2 DOF DYNAMIC ACCURACY MONITORING FOR ROBOT AND MACHINE TOOL MANIPULATORS

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Abstract

Trajectory monitoring at high speed is an important precondition for dynamic performance identification as well as dynamic modeling of robot and machine tool manipulators. In this contribution, a planar parallel measurement system for two dimensional trajectory monitoring is shown that combines accuracy and speed with robust design and low manufacturing costs. Due to the manufacturing, component and assembly errors a suitable calibration method is required that allows error identification and compensation of the parallel mechanism with respect to the rough machine tool or industrial robot environment.
The work reported in this paper deals with the calibration of planar parallel measurement systems. Therefore, the high absolute precision of the lattice grid plate in the range of one micrometer is used to identify the errors of the parallel mechanisms. A nonlinear least-squares fit analysis using the Levenberg-Marquardt-Method yields a very robust error identification algorithm that requires only a few minutes of calibration time using state-of-the-art computing software.
Exemplary manipulator measurements at machine tools elucidate the performance of this new measurement system that allows high precision measurements in the range of 3 micrometers even with path velocities of 60m/min.

1 Introduction

Up to the early 90‘s acceptance tests of machine tool and robot manipulators have been realized by static positioning accuracy measurements, e.g. using laser interferometers. With the increasing demand for higher manipulator performance dynamic trajectory monitoring became important.

The most sophisticated inspection tool for arbitrary trajectories (e.g. [1]) is the Lattice Grid Plate [2]. It yields high precision (ca. 1 µm) as well as high resolution (ca. 5 nm) path monitoring at velocities up to 0.5 m/s. The Lattice Grid Plate consists of a steel substrate with a grid of pattern squares. A scanning unit that has no mechanical contact to the plate measures the position with two degrees of freedom (2 DOF). The air gap between plate and scanning unit is in the range of 0.5 - 1 mm.

Inspection devices to measure 3 and more DOF movements are subject of further developments [3]. These high precision systems require careful use, especially in the rough manufacturing environment. Operator or path errors rectangular to the measurement plane as well as falling screws, tools, etc. can cause severe damages to the inspection devices. Especially robot inspection devices require adequate robustness against path errors. On the other hand, the measurement precision for robot acceptance tests is much smaller than the required precision for machine tools.

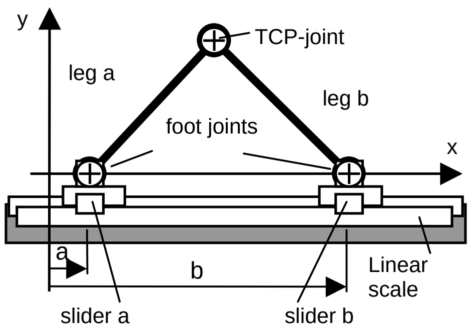

Figure 1: Principle sketch of a parallel 2DOF inspection system.

Experiences gained with parallel manipulators show that these kinematic principles yield very high repeatability with moderate effort [4]. Based on these experiences and the growing need to inspect robot manipulators a parallel 2 DOF inspection device was developed (see Fig. 1 and Fig. 2). The end effector of the robot or the tool center point (**TCP**) of the machine tool is attached at the top joint. The foot joints are guided on a straight line. Their position is measured by a standard linear encoder with two scanning units. For convenience the parallel 2DOF inspection device is from now on called 2DOF-System.

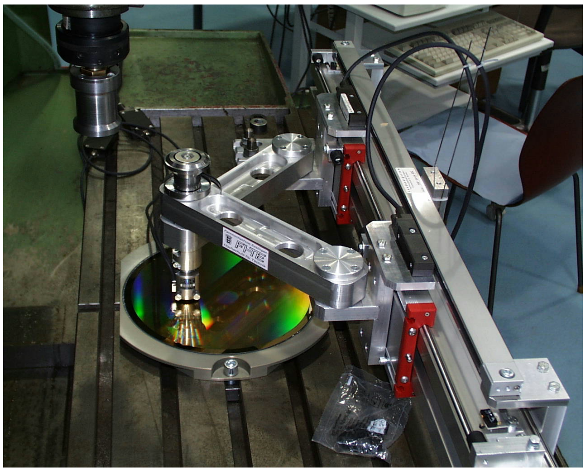

Figure 2: Prototype of the parallel 2 DOF inspection system in the FHTE machine tool laboratory - arranged above the Lattice Grid Plate [2]

