3D Volumetric Positioning Accuracy: Measurement, Compensation and Verification

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Abstract
The competition in global manufacturing today requires higher speed, higher accuracy and better quality machine tools. Twenty years ago, the largest machine tool positioning errors are lead screw pitch error and thermal expansion error. Hence measuring the 3 axes linear displacement errors is enough. Now, the linear displacement errors or lead screw pitch errors have been reduced by better ball-screw or linear encoder and pitch error compensation. The largest machine tool positioning errors become squareness errors and straightness errors. Hence to determine the 3D volumetric positioning accuracy, all 3 displacement errors, 6 straightness errors and 3 squareness errors have to be measured and compensated.

Recently, Optodyne has developed a new laser vector measurement technique for the determination of volumetric positioning errors including 3 displacement errors, 6 straightness errors and 3 squareness errors, in a few hours instead of a few days. Furthermore, assume the machine is repeatable, the pitch and yaw angular errors can also be determined.

Reported here is a complete positioning error measurement, including linear displacement errors, straightness errors, squareness errors, and pitch and yaw angular errors, of 4 Deckel Maho Gildemeister universal milling machines by using the latest LDDM technology and the laser vector measurement technique. The result of the measurement, the effect of volumetric compensation, and the quick check by body diagonal displacement, will be discussed.

Keywords
Manufacturing, CNC, Laser calibration, positioning errors, compensation, parts program.

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I . Introduction

Competition in global manufacturing today requires improving machine tool performance to achieve higher productivity, better quality and less downtime. To keep up with the speed and increased accuracy requirements, the machines have to be kept within tolerance, which means laser volumetric calibration and compensation are very important.

Twenty years ago, the largest machine tool positioning errors are lead screw pitch error and thermal expansion error. Hence measuring the 3 axes linear displacement errors is enough. Now, the linear displacement errors or lead screw pitch errors have been reduced by better ball-screw or linear encoder and pitch error compensation. The largest machine tool positioning errors become squareness errors and straightness errors.

To improve the volumetric positioning accuracy of the existing machine tools and to cut more accurate parts, the key is 3 D volumetric calibration and compensation. Using conventional laser interferometer to measure all these errors are time consuming and costly. However, using the new revolutionary laser vector measurement technique developed by Optodyne, the 3 D volumetric positioning errors, including 3 displacement errors, 6 straightness errors and 3 squareness errors, can all be measured in a few hours instead of a few days by a conventional laser interferometer. Hence the 3 D volumetric calibration and compensation become practical and enable tighter tolerance to be achieved.

Reported here is a complete measurement, including pitch and yaw angular errors, linear displacement errors, straightness errors, and squareness errors of 4 Deckel Maho Gildemeister Universal milling machine model DMU 80T by using the latest LDDM technology and the laser vector measurement technique. The result of the measurement, the effect of volumetric compensation, and the quick check by body diagonal displacement, will be discussed.

II. Rigid body positioning errors

For a 3-axis machine, there are 6 errors per axis or a total of 18 errors plus 3 squareness errors. These 21 rigid body errors [1] can be expressed as the following.

Linear displacement errors: Dx(x), Dy(y), and Dz(z)
Vertical straightness errors: Dy(x), Dx(y), and Dx(z)
Horizontal straightness errors: Dz(x), Dz(y), and Dy(z)
Roll angular errors: Ax(x), Ay(y), and Az(z)
Pitch angular errors: Ay(x),Ax(y), and Ax(z)
Yaw angular errors: Az(x), Az(y), and Ay(z)
Squareness errors: Øxy, Øyz, Øzx,
where, D is the linear error, subscript is the error direction and the position coordinate is inside the parenthesis, A is the angular error, subscript is the axis of rotation and the position coordinate is inside the parenthesis. The machine configuration is ZFXY, and the working volume is x = 0 to X, y = 0 to Y, and z = 0 to Z.

III. Pitch and yaw angular error measurement

For the linear displacement error measurement, the measured error D along x, y, and z-axis at each increment can be expressed as [2]:

$$DX = Dx(x) + m * Ay(x) + p * Az(x), \quad (1)$$
$$DY = Dy(y) + q * Ax(y) + s * Az(y), \quad (2)$$
$$DZ = Dz(z) + t * Ax(z) + u * Ay(z), \quad (3)$$

where Abbe offsets m and p are distances from the measurement line to the reference line in y and z directions respectively, q and s are distances from the measurement line to the reference line in x and z directions respectively, t and u are distances from the measurement line to the reference line in x and y directions respectively.

Hence, the linear displacement measurement can be used to determine the pitch and yaw angular errors by making 3 measurements, one along the top edge, one along the bottom edge, and one along the side edge of the working volume. The differences in the two measurements along the vertical edges (top and bottom) divided by the Abbe offset is the pitch angular error, and the differences in the two measurements along the horizontal edges (left and right) divided by the Abbe offset is the yaw angular error.

For 3 measurements along X-axis at 3 different locations with known Abbe offsets m1,p1; m2, p2; and m3, p3, the Eq. 1 becomes,

$$DX1 = Dx(x) + m1 * Ay(x) + p1 * Az(x), \quad (4)$$
$$DX2 = Dx(x) + m2 * Ay(x) + p2 * Az(x), \quad (5)$$
$$DX3 = Dx(x) + m3 * Ay(x) + p3 * Az(x), \quad (6)$$

There are 3 sets of data DX1, DX2 and DX3 and 3 unknowns Dx(x), Ay(x) and Az(x). The solutions are,

$$Ay(x) = [(m3-m1)*(DX2-DX1)-(m2-m1)*(DX3-DX1)] / [(m3-m1)* (p2-p1) - (m2-m1)*(p3-p1)]. \quad (7)$$
$$Az(x) = [(p3-p1)*(DX2-DX1)-(p2-p1)*(DX3-DX1)] / [(m3-m1)* (p2-p1) - (m2-m1)*(p3-p1)]. \quad (8)$$
$$Dx(x) = DX1*(m2*p3-m3*p2) + DX2*(m3*p1 - m1*p3) + DX3* (m1*p2 - m2*p1) / [(m3-m1)*(p2-p1)-(m2-m1)*(p3-p1)]. \quad (9)$$

Similarly for the Y- and Z-axis errors, Ax(y), Az(y), Dy(y), Ax(z), Ay(z), and Dz(z) can all be determined.

V. Body diagonal displacement error measurement

The performance or the accuracy of a CNC machine tool is determined by the 3 D volumetric positioning accuracy, which includes the linear displacement error, the straightness error, the angular error and the thermal induced error. A complete measurement of those errors is very complex and time consuming, for those reasons the measurement of the body diagonal displacement errors is recommended by many standards such as ASME B5.54 [3] and ISO 230-6 [4] for a fast check of the volumetric performance. This is because the body diagonal displacement measurement is sensitive to all of the error components [2].

Briefly, similar to a laser linear displacement measurement, instead of pointing the laser beam in the axis direction, pointing the laser beam in the body diagonal direction. Mount a retroreflector on the spindle and move the spindle in the body diagonal direction from the lower corner (X=0 Y=0 Z=0) to the opposite upper corner (Xmax, Ymax, Zmax). Starting from the zero position and at each increment of the three axes, which are moved together to reach the new position along the diagonal, the displacement error is measured. The accuracy of each position along the diagonal depends on the positioning accuracy of the three axes, including the straightness errors, angular errors and squareness errors. Hence the body diagonal displacement measurement is a good method for the machine verification.

