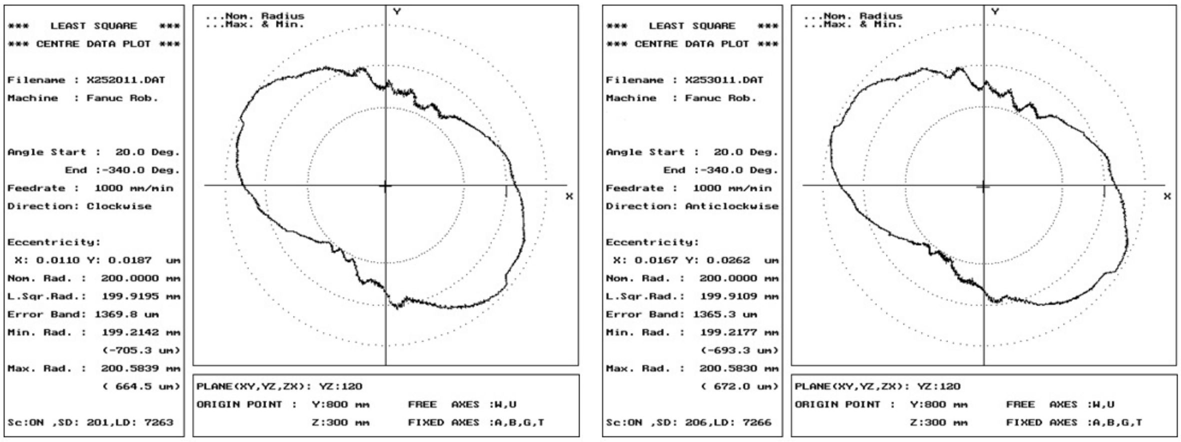
Fig. 4. Circle generating method using the W and U axes

A circle with 200 mm radius was generated by movement of the W and U axes in the robot working space. The circle points were programmed in the robot controller through the teach pendant; the path being generated by rotating the W and U axes only. Note that the other axes were constrained in the inverse kinematic calculation. The circle radius was measured with a ball-bar link system over the circle contouring in both directions. The results are shown in Figures 5 and 6. Figure 5 shows the results for both directions at the circle 1 position. Similarly figure 6 shows result at the circle 2 position. As can be seen that for a nominal radius is 200.00 mm, the actual radius of the least squares circle is more than 200.00 mm in figure 5, and less than 200.00 mm in figure 6. The figures 5 and 6 also indicate a large error band about 843.9μm to 1369.9 μm. Again by comparing the two sets of data, the two plots should show the same error band and least squares circle radius i.e. circle 1 and circle 2 should be same radius and circular shape.



(a) clockwise (b) anticlockwise

Fig. 5. Experimental data of circle contouring using two axes on circle 1



(a) clockwise (b) anticlockwise

Fig. 6. Experimental data of circle contouring using two axes on circle 2

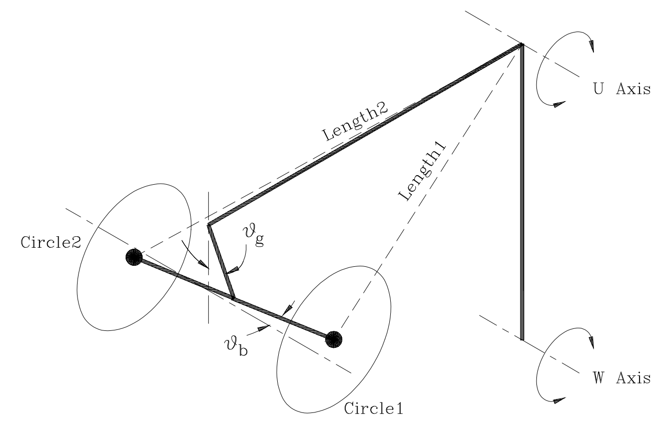
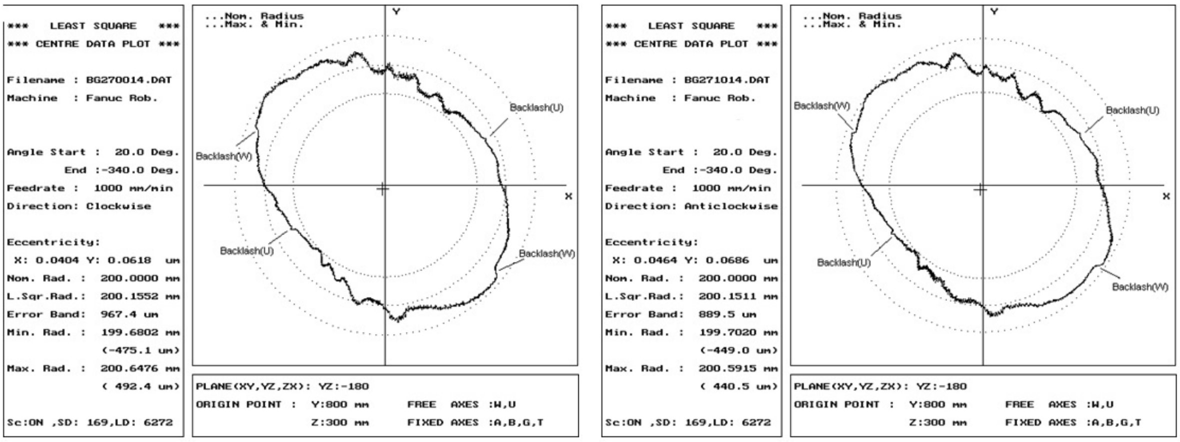