2 Requirements and design

The mechanical and operational requirements for the parallel 2 DOF inspection device are:

- circular measurement area (100 mm radius)
- 10µm absolute precision in the measurement area
- 1 m/s resp. 60 m/min maximum path velocity
- robustness against operator errors
- low cost design
- easy to use calibration method

For the recommended circular measurement face the ratio of device size to measurement range is high. Prolongation of the measurement area in the preferred direction parallel to the linear encoder yields better ratios. Thus the system is scalable without any changes to the here shown principle. Especially for large measurement ranges, the „inverse Dinosaur effect“ [4] of parallel manipulators leads to increasing system performance of the concept.
The mechanical design of the inspection device is based on standard components. The sliders on the guideway support the foot joints of the legs. The scanning units of the linear encoder are connected to the sliders as well. The backlash free and stiff joints with one rotary DOF are realized with angular contact ball bearings. To avoid mechanical stress caused by operator errors (exceeding the measurement range, movements rectangular to the measurement plane) the mechanical interface to the tool center point (TCP) is equipped with a magnetic joint. Braking of a machine tool spindle is not necessary [3].
A PC interface board captures the linear encoder positions. Real time measurement and data recording is implemented in C. Forward transformation and error compensation requires no real time programming. Thus it is integrated in a postprocessor step as well as the graphical display of the inspection result. The application of standard components reduces the costs for the parallel inspection device to a fraction of the Lattice Grid Plate system price. Scaling up the measurement range will cause minor additional costs.

3 Calibration

Neglecting all geometric errors, the forward transformation to calculate the x,y-coordinates of the Tool Center Point (TCP) from the scanning unit positions (a,b) is given by (1)

$$x = \frac{L_a{}^2 - L_b{}^2 + b^2 - a^2}{2 \cdot (b-a)}, \quad y = \sqrt{L_b{}^2 - (x-b)^2},$$

where $L_{a,b}$ are the leg lengths of the device. If the four variables L_a, L_b, a and b are known, then the exact position of the TCP in the x,y-coordinate system can be calculated. However, due to the manufacturing, component and assembly errors shown in Fig. 3 this is not possible.

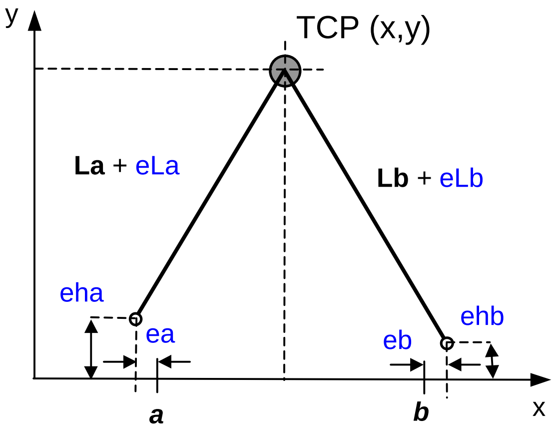

Figure 3: Assembly and manufacturing errors

In order to calculate the TCP coordinates including the possible errors a more general approach has been chosen. With the help of Fig. 4 the x,y-coordinates of the TCP can be related to the four vectors $\vec{r}_a$, $\vec{r}_b$ $\vec{L}_a$ and $\vec{L}_b$.

With $\vec{r}_a = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$, $\vec{r}_b = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}$, $\vec{r} = \begin{pmatrix} x \\ y \end{pmatrix}$ and the relationships $\vec{L}_a = \vec{r} - \vec{r}_a$ and $\vec{L}_b = \vec{r} - \vec{r}_b$, the following set of two equations can be obtained.

$L_a^2 = (x - a_1)^2 + (y - a_2)^2$ and

$L_b^2 = (x - b_1)^2 + (y - b_2)^2$.

The solution of this set of equations will lead the x,y-coordinates of the TCP position in the coordinate system of Fig. 4.

$x = f(a_1, a_2, b_1, b_2, L_a, L_b)$ (2a)

$y = f(a_1, a_2, b_1, b_2, L_a, L_b)$ (2b)

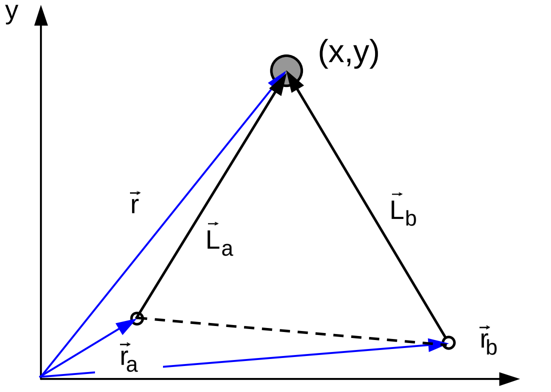

Figure 4: Vector analysis of the TCP position.