The ASME B5.54 body diagonal displacement tests have been used by Boeing Aircraft and many others for many years with very good results and success in determine the volumetric positioning accuracy. Hence, it is a quick check on the volumetric positioning accuracy. However, if the machine is not accuracy, there is not enough information on where the errors are and how to compensate them.

IV. Sequential step diagonal measurement

The sequential step diagonal measurement or laser vector measurement technique is developed by Optodyne for the calibration of 3 D volumetric positioning accuracy of a machine tool [5,6]. Similar to the ASME B5.54 standard body diagonal displacement measurement, the laser beam is pointing in the body diagonal direction. However, instead of move x, y, and z-axis together along the body diagonal direction, stop and collect data as shown in Fig. 1, now move x only, stop and collect data, then move y only, stop and collect data, then move z only, stop and collect data, and so on until the opposite corner is reached. Hence, 3 times more data can be collected. For 4 body diagonal measurement, a total of 12 sets of data can be collected and the volumetric positioning errors determined. The measurement time is short, the equipment is compact, the setup and alignment is simple and therefore the cost is low.

In the conventional body diagonal displacement measurement, the target trajectory is a straight line and it is possible to use the corner cube as target that can tolerate a small lateral displacement. In the vector method, the movement is alternatively along the X axis, than along the Y axis and than along the Z axis, and repeated until the opposite corner of the diagonal is reached. As shown in Fig. 1, the trajectory of the target is not parallel to the laser beam direction and the lateral movement is quite large. Hence it is not possible to use a conventional interferometer that cannot tolerate such large lateral movement. A laser interferometer with single aperture is used with a flat mirror as target. It is noted that with a flat mirror as target, the movement parallel to the mirror do not displace the laser beam and do not change the distance from the source so the measurement is not influenced. Hence, it measures the movement along the beam direction and tolerates a large lateral movement of the target. This technique has been successfully used to measure the 3 D volumetric positioning accuracy of many CNC machines [8, 9].

IV. 3 D volumetric positioning error compensation

For the existing machine tools, as long as they are repeatable, the volumetric positioning accuracy can be improved up to the positioning repeatability of the machine. Many CNC machines with advanced controllers have the capability to perform the 3 D volumetric compensation, such as Fanuc with straightness compensation capability, Heidenhain with nonlinear compensation capability and Siemens with sag compensation capability. For some CNC machines without the volumetric compensation capability, the 3 D volumetric compensation can be achieved by compensate the parts program using the formulae below.

$$Dx(x,y,z) = Dx(x) + Dx(y) + Dx(z) \tag{10}$$
$$Dy(x,y,z) = Dy(x) + Dy(y) + Dy(z) + Øxy*x/X \tag{11}$$
$$Dz(x,y,z) = Dz(x) + Dz(y) + Dz(z) + Øyz*y/Y + Øzx*x/X. \tag{12}$$

Where the Dx(x,y,z), Dy(x,y,z) and Dz(x,y,z) are correction values in the x, y, and z direction at the position (x,y,z). Many software can be used to convert an existing parts program to a new parts program with corrected positions[7].

VI. Measurement on 4 DMU machines

The measurements were performed on 4 Deckel Maho Gildemeister Universal milling machine model DMU 80T with Heidenhain TNC 430 controller. The working volume is 780 mm x 585 mm x 450 mm.

The laser calibration system used was a Laser Doppler Displacement Meter (LDDM), OPTODYNE model MCV-500. The target on the moving part of the machine was a 75×100 mm flat mirror. The Air temperature and pressure were measured to compensate the changes in speed of light and the machine temperature was measured to compensate the machine thermal expansion. The automatic data acquisition, the error analysis and automatic generation of the compensation tables, were performed by the Optodyne LDDM Windows software version 2.50.

The laser was mounted on the machine table and using the steering mirror to aligned the laser beam parallel to the diagonal. The flat mirror was mounted on the spindle with the surface perpendicular to the laser beam, as shown in the Fig. 2. The machine was programmed to move the spindle starting from one corner to the opposite corner. The measurement data were automatically collected by the Windows LDDM software at every machine stop or at each single axis of movement. The error data has been analyzed by the LDDM software. The errors for each axis were automatically calculated.

It is noted that, the laser vector measurement only took 2 to 4 hours instead of 20 to 40 hours by a conventional laser interferometer. The laser setup is very simple and the data collection is automatic. The data processing and compensation file generation are all automatic without manual compilation to minimize errors. Hence, a machine operator may be trained to perform the laser calibration and compensation without the need of an experienced quality engineer.

VII. Measurement results

The pitch and yaw angular errors of each axis were measured by measuring the linear displacement errors at 3 different locations. Combining these 3 linear displacement measurement, the pitch and yaw angular errors of x-axis are plotted in Fig. 3a and 3b respectively. Similarly, the pitch and yaw angular errors of y-axis and z-axis are plotted in Fig. 4a, 4b and Fig. 5a, 5b, respectively.

The displacement errors, vertical and horizontal straightness errors and squareness errors of each axis were measured by the sequential step diagonal method. Fig. 6 is a plot of x-axis displacement error, vertical straightness error and horizontal straightness error, where LF and LB are the displacement errors in the forward and backward directions, VF and VB are the vertical straightness in the forward and backward directions, and HF and HB are the horizontal straightness in the forward and backward directions. Similarly, Fig 7 and Fig. 8 are plots of y-axis and z-axis, respectively.

It is noted that these straightness errors are the same magnitude as the linear displacement errors. Hence, just using glass scales for all 3 axes or only compensating the 3 displacement errors (or the lead screw pitch errors) is not enough. All the straightness errors should also be compensated to achieve higher volumetric positioning accuracy. At the completion of the error analysis, the Windows LDDM software can automatically generate the 3-D volumetric error compensation table for various controllers. However, for controllers do not have the volumetric error compensation capability, a compensated tool path can be generated [7].

The 4 body diagonal displacement errors are plotted in Fig. 9, and the 4 body diagonal displacement errors measured with volumetric compensated tool paths are plotted in Fig. 10.

All the measurements were performed bidirectional and repeated 5 times. Based on the ASME B5.57 standard or the ISO 230-2 standard, the accuracy A, the repeatability R, the systematic deviation E, and reversal value B were calculated and tabulated in the tables. Table 1 is the x-axis linear displacement errors, Table 2 and Table 3 are the x-axis vertical and horizontal straightness errors, respectively.

The measured results are summarized in the following.