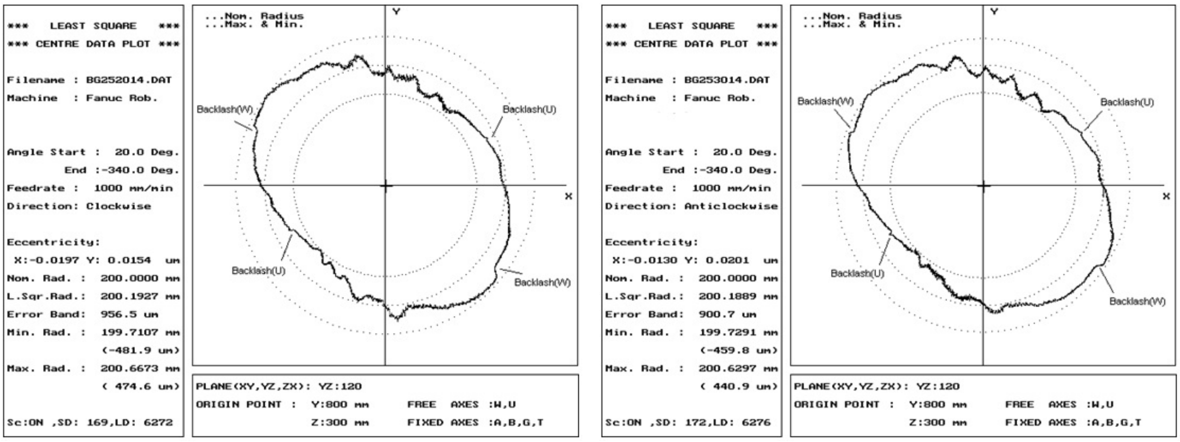
Fig. 7. Error configurations of the Gamma and Beta axes

Figures 8 and 9 are shown the corresponding experimental results after compensating for the datum location error of the Gamma and Beta axes. Comparing figures 8 and 9 shows circle shapes that are similar and the error bands and least squares circles that are almost identical. Therefore the different shapes of circles shown in figures 5 and 6 are clearly due to the result of datum location error of the Gamma and Beta axes.



(a) clockwise (b) anticlockwise

Fig. 8. Experimental data after compensation of the Gamma and Beta axes datum location error on circle 1



(a) clockwise (b) anticlockwise

Fig. 9. Experimental data after compensation of the Gamma and Beta axes datum location error on circle 2

B. *Simulation result of datum location error of the Gamma and Beta axes of the industrial robot*

The X, Y and Z positions to make the theoretical circle contouring in the robot working space is calculated and input into the inverse kinematic solution program, and then the corresponding angles of the W and U axes are found i.e. the X, Y and Z positions in the robot working space correspond to the angles of the W and U axes. The calculated angles and the datum location error of the Gamma and Beta axes were input in the kinematic solution. The result of this computation gives the X, Y and Z positions of the robot with the influence of the datum location error of the Gamma and Beta axes. For comparison with the experimental results the circle radius and error band were evaluated. The simulation procedure is shown figure 10.