The analytic solution is calculated with the help of the computer algebra program MAPLE, but due to the size of the equations the results are not shown here. The six error possibilities of Fig. 3 related to the leg lengths (L_a, L_b) and the scanning positions (a,b) are documented in Table 1.

Variable Name	Comments	Error Variables
L_a	Manufactured leg length $L_a \approx 250$ mm.	eLa
L_b	Manufactured leg length $L_b \approx 250$ mm.	eLb
a_1	Scanning position of the left measuring head.	ea
a_2	a_2 = eha (see Fig. 3)	eha
b_1	Scanning position of the right measuring head.	eb
b_2	b_2 = ehb (see Fig. 3)	ehb

Table 1: Error classification

For the actual calibration measurement the TCP is brought to some arbitrary point in the x,y-plane (the starting point). The measurement software will simultaneously record the x,y-coordinates of the lattice grid plate (LGP) and the two scanning unit positions a_1 and b_1 of the 2DOF inspection device. Then the machine will move the TCP to the next point and the measurement procedure is repeated. Altogether a set of 25 data points from a (40 mm x 40 mm) square were recorded (s. Fig. 5).

Until now the data has been recorded in two different coordinate systems. For comparison a common reference point must be chosen, which

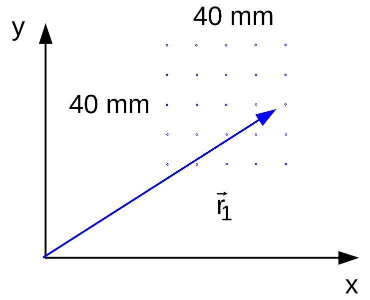

Figure 5: Shape, size and pattern of the measurement area.

will be defined to be the origin of a new mutual coordinate system (This reference point could be any of the 25 data points).

With this definition the new data vectors for the remaining 24 points are calculated for the 2DOF-System as well as for the LGP. Now, if the variables L_a, L_b, a_1, a_2, b_1 and b_2 were known precisely, the calculated x,y-position of the data points in the 2DOF coordinate system should coincide exactly within the accuracy of the LGP coordinate system (As mentioned before, the precision of the LGP in x or y direction is about 1 µm).

A direct comparison of the two data sets after the coordinate transformation with the assumptions $L_a = L_b = 250$ mm (manufacturing specification) and all errors of Table 5 set equal to zero is shown in Fig. 6.

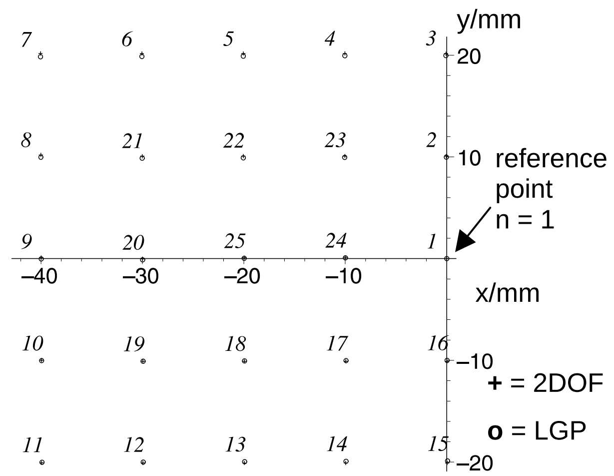

Figure 6: Data points of the LGP and the 2DOF-System after the coordinate transformation (reference point n = 1).

The numbers in Fig. 6 represent the sequence in which the data points were taken and despite the large scale on x and y-axis the deviation between the two data sets can be seen quite well for a number of data points (e.g. n = 5, 6, 7,...). The individual differences in position can be demonstrated much better by calculating the absolute values dL of the difference vector for each data pair (see Fig. 7)

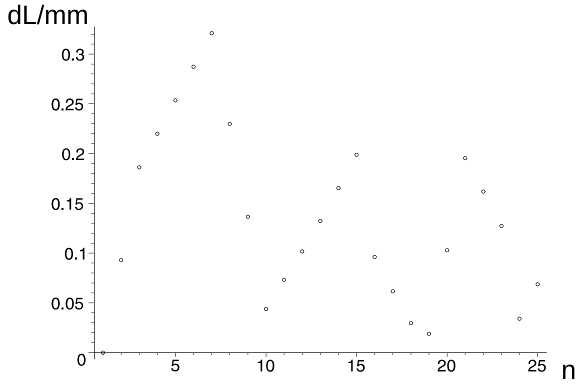

Figure 7: Individual deviations of the two data sets.