1. Angular errors
   X-axis: maximum yaw angular error = 7 arcsec
   maximum pitch angular error = 3.5 arcsec
   Y-axis: maximum yaw angular error = 1 arcsec
   maximum pitch angular error =   arcsec
   Z-axis: maximum yaw angular error = 2.5 arcsec
   maximum pitch angular error = 1.5 arcsec.
2. Linear displacement errors
   X-axis: maximum error = 0.002 mm
   Y-axis: maximum error = 0.014 mm
   Z-axis: maximum error = 0.011 mm
3. Straightness errors
   X-axis: maximum error = 0.003 mm
   Y-axis: maximum error = 0.004 mm
   Z-axis: maximum error = 0.005 mm
4. Squareness errors
   XY = 2.02 arcsec, YZ = -11.35 arcsec, and ZX = 1.72 arcsec.
5. Body diagonal displacement errors

Maximum error = 0.027 mm

Here the largest error is the squareness error, the next is the linear error, then the straightness error. The angular errors were relatively small. With volumetric compensation, the squareness errors, straightness errors and linear errors can all be compensated. The body diagonal displacement errors was reduced from 0.027 mm to 0.007 mm, an factor of 3.8 improvement in positioning accuracy.

VIII. Summary and conclusion

The linear displacement errors were measured at 3 different locations for 3 axes. With the new software, the pitch and yaw angular errors of all 3 axes can be calculated. The new **vector** technique or sequential step diagonal technique have been used to measure the 3 D volumetric positioning errors, including 3 linear displacement errors, 6 straightness errors, and 3 squareness errors. The measured 3 D volumetric positioning errors have been used to generate the compensated parts program. The 4 body diagonal displacement errors were reduced considerably with the volumetric compensation. Hence, only compensate the pitch errors are not enough. It is more important to compensate both the pitch errors and straightness errors.

In conclusion, as manufacturers continue to expand six sigma quality programs to improve products and reduce costs, their vendors are being required to improve the quality of their work. To comply with quality programs, shops should be required to calibrate and compensate machine tools volumetrically instead of just linearly. With 3 D volumetric calibration and compensation, better quality and higher precision parts can be cut.

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List of Tables

Figure captions

1. Schematics of the sequential diagonal measurement. The working volume is divided into elementary blocks and the measurement is done for three sides of the blocks along the diagonal path.
2. A photo of the DMU 80T Universal milling machine and the sequential diagonal measurement setup with the laser on the table and the flat mirror on the spindle.
3. X-axis pitch and yaw angular error, a) is the pitch angular error and b) is the yaw angular error.
4. Y-axis pitch and yaw angular error, a) is the pitch angular error and b) is the yaw angular error.
5. Z-axis pitch and yaw angular error, a) is the pitch angular error and b) is the yaw angular error.
6. X-axis displacement error, vertical straightness error and horizontal straightness error.
7. Y-axis displacement error, vertical straightness error and horizontal straightness error.
8. Z-axis displacement error, vertical straightness error and horizontal straightness error.
9. Four body diagonal displacement errors without compensation. The total error is 0.027 mm.
10. Four body diagonal displacement errors measured with 3 D volumetric error compensation. The total error is 0.007 mm, an improvement of 380%.

Table 1, Linear displacement errors of X-axis based on the ASME B5.57 standard

Position Measurement (Linear), ISO-230-2 (1997) (mm) *Date :06.19.03*
File=C:\Lddm232\DMUSOT-1\dmU80tlAR5.SdX *By :Bobes Bobr*
Machine :DMU80T *SIN :I-1-4447L*
Start Position: (0,0,0) *End Position: (780,585,450)*
Total Travel = 1073.8365797mm *Points = 11* *No Runs= 5*
Air Temp: 23.58 *Pressure: 743.04* *Humidity: 50.00*
Material Temp: 23.05 *MTE = .999985*

Forward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000001	0.000003	0.000003	-0.000002
1	78.000000	0.000615	0.000358	0.000973	0.000258
2	156.000000	0.000769	0.000520	0.001290	0.000249
3	234.000000	0.000398	0.000631.	0.001029	-0.000232
4	312.000000	0.000729	0.000742	0.001471	-0.000014
5	390.000000	0.000371	0.000900	0.001271	-0.000529
6	468.000000	-0.000291	0.001142	0.000851	-0.001433
7	546.000000	-0.000141	0.000969	0.000828	-0.001110
8	624.000000	-0.000847	0.000802	-0.000045	-0.001648
9	702.000000	-0.002172	0.000954	-0.001218	-0.003125
10	780.000000	-0.001465	0.001031	-0.000434	-0.002496
Average		-0.000185	0.000732		

Backward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000001	0.000003	0.000003	-0.000002
1	78.000000	0.000145	0.000310	0.000454	-0.000165
2	156.000000	0.000485	0.000483	0.000968	0.000001
3	234.000000	0.000238	0.000741	0.000979	-0.000503
4	312.000000	0.000410	0.000779	0.001189	-0.000369
5	390.000000	0.000135	0.000818	0.000952	-0.000683
6	468.000000	-0.000444	0.000803	0.000359	-0.001247
7	546.000000	-0.000144	0.000994	0.000850	-0.001138
8	624.000000	-0.000740	0.000920	0.000180	-0.001661
9	702.000000	-0.001754	0.000970	-0.000784	-0.002724
10	780.000000	-0.001465	0.001031	-0.000434	-0.002496
Average		-0.000285	0.000714		

Reversal value, B= 0.000471(at point=1)
Mean reversal value, <B>= 0.000100
Range mean bidirectional positional deviation, M= 0.002590
Systematic deviation of positioning, E=
0.002941 (0.000769, -0.002172) (Forward),
0.002239 (0.000485, -0.001754) (Backward),
0.002941 (0.000769, -0.002172) (Bi-directional).
Repeatability of positioning, R=
0.002284 (at point=6) (Forward),
0.002062 (at point=10) (Backward),
0.002342 (at point=9) (Bi-directional).
Accuracy, A=
0.004597 (0.001471, -0.003125) (Forward),
0.003913 (0.001189, -0.002724) (Backward),
0.004597 (0.001471, -0.003125)(Bi-directional).

Table 2, Vertical straightness errors of X-axis based on the ASME B5.57 standard

Position Measurement (Vertical), ISO-230-2 (1997) (mm) *Date :06.19.03*
File=C:\Lddm232\DMU80T-l\dmu80t1AR5.sdx *By :Bobes Bobr*
Machine :DMU80T *SIN :I-1-4447L*
Start Position: (0,0,0) *End Position: (780,585,450)*
Total Travel = 1073.8365797mm *Points = 11* *No Runs= 5*
Air Temp: 23.58 *Pressure: 743.04* *Humidity: 50.00*
Material Temp: 23.05 *MTE = .999985*

Forward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000000	0.000000	0.000000	0.000000
1	78.000000	0.001773	0.000763	0.002535	0.001010
2	156.000000	0.002874	0.000809	0.003683	0.002065
3	234.000000	0.003242	0.001009	0.004252	0.002233
4	312.000000	0.005749	0.000756	0.006505	0.004994
5	390.000000	0.007458	0.000833	0.008292	0.006625
6	468.000000	0.009011	0.001121	0.010133	0.007890
7	546.000000	0.010310	0.000810	0.011121	0.009500
8	624.000000	0.012343	0.000494	0.012837	0.011849
9	702.000000	0.014063	0.000876	0.014938	0.013187
10	780.000000	0.016849	0.000000	0.016849	0.016849
Average		0.007606	0.000679		