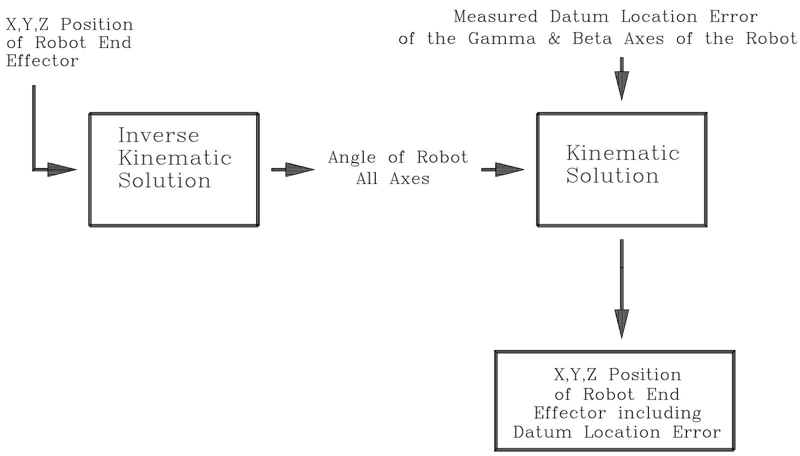
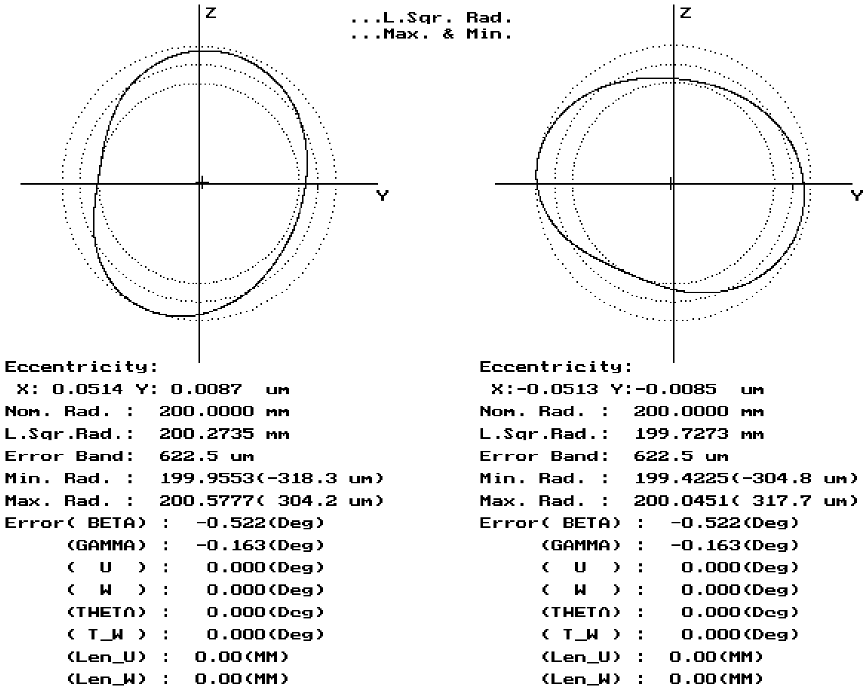


Fig. 10. Procedure of the simulation data processing

Figure 11 shows the simulation result having combined datum location error of the Gamma(-0.163) and Beta(-0.522) axes. The simulation result shows the different shapes of the circles produced at position circle 1 and 2. The least squares circle and the error band match the corresponding results shown in the experimental data depicted in figures 5 and 6. Therefore it can be confirmed that the error source in the experimental plot data of figures 5 and 6 is due to the datum location error of the Gamma and Beta axes. However as the circle shape is still elliptical, it could be due to the backlash and gear transmission error of the W and U axes in the intermediate joint reduction gear mechanism and the datum location error of the U axis, i.e. the angle between the arm of U and W axes is not a right angle in the robot configuration. The gear transmission error is introduced and measured and analysed gear transmission error [8].



(a) Clockwise (b) anticlockwise

Fig. 11. Simulation data having the datum location error of the wrist axes.