From Fig. 7 it can be seen that the maximum deviation is about 320 µm. Notice that the reference point (here n = 1) has no deviation by definition. The average value of all 25 data points comes out to be about 134 µm, which is not an acceptable value compared to the desired precision of at least 10 µm.
It must also be mentioned that another assumption had to be made before plotting the Data in Fig. 7. The x-axis of the LGP was aligned carefully with the x-axis of the 2DOF-System (track in which the scanning positions a and b run). This, however, doesn't guarantee that φ = 0 and the actual value for φ at this point is unknown (s. Fig. 8).

In general the angle φ must be added to the list

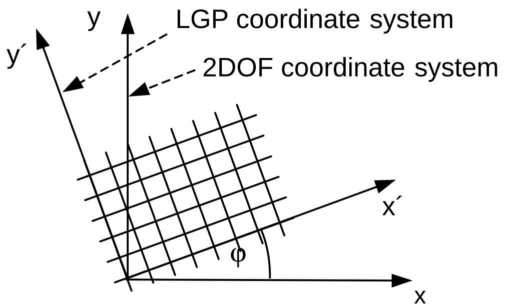

Figure 8: Alignment of the LGP relative to the 2DOF coordinate system.

of error possibilities, because small deviations from a perfect alignment will lead to a wrong calibration. At first it seems, that including the angle φ in the list of unknowns makes the task more difficult. However, if the calibration algorithm works despite the additional variable φ, then the LGP can simply be put in the x,y-plane without a tedious and time consuming alignment. With the angle φ, a comparison of the two data sets requires an additional rotation of one of the two data sets by the rotation matrix

$$\vec{r}' = \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix} \vec{r} \, .$$

Before discussing the details of the calibration procedure jet another difficulty must be pointed out. As mentioned above, a common reference point was chosen with the assumption, that the TCP and the LGP coordinate systems are fixed in space when the data is acquired. However, due to inevitable vibrations of the running machine there is always some random movement in the order of a few µm (This variation can be estimated in a static position from the digital reading of the LGP positions). Therefore, we cannot assume that the measurement of the reference point in the LGP coordinate system would always give the exact same readings. In fact this has to be compensated for by two more fit-parameters exK and eyK, the random errors in the x,y-positions of the LGP at the instantaneous moment of the data acquisition. In summary this leaves us with the problem of how to find the best estimates for the possible errors eLa, eLb, ea, eha, eb, ehb, φ, exK and eyK in order to find the lowest average deviation.
By closer examination two of the 9 variables can be omitted right away. If we go back to Fig. 3 one can see, that in principle it takes 6 degrees of freedom to determine the absolute position of the triangle (a, b, TCP) in space. Choosing a common reference point in space for the two coordinate systems eliminates two degrees of freedom, because the absolute position in space of the triangle becomes unimportant. Relevant now, is only the shape and orientation of the triangle and for that 4 parameters are sufficient. Our choice was to set eb and ehb equal to zero and work only with the variables eLa, eLb, ea and eha in addition to φ, exK and eyK. This leaves us with the problem of adjusting 7 parameters for a best result. The main idea how to accomplish this is task is shown in Fig. 9.

For each data point the length of the difference vector dL_i should be as small as possible. It is therefore reasonable to define a function F as the sum of all quadratic errors

$$F = \sum_i (d\vec{L}_i)^2 \, ,$$

which should also be as small as possible.
Because each $d\vec{L}_i$ is a function of eLa, eLb, ea, eha, φ, exK and eyK this function needs to be

minimized with respect to the above parameters. With the definition of the parameter vector $\vec{u} = (u_1, ..., u_m) = (eLa, eLb, ea, eha, \varphi, exK, eyK)$ the minimum of the scalar function F can be found by setting the gradient of F equal to zero, so that the condition $\nabla F(\vec{u}) = 0$ must be solved for the desired calibration parameters.