Backward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000000	0.000000	0.000000	0.000000
1	78.000000	0.001758	0.000355	0.002113	0.001403
2	156.000000	0.002851	0.000338	0.003188	0.002513
3	234.000000	0.003339	0.000501	0.003841	0.002838
4	312.000000	0.005600	0.000471	0.006071	0.005129
5	390.000000	0.007484	0.000500	0.007985	0.006984
6	468.000000	0.009302	0.000948	0.010251	0.008354
7	546.000000	0.010681	0.000962	0.011643	0.009718
8	624.000000	0.012483	0.000381	0.012864	0.012103
9	702.000000	0.014453	0.000319	0.014772	0.014133
10	780.000000	0.016849	0.000000	0.016849	0.016849
Average		0.007709	0.000434		

Reversal value, B= 0.000149 (at point=4)
Mean reversal value, <B>= =0.000103
Range mean bidirectional positional deviation, M= 0.016849
Systematic deviation of positioning, E=
0.016849 (0.016849, 0.000000) (Forward),
0.016849 (0.016849, 0.000000) (Backward),
0.016849 (0.016849, 0.000000) (Bi-directional).
Repeatability of positioning, R=
0.002243 (at point=6) (Forward),
0.001925 (at point=7) (Backward),
0.002361 (at point=6) (Bi-directional).
Accuracy, A=
0.016849 (0.016849, 0.000000) (Forward),
0.016849 (0.016849, 0.000000) (Backward),
0.016849 (0.016849, 0.000000)(Bi-directional).

Table 3, Horizontal straightness errors of X-axis based on the ASME B5.57

Position Measurement (Horizontal), ISO-230-2 (1997) (mm) *Date :06.19.03*
File=C:\Lddm232\DMU80T-1\dmu80tlAR5.SdX *By :Robes Bobr*
Machine :DMU80T *SIN :I-1-4447L*
Start Position: (0,0,0) *End Position: (780,585,450)*
Total Travel = 1073.8365797mm *Points = 11* *No Runs= 5*
Air Temp: 23.58 *Pressure: 743.04* *Humidity: 50.00*
Material Temp: 23.05 *MTE = .999985*

Forward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000000	0.000000	0.000000	0.000000
1	78.000000	0.001962	0.001166	0.003128	0.000795
2	156.000000	0.002847	0.001222	0.004069	0.001625
3	234.000000	0.004605	0.001325	0.005931	0.003280
4	312.000000	0.008435	0.002507	0.010943	0.005928
5	390.000000	0.010163	0.002213	0.012376	0.007950
6	468.000000	0.010595	0.002854	0.013449	0.007741
7	546.000000	0.011728	0.002780	0.014508	0.008948
8	624.000000	0.014447	0.002352	0.016799	0.012094
9	702.000000	0.016008	0.002006	0.018015	0.014002
10	780.000000	0.016849	0.000000	0.016849	0.016849
Average		0.008876	0.001675		

Backward measurement

Point	Position (mm)	Mean Deviation	2*Sigma	X(avg)+ 2*Sigma	X(avg)- 2*Sigma
0	0.000000	0.000000	0.000000	0.000000	0.000000
1	78.000000	0.001088	0.000442	0.001530	0.000646
2	156.000000	0.002327	0.000909	0.003236	0.001419
3	234.000000	0.004565	0.001693	0.006259	0.002872
4	312.000000	0.008029	0.001147	0.009176	0.006881
5	390.000000	0.009416	0.001157	0.010573	0.008259
6	468.000000	0.010284	0.001594	0.011878	0.008691
7	546.000000	0.011976	0.001409	0.013385	0.010567
8	624.000000	0.014085	0.000457	0.014542	0.013627
9	702.000000	0.015722	0.000289	0.016012	0.015433
10	780.000000	0.016849	0.000000	0.016849	0.016849
Average		0.008576	0.000827		

Reversal value, B= 0.000874 (at point=1)
Mean reversal value, <B>= 0.000300
Range mean bidirectional positional deviation, M= 0.016849
Systematic deviation of positioning, E=
0.016849 (0.016849, 0.000000) (Forward),
0.016849 (0.016849, 0.000000) (Backward),
0.016849 (0.016849, 0.000000) (Bi-directional).
Repeatability of positioning, R=
0.005708 (at point=6) (Forward),
0.003387 (at point=3) (Backward),
0.004758 (at point=6) (Bi-directional).
Accuracy, A=
0.018015 (0.018015, 0.000000) (Forward),
0.016849 (0.016849, 0.000000) (Backward),
0.018015 (0.018015, 0.000000)(Bi-directional).

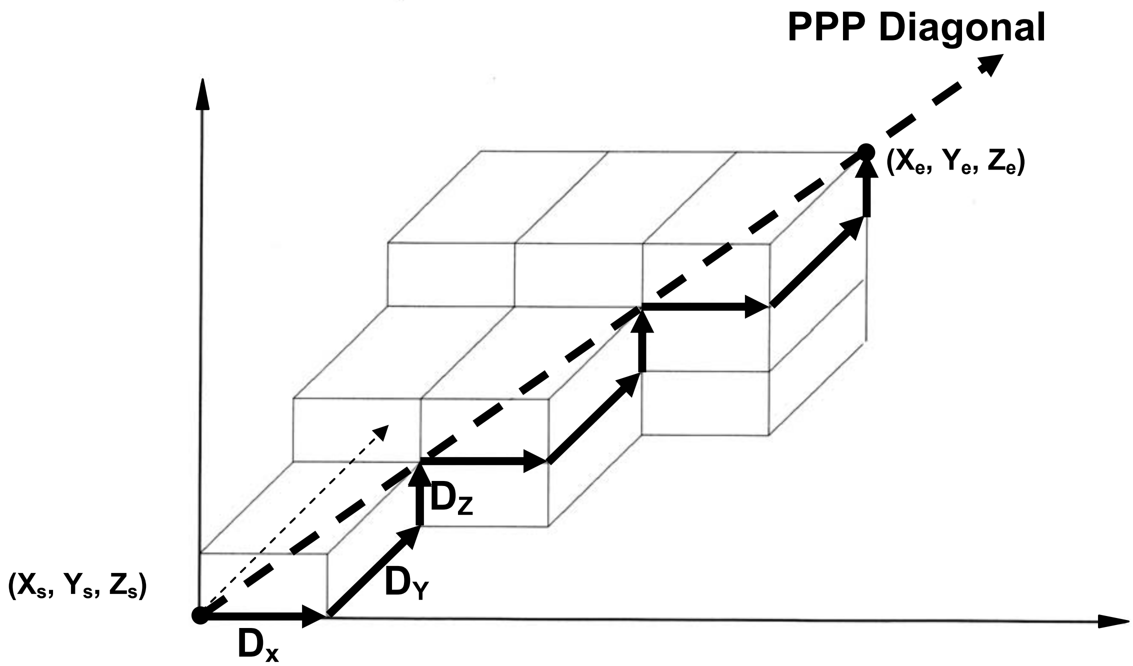

Fig. 1 Schematics of the sequential diagonal measurement. The working volume is divided into elementary blocks and the measurement is done for three sides of the blocks along the diagonal path.