C. Joint backlash of U and W axes

Joint backlash is an error source which has a significant contribution not only on degrading the positioning accuracy of the joint but on the dynamic stability as well. In machine tool calibration the common method used to check for backlash is the bi-directional approach to the same target or alternatively the circular contouring motion method. The backlash is evaluated as the difference in a position when approached in a positive and in a negative direction. A similar approach can be adopted to assess the manipulator joint backlash. However in the circular contouring motion for robot applications, the backlash occurs at the direction changing point of the robot axes angle during circle contouring.

D. Trace of angle change of robot axes during the circle

Figure 12 shows the angle change of the W and U axes during a simulated circle contouring path. The displacement angle in the W axis changes from 30 degrees to -10 degrees during the circle generation and the U axis is changed from 10 degrees to -45 degrees. The negative direction of motion of the W axis changes to a positive direction at 157.0 degrees on the circle and shows the minimum angle position of the W axis. The positive direction of motion of the W axis changes to a negative direction at 323.5 degrees on the circle and shows the maximum angle position of the W axis. These angular change points are expected backlash effects if backlash errors as described previous section were presents. When the circle is generated, the radius of circle should suddenly increase or decrease by the amount of backlash error at the point of the angle direction change.

When the circle contouring is plotted using real data as in figures 8 and 9. The large displacement change in the circle radius shows at the 157.0 and 323.5 degrees position. These points correspond with the maximum and minimum angle points of the W axis (i.e. backlash). The backlash points of the U axis are at 26.6 degrees and 206.6 degrees on the circular contouring. As shown in figures 8 and 9, these backlash points of the W and U axes are exactly matched with the angle change graph of figure 12 and indicate that the backlash error of the W and U axes is relatively small.

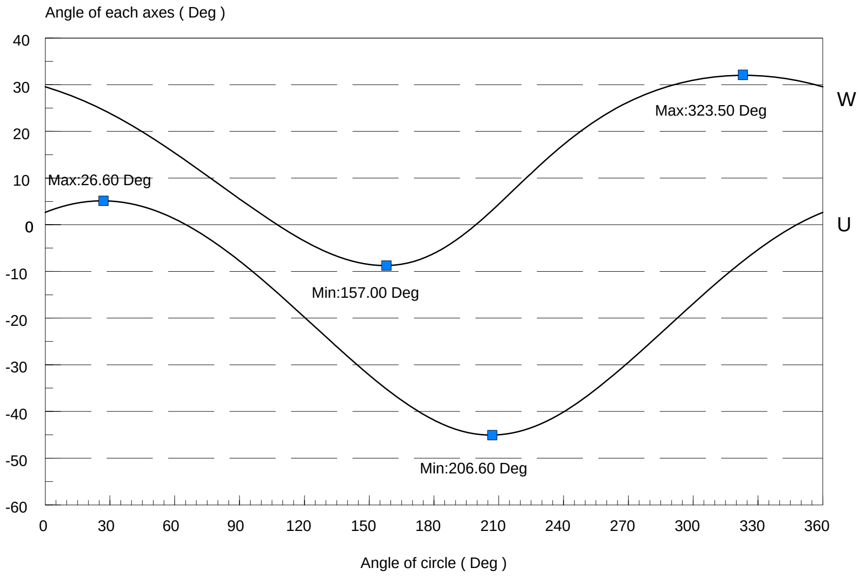


Fig. 12. Trace angle changes of the W and U axes during the circle

As shown in figures 8 and 9, the datum location error of the Gamma and Beta axes has been compensated, but there is a noticeable fluctuation around 90 and 270 degrees on the circle contouring. The source of these fluctuations could be the mechanical/constructional errors in the operation of the robot axes. For instance these fluctuations could be due to the gear transmission error which is the eccentric and pitch error in the reduction gear units driving the W and U axes. The gear transmission error is introduced and he measured and analysed gear transmission error [5].

IV. DATUM LOCATION ERROR OF THE W AXIS

A. Significance of the datum location error of the W axis

The industrial robot is normally set with the main axis(Theta) parallel to the link of the W axis in the robot configuration i.e. the link of W axis is perpendicular to the XY plane. Figure 13 shows an example of the W axis datum location error model between the Theta and W axes. If the datum location error of the W axis does not exist in the robot configuration and the circle contouring is created with the three axes operating in the XY plane, then the resultant circle shape should be a perfect circle. However if the circle is generated with the W axis covering a datum location error due to inaccurate robot configuration, the circle shape will be changed due to the datum location error of the W axis.