In order to solve this problem we adapted a nonlinear least squares fit algorithm which can be found in the book by Hörhager [5]. In the

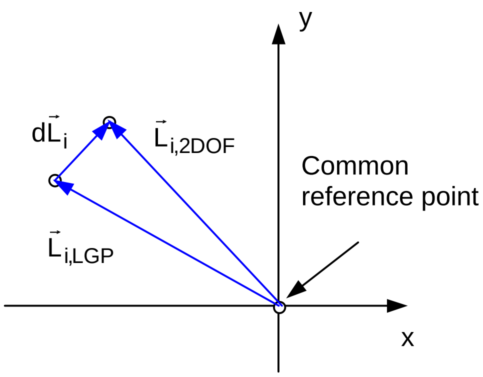

Figure 9: Difference Vector $d\vec{L}_i$ between the LGP and the 2DOF-System.

same book there is also a brief discussion of the Levenberg-Marquardt method, which is the basis of this program. Unfortunately this program only returns the optimized parameters $(u_1...u_m)$ without the uncertainties in the parameters. This, however, is an essential information for a good calibration routine. A more detailed explanation of the Levenberg-Marquardt method can be found in the book by Bevington and Robinson [6]. There it is also explained how to retrieve the standard deviations $(s_1...s_m)$ and the covariances $(c_{12}, c_{13}, ...c_{m,m-1})$ of the optimized parameters from the error matrix.

Before running the procedure not only the function $F(\vec{u})$, but also a starting vector $\vec{u}_0$ needs to be passed on to the program. The starting vector and the results of the optimized parameters for the first measurement are shown in the Table 2.

With seven fit-parameters the calibration routine takes about 3 min for conversion using a Pentium 4 processor with 1024 MB RAM. Using the optimized values the individual deviations were calculated and displayed in Fig. 10.

In comparison to Fig. 7, a significant reduction of the individual deviation has been achieved.

Parameters	Starting values	Optimized values	Standard deviation s_i
eLa	0.1 mm	0.30 mm	0.18 mm
eLb	0.1 mm	0.10 mm	0.18 mm
ea	1.0 mm	1.53 mm	0.18 mm
eha	0.1 mm	0.13 mm	0.18 mm
φ	0.057°	-0.184°	0.003°
exK	3 µm	-2.1 µm	1.0 µm
eyK	3 µm	0.7 µm	1.4 µm

Table 2: Starting values and optimized values for the best fit.

Almost all deviations between the 2DOF-System and the LGP are less than 5 µm. The worst data point (n = 11), gives about 6 µm and about 20% of the data pairs are less than 1 µm apart. Please note also, that the deviation for data point n = 1 (reference point) is not zero. From Fig. 10 it can be seen that the deviation for n = 1 is about 2.2 µm, which is nothing else then the numerical value of $\sqrt{exK^2 + eyK^2}$ using the data of Table 2. As a matter of fact, the determined values of exK and eyK mirrors the expected vibrational amplitudes of the machine movement. The average value of all 25 data points has been calculated to 2.3 µm. It might be pointed out, that the choice of a reference point other than n = 1 would lead to a different graph then Fig. 10, but the average value of all data points would always be the same. This outcome for different reference points was verified numerically, which is an important validation of this calibration algorithm.

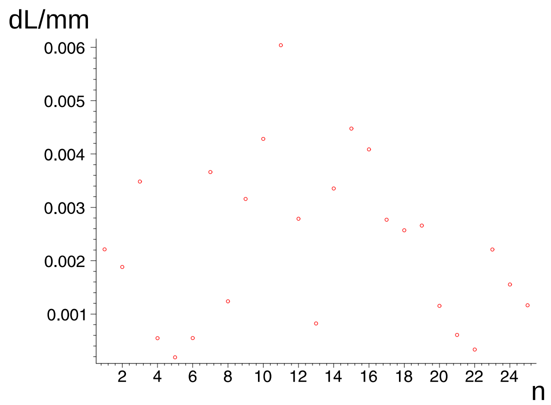

Figure 10: Individual deviation with optimized fit parameters

It might be emphasized that the average deviation of 2.3 µm for different reference points could not be achieved if the two fitting parameters exK and eyK were excluded from the fit. In this case the average value could be significantly larger (up to 70%) in comparison to the minimum value. The mere fact that the optimized parameters in Table 2 produce the graph in Fig. 10 is sufficient evidence, that the calibration routine works extremely well to achieve an excellent precision. A number of other verifications for the validity of the procedure will be given below.