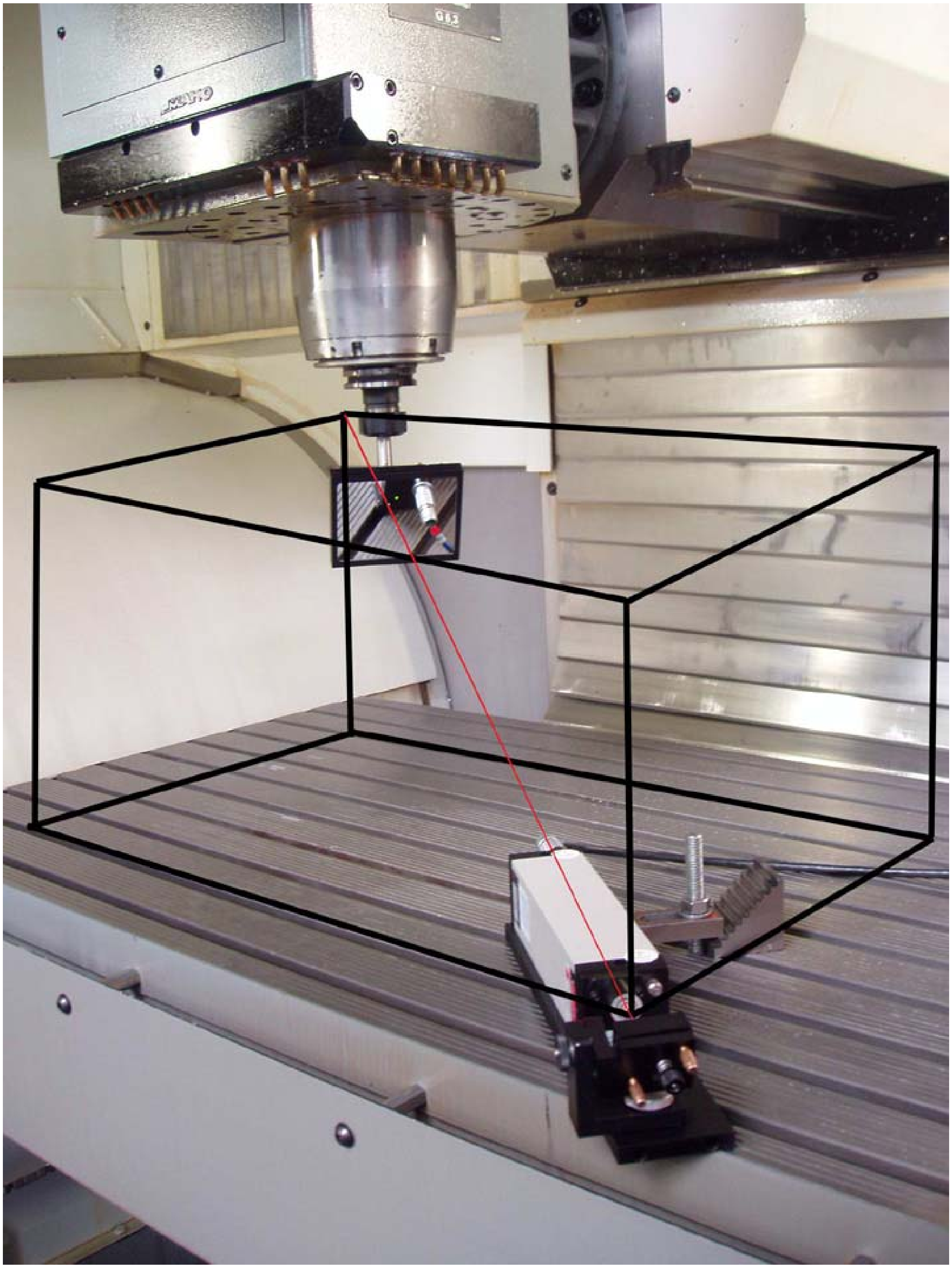

Fig. 2 A photo of the DMU 80T Universal milling machine and the sequential diagonal Measurement setup with the laser on the table and the flat mirror on the spindle.