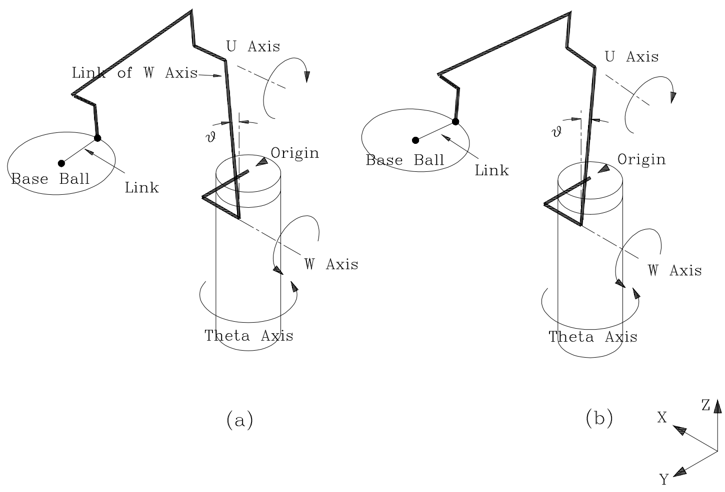
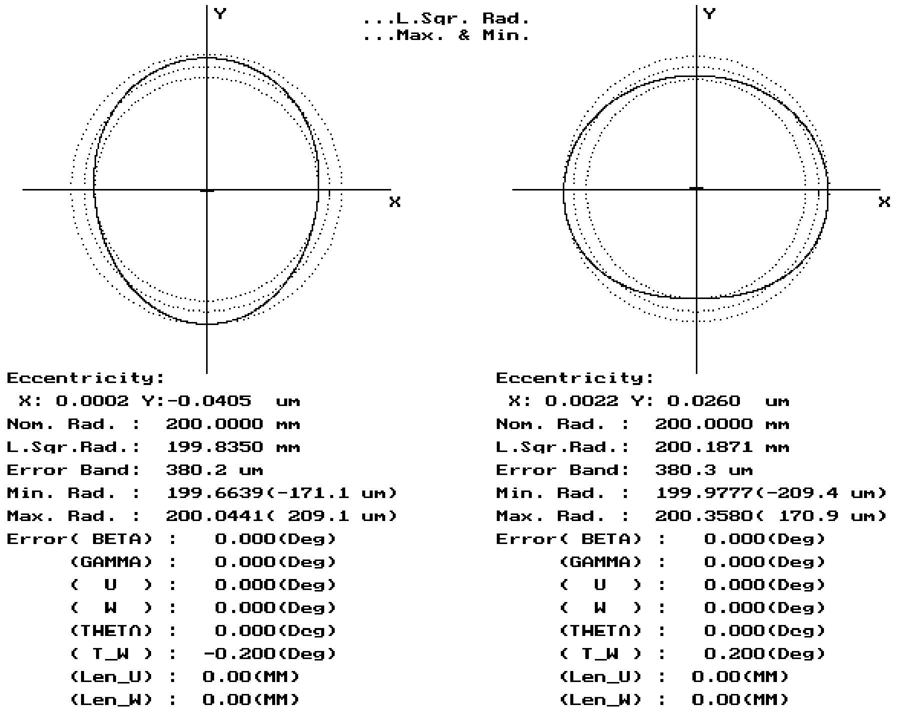


Fig. 13. Error configuration of the datum location error of the W axis link



(a) (b)

Fig. 14. Simulation result on the datum location error of the W axis

Figure 14 shows the simulation output with a ±0.2 degrees datum location error of the W axis, if the link of the W axis is not square to the XY plane, the circle becomes an elliptical shape as shown in figure 14(a) and (b). Comparing figure 14 (a) and (b), the error bands are almost identical, but the circle shape and radius of circle are different due to the datum location error of the W axis. Figure 15 shows the relationship between the error band and the datum location error of the W axis. As the datum location error is increased, the error band also increases. When the datum location error is positive, the radius of the least squares circle is larger than the nominal radius. Conversely when the datum location error is negative, the radius of the least squares circle is smaller than the nominal. The intersection point of the two least squares lines in the error band is at 0 degrees of datum location in the W axis as shown in figure 15.