It might also be remarked that the determined angle φ = - 0.184° (see Table 2) indicates a fairly good alignment between the 2DOF-System and the LGP. However, if the fit is performed without the angle φ (i.e. $\varphi = 0$ assumed), the best average value for the above data set would be about 43 µm. In comparison to the actually achieved 2.3 µm this indicates how crucial it is to include the angle φ in the calibration routine.

The low average deviation was verified by calculating the standard deviation s_r of the position vector $\bar{r}$.

$$s_r = \sqrt{(\frac{\partial r}{\partial u_1})^2 s_1{}^2 + (\frac{\partial r}{\partial u_2})^2 s_2{}^2 + \ldots + 2\, c_{12}(\frac{\partial r}{\partial u_1})(\frac{\partial r}{\partial u_2}) + \ldots}$$

Including all standard deviations and covariances of the fit variables s_r was calculated to be 2.0 µm which is in excellent agreement of 2.3 µm.

In addition the straight leg position of the TCP was measured directly by the positions a_1 and b_1 of the 2DOF-System

$L_0 = b_1 – a_1 = (501.768 \pm 0.002)$ mm

and was calculated from the determined fit parameters of Table 2

$L_0 = ea + L_a + L_b = (501.93 \pm 0.11$ mm).

One can see, that the directly measured value of 501.768 mm lies within two standard deviations of the calculated result, which represents a 95 % confidence level.

In order to show reproducibility the measurement of the 25 data points was repeated three times. First the LGP was left in place, but a different location in absolute space was chosen for the square of the data points (Data set 2). Then two more measurements were performed, where the LGP was rotated by about an angle of 30° (Data set 3 and 4). It was our goal to show, that the calibration routine works equally well for arbitrary angles between LGP and 2DOF coordinate systems (s. Fig. 8). The result for the average deviation of all four measurements is shown in Fig. 11.

All measurement show reproducible average values around 3 µm. The standard deviation for each measurement is about 1.6 µm, so that one can conclude that a precision of less than 6.2 µm can be assumed for any data point with a 95 % confidence level.

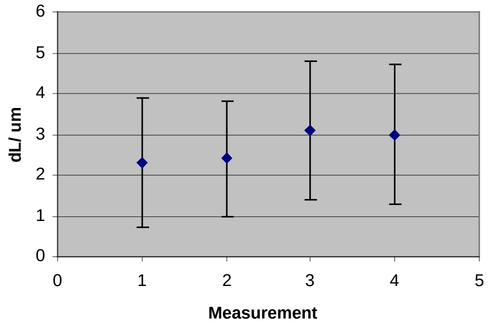

Figure 11: Average deviation between LGP and 2DOF for four different measurements (25 data points each).

5 Summary

The parallel 2 DOF inspection device is an easy to use trajectory monitoring tool for machine tool and robot manipulators. The high repeatability of parallel mechanisms and suitable error compensation yield sufficient accuracy in the range of 3 µm. As the amplitudes of the mechanical vibrations of the machine are also in the order of a few µm, this accuracy represents a result close to the lowest possible limiting values.

The system has a simple and low cost mechanical design. It is robust against operator and path errors as well as manufacturing environment influences. The new inspection tool will be used at the FHTE for machine tool diagnosis as well as for dynamic robot manipulator measurements to validate simulation models.

References

[1] N.N.: *ISO 230-1..4 – Test code for machine tools* International Organization of Standardization, 1996.
[2] Zirn, O.; Weikert, S.: *Dynamic Accuracy Monitoring for the Comparison and Optimization of Fast Axis Feed Drives.* Proceedings ASPE 12th Annual Meeting, , Norfolk, 1997.
[3] Weikert, S.: *Dynamic Accuracy Monitoring.* Proceedings ASPE 14th Annual Meeting, 1999.
[4] Zirn, O.; Treib, T.: *Similarity Laws of Parallel and Serial Manipulators for Machine Tools.* Proceedings, MOVIC'98, IfR ETH Zürich, 1998.
[5] M. Hörhager, *Maple in Technik und Wissenschaft*, (Addison-Wesley, 1996)
[6] P. R. Bevington and K. D. Robinson, *Data Reduction and Error Analysis for the Physical Sciences* (McGraw-Hill, 1992).
[7] J. R. Taylor, *An Introduction to Error Analysis* (University Science Books, 1997).