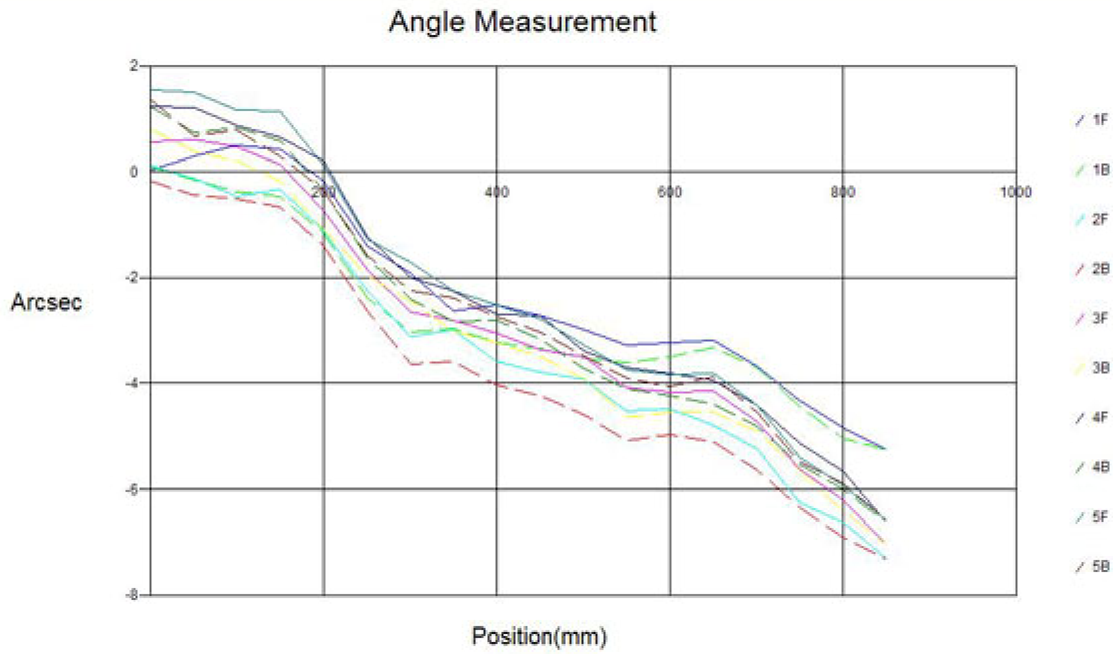

Fig. 3a X-axis pitch angular error

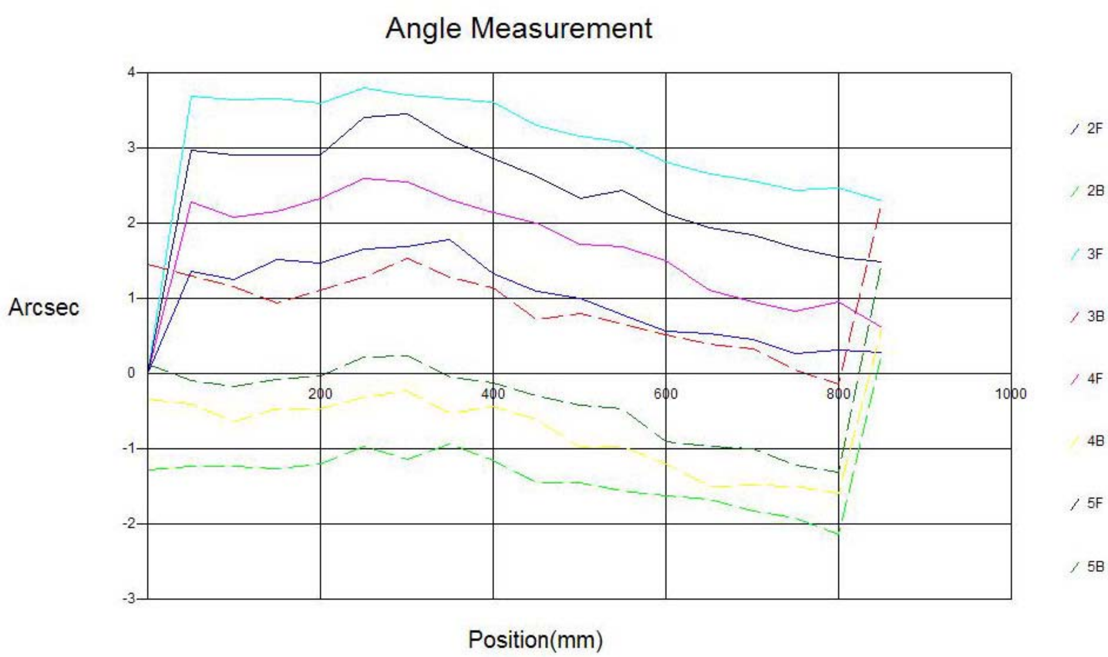

Fig. 3b X-axis yaw angular error

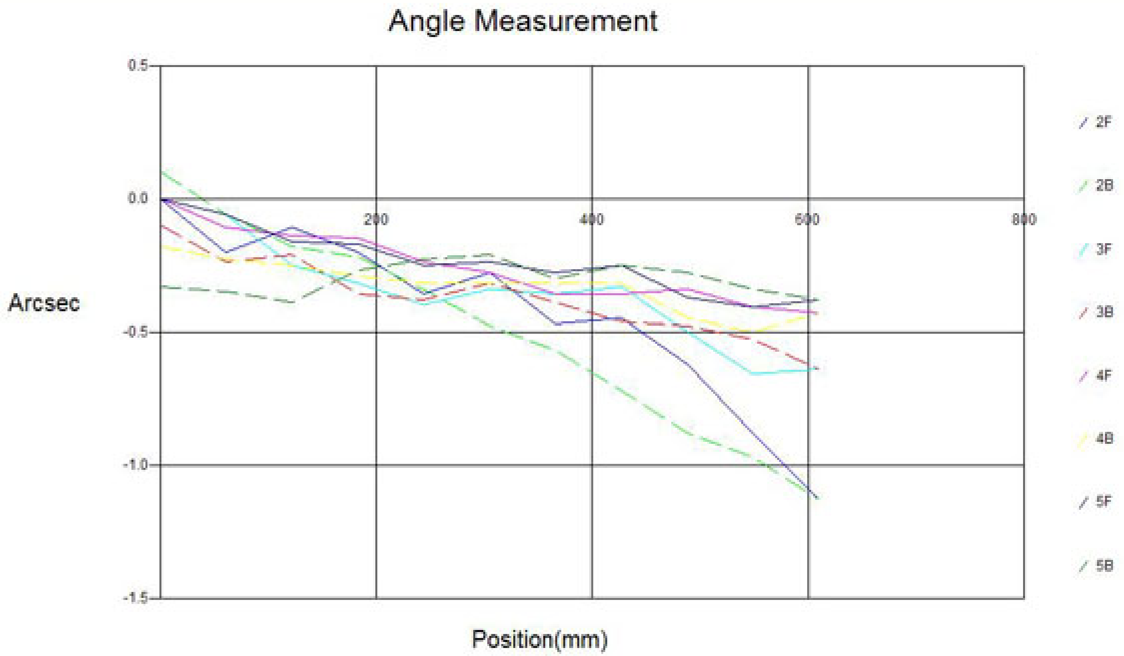

Fig. 4a Y-axis pitch angular error

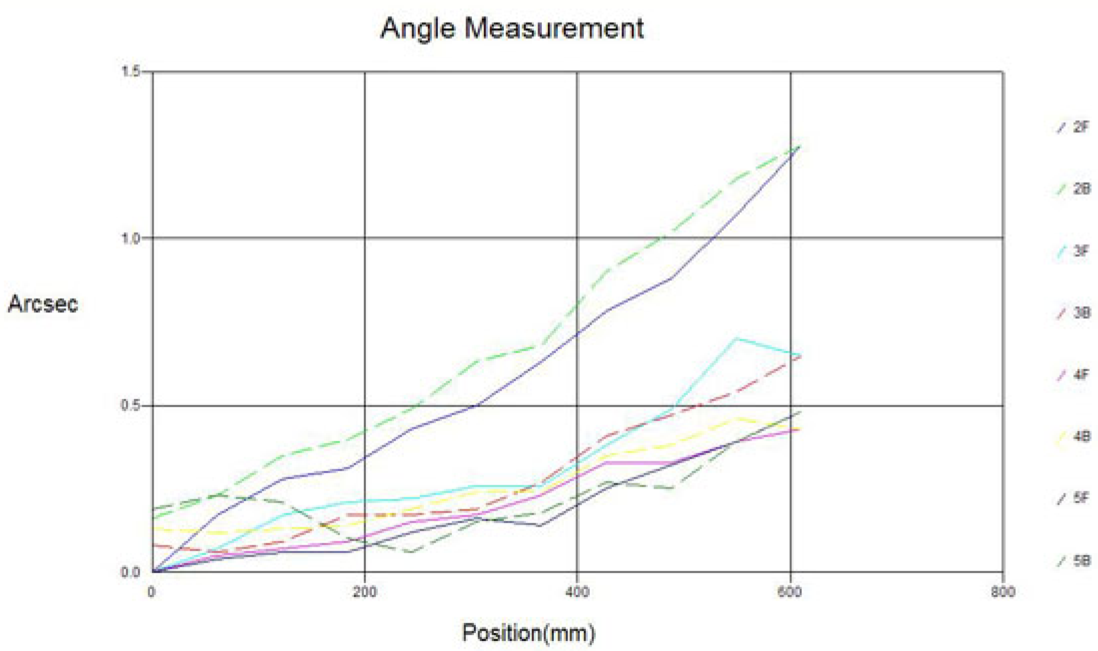

Fig. 4b Y-axis yaw angular error