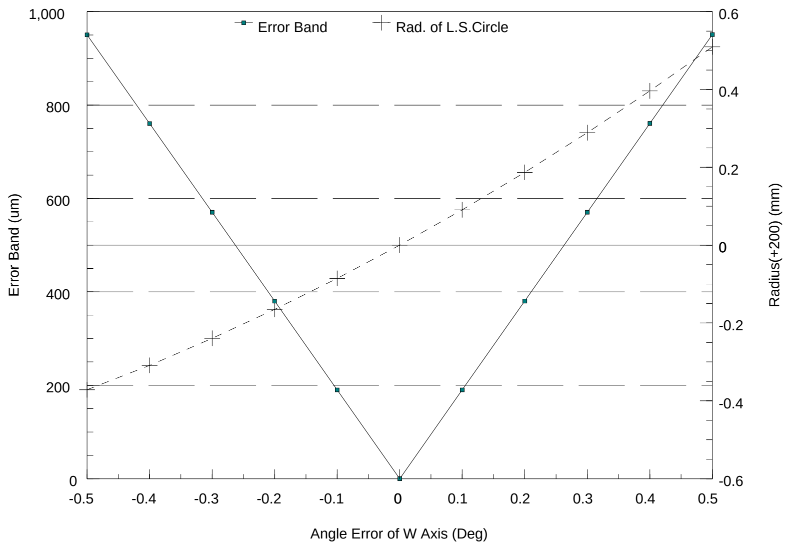
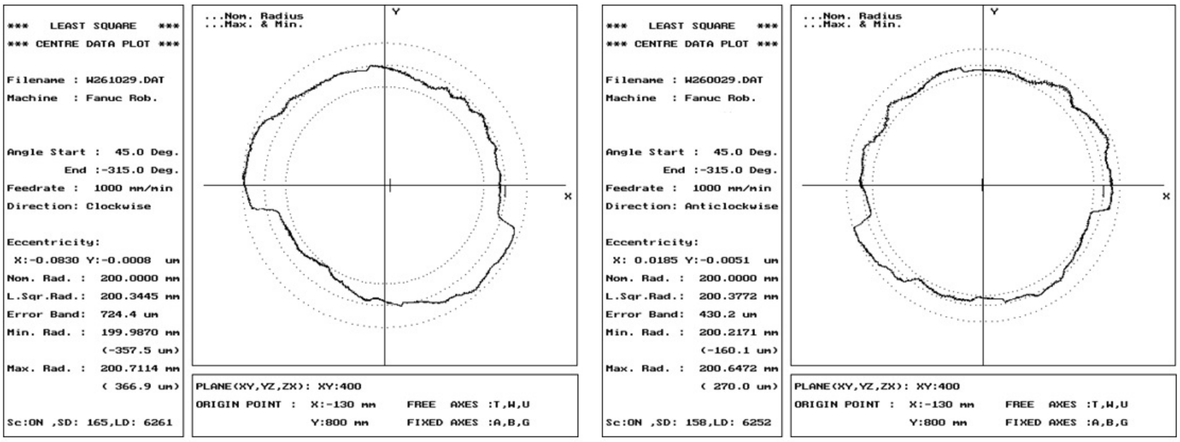


Fig. 15. The error band and radius Vs datum location error (W axis)

B. Compensation of the datum location error in the W axis

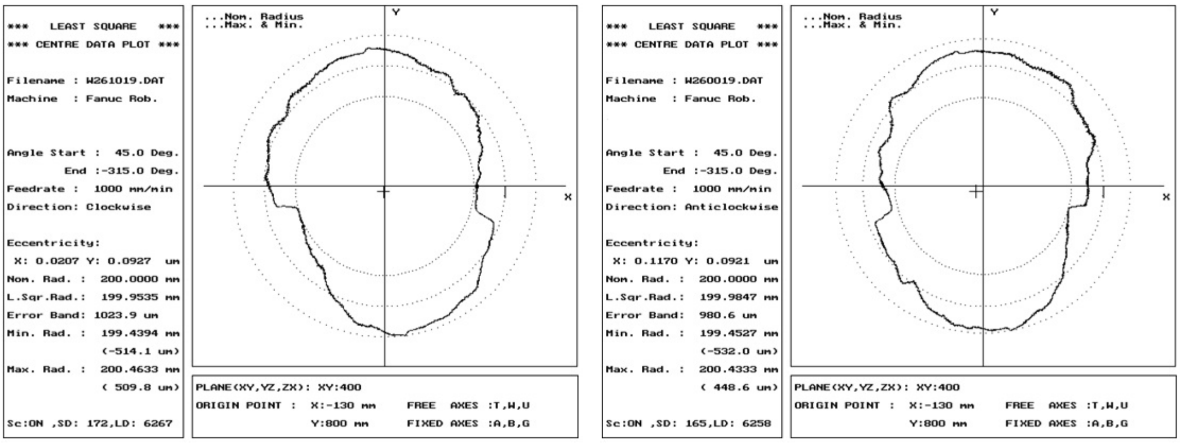
Figure 16 shows the experimental result with a 0.20° change of initial angle in the W axis. The radius in the anticlockwise direction is slightly larger than in the clockwise direction. Comparing figure 14 and 16, the radius of the least squares circle and error band are also increased. Figure 17 shows the result with a -0.20° change of initial angle in the W axis. Comparing figures 14 and 17, the error band is increased but the radius of the least squares circle is decreased. The circle shape is also extended in the Y axis direction. The large step on the circles is precisely observed due to the backlash of the Theta axis.

The relationship between the error band and the datum location error of the W axis is plotted and shown in figure 18. The diamond marked line on the graph shows experimental data, and the rectangular marked line shows the result after compensation for the gear transmission error of the robot axes. The two least squares lines were found with the compensated data. The slopes of the two straight lines appear in opposite directions. Therefore the optimum position of the W axis is defined by the intersection point of the two straight lines; the optimum angle of W axis being 0.0048 degree from the initial position of the W axis.



(a) clockwise (b) anticlockwise

Fig. 16. Experimental results with 0.20° of the datum location error of W axis



(a) clockwise (b) anticlockwise

Fig. 17. Experimental results with -0.20° of the datum location error of W axis

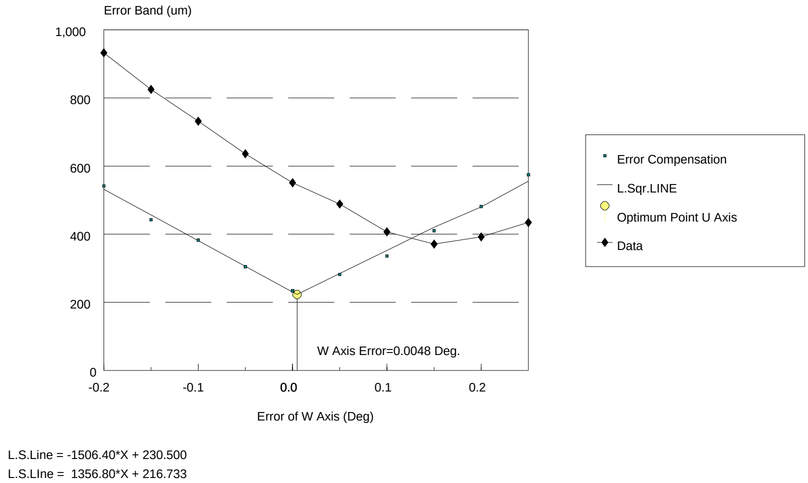
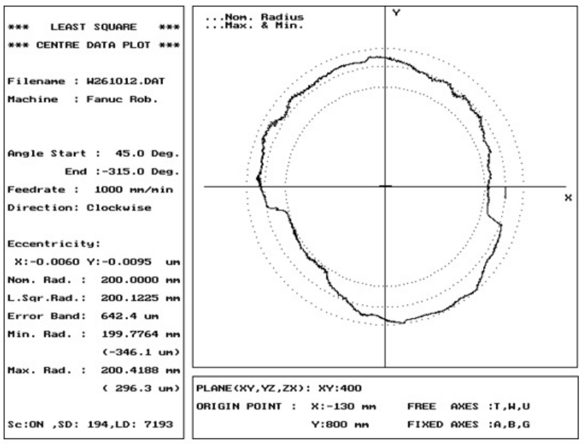
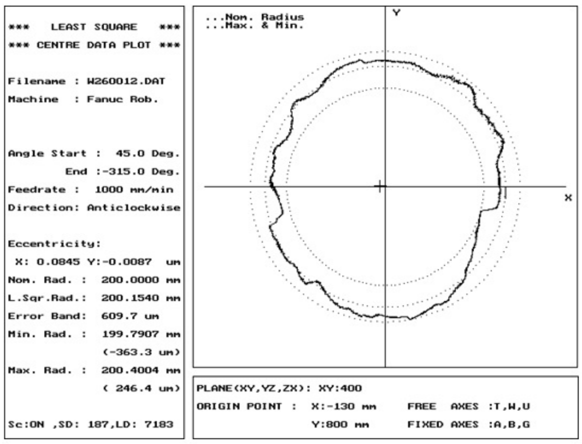