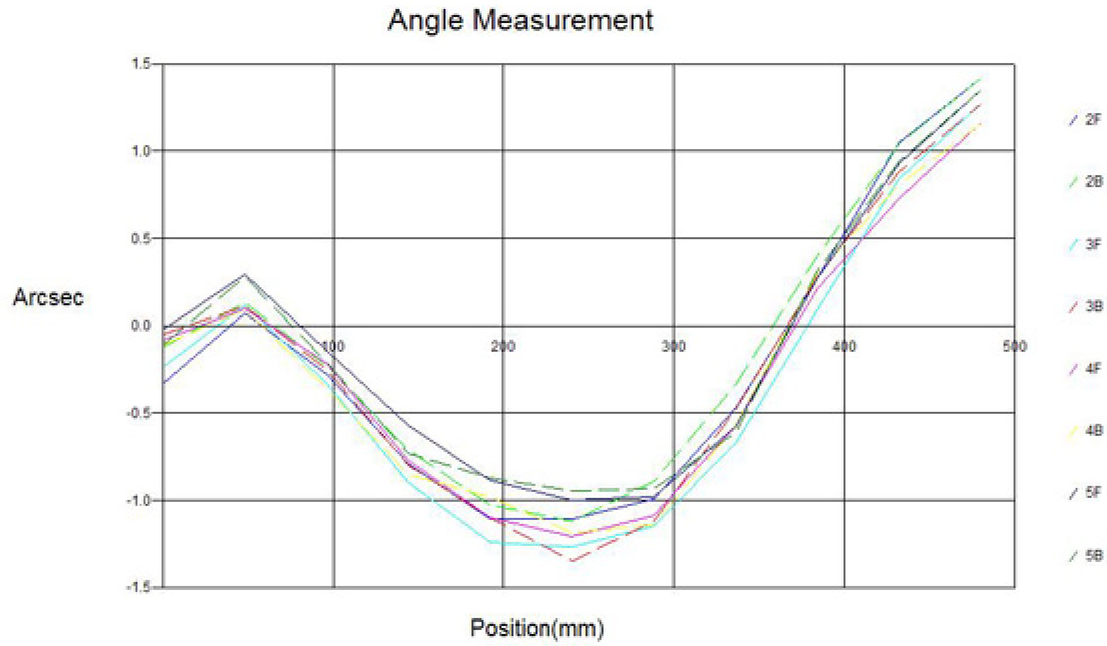

Fig. 5a Z-axis pitch angular error

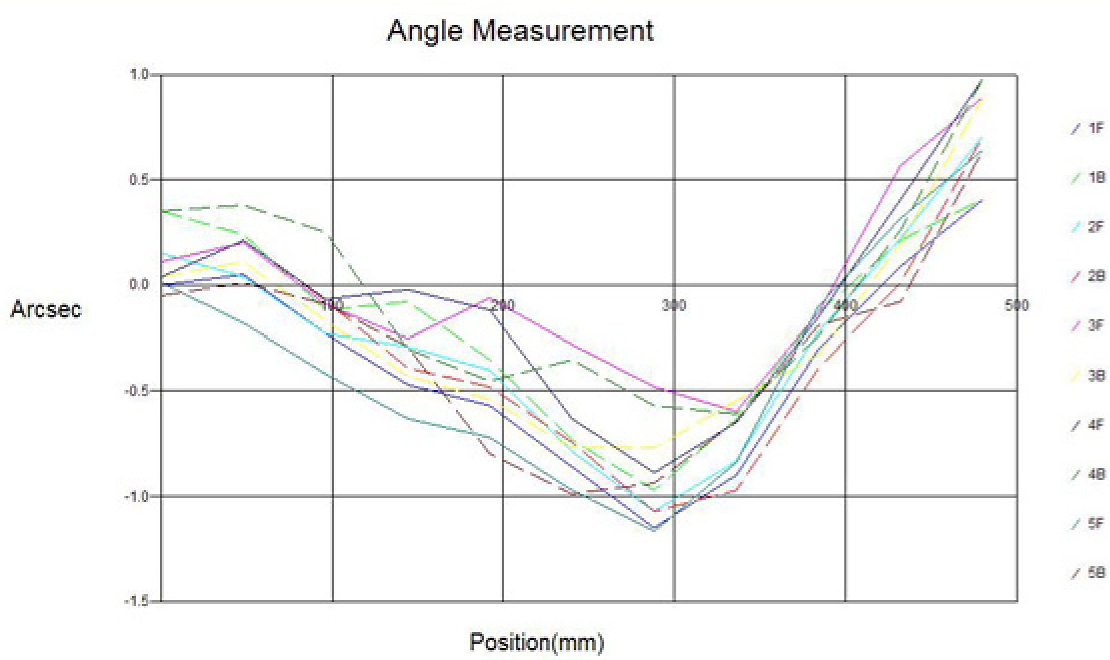

Fig. 5b Z-axis yaw angular error

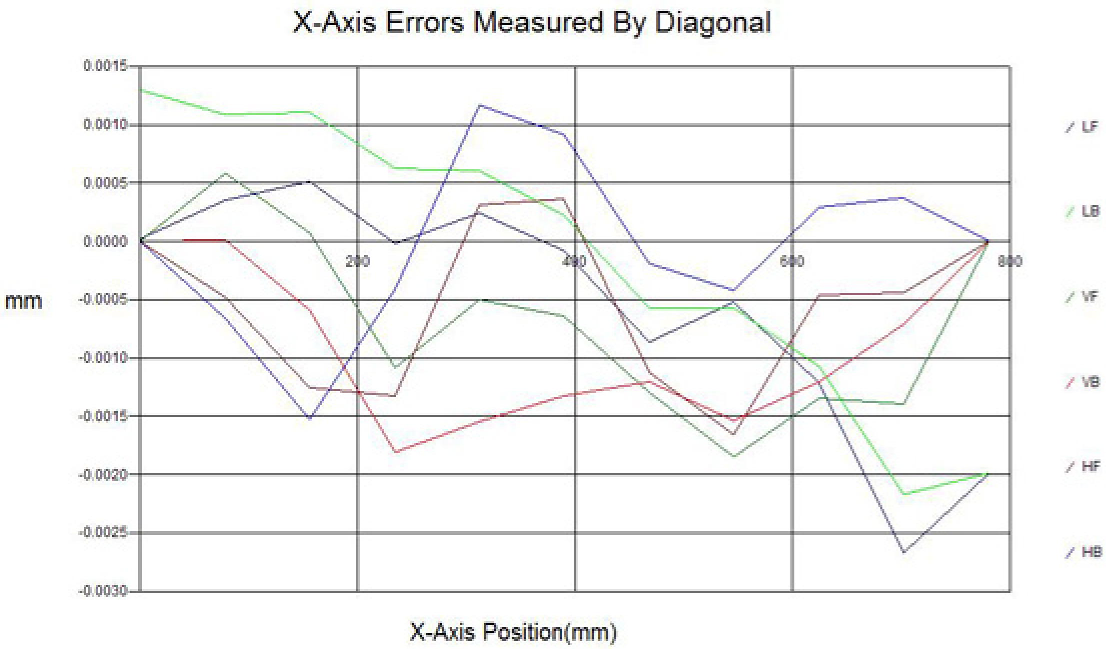

Fig. 6 X-axis displacement error, vertical straightness error and horizontal straightness error.