Fig. 18. Datum location error Vs. Error band in W axis

After the industrial robot was re-mastered to 0.0048° from the initial point of the W axis, the circle contouring was generated after this compensation, and the circle radius measured. The result is shown in figure 19 in the clockwise and anticlockwise direction respectively. These figures are similar to the circle shape in figure 20, which corresponds to the simulation data. The backlash points are shown at the same positions. The least squares radius for the experimental is 200.1225 mm for the clockwise direction as shown in figure 19(a) and 200.1156 mm as shown figure 20 for the simulation data. The corresponding error band shows almost the same value. The experimental plot figure 19(b) and the corresponding simulation plot figure 20 with backlash and datum location error, are also almost identical. Therefore it is confirm that the optimum position of the W axis is 0.0048° from the initial position of W axis.



(a) clockwise



(b) anticlockwise

Fig. 19. Experimental data after compensation of the datum location error of the W axis

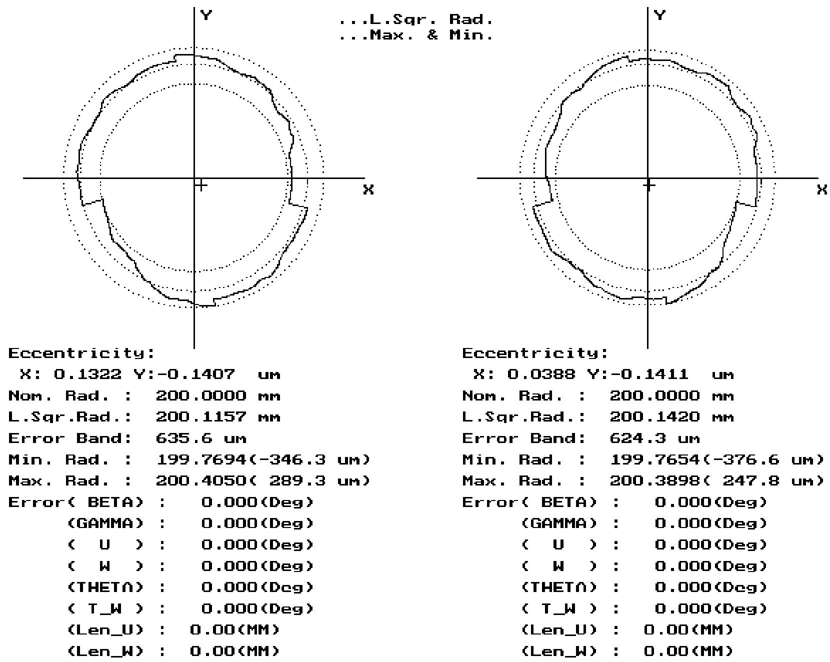


Fig. 20. Gear transmission and backlash error of Theta W and U axes(simulation)

V. CONCLUSION

The following conclusions can be drawn from investigation on the datum location error of robot axes. Geometric error components of industrial robots are generally difficult to establish compare with the orthogonal linear axes of machine tools. The error characteristic of industrial robot has totally different compare to machine tools in the circular test. Circular test data is a valuable technique for characteristic the robot error in terms of datum location error, backlash and gear transmission error etc. The datum location errors can be minimised by the procedure and technique proposed. Therefore the datum location error was shown a significant factor influencing the accuracy of the robot end effector. The test strategy devised using error band data from circular test, enabled the optimum poison of the datum to be established with a general methodology. Proposed techniques are useful to set up the industrial robot in the industrial site.

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