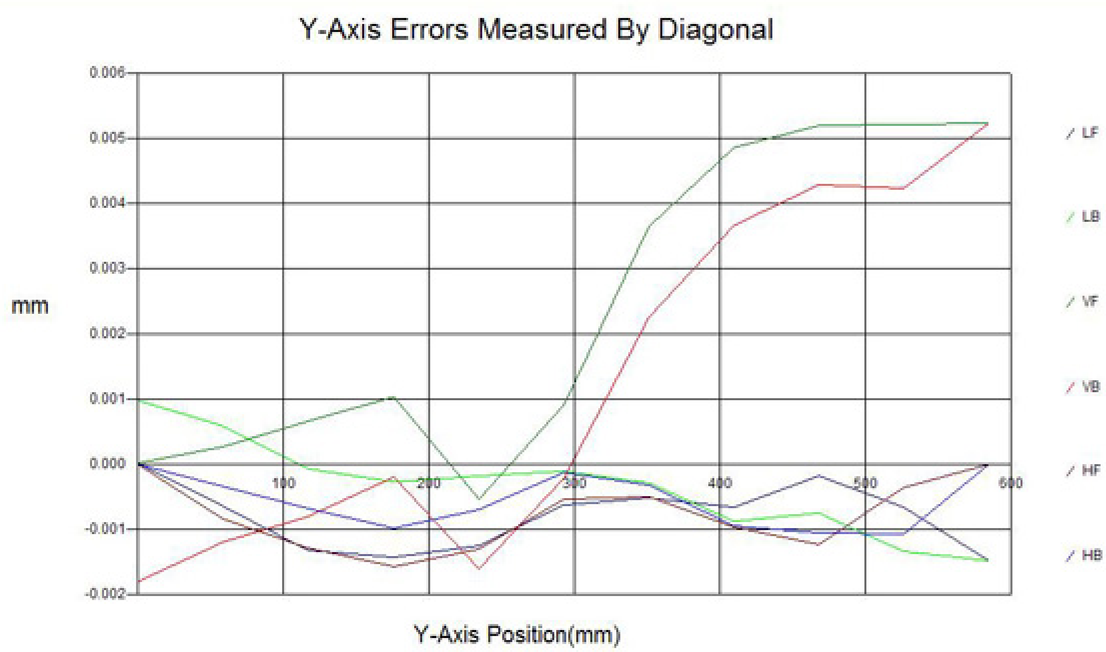

Fig. 7 Y-axis displacement error, vertical straightness error and horizontal straightness error.

Fig. 8 Z-axis displacement error, vertical straightness error and horizontal straightness error.

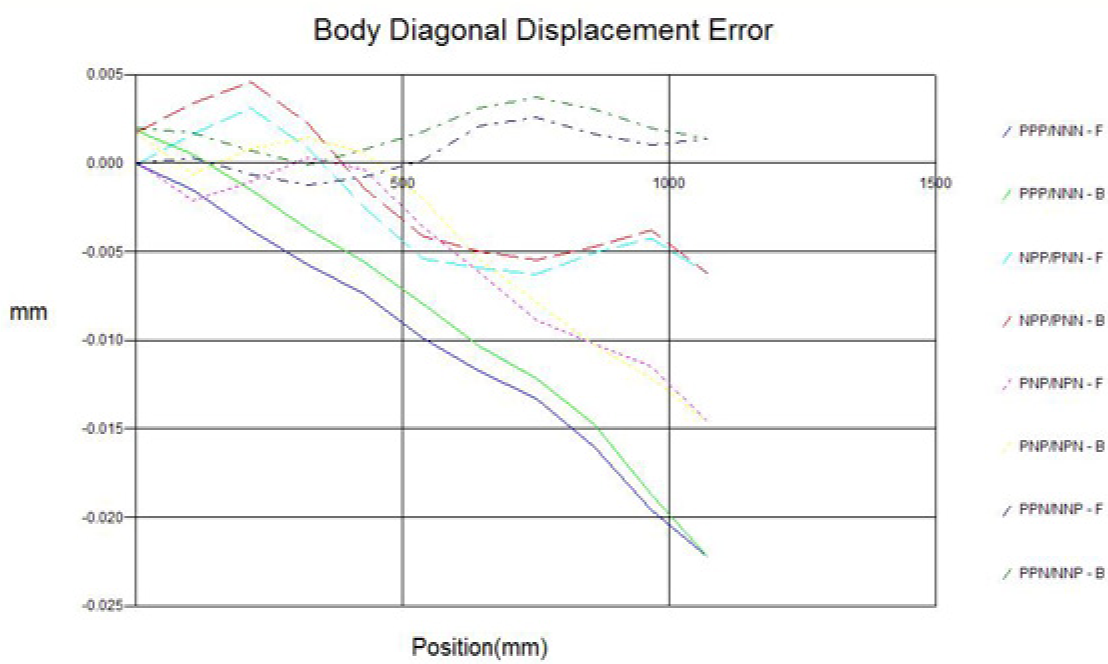

Fig. 9 Four body diagonal displacement errors without compensation. The total error is 0.027mm.

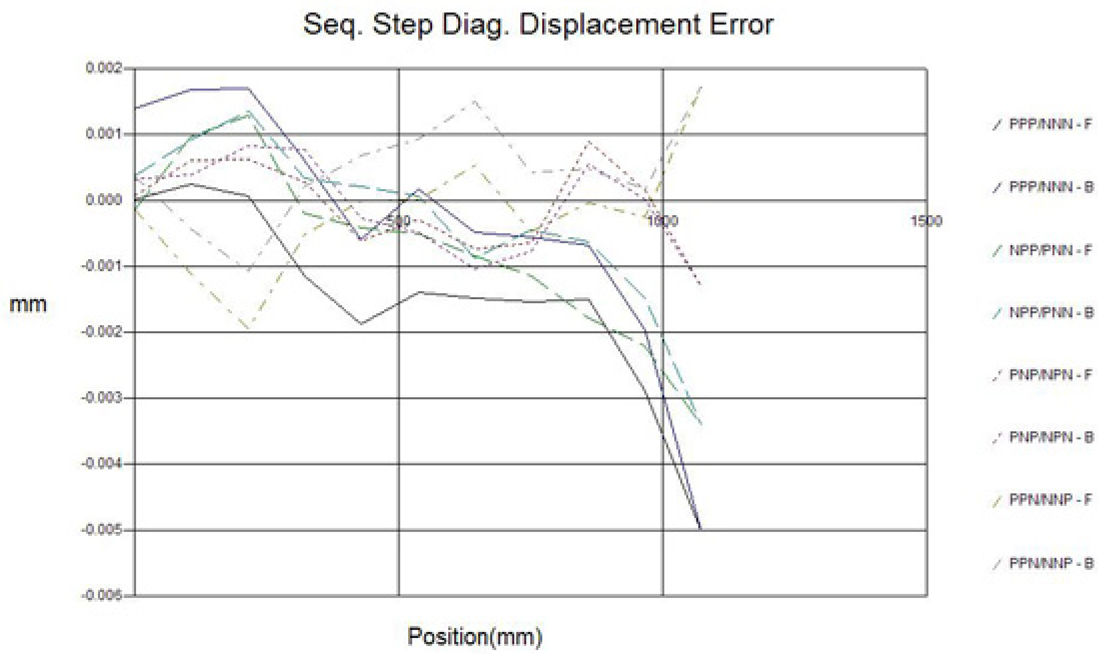

Fig. 10 Four body diagonal displacement errors measured with 3D volumetric error compensation. The total error is 0.007mm, an improvement of 380%.