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Abstract

At the 1989 CIRP annual meeting, we reported on the design of a specialized, ultra-precision CNC measuring machine, and on the error budget that was developed to guide the design process. In our paper we proposed a combinatorial rule for merging estimated and/or calculated values for all known sources of error, to yield a single overall predicted accuracy for the machine. In this paper we compare our original predictions with measured performance of the completed instrument.

Error Budgeting as a Design Tool

The error budget has become an essential tool for the designer of precision machine tools and other precision systems. As defined by Donaldson [1], "...an error budget is a systems analysis tool, used for prediction and control of the total error of a system at the design stage for systems where accuracy is an important measure of performance. Given a system-error goal, an error budget can be used in a control mode to set individual subsystem error limits, while also making trade-offs that balance the level of difficulty among the subsystems. In a predictive mode, proposed subsystem design can be assessed for error contributions, leading to a predicted overall system error."

Accurate input to an error budget can be derived from a number of sources. Typically the input is in the form of parametric error values for individual sources of error. Thus the use of proven subsystem design concepts allows the measurement of error values, and their direct insertion into the error budget. In those instances where empirical data is not available, a variety of analytical tools can be used. Most notable is the application of finite element modeling to assess both subsystem and overall system error sources.

The process of design using these error budget analysis is obviously iterative. Individual sub-systems are evaluated and optimized for cost and performance, while simultaneously an error budget is used to predict overall system performance. The error budget allows the designer to assess, for example, the impact of a cost-motivated design change on final system performance. Continued iterations of the design/analysis/error budget sequence can be used to ensure that costs can be optimized without compromising performance goals. Implicit in this process is the assumption that significantly exceeding performance goals is as undesirable (from a cost standpoint) as failing to meet performance goals. Thus the accuracy of the error budget is critical to the success of the design process.

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Selection of a Combinatorial Rule

The greatest difficulty in using error budgeting for predicting absolute machine performance stems from the lack of a mathematically defensible combinatorial rule for summing individual error source values into a single performance figure. Lacking sufficient information about the spatial or temporal distribution of individual error sources, an overall upper bound error for a given set of conditions may be obtained by arithmetically summing all of the individual error values for a given coordinate direction (e.g., y and z) separately, and calculating the maximum surface-normal error by taking the vector sum of the two. This approach is obviously extremely conservative; the probability of all errors reaching maxima at the same point in time and space with the same directional sense is very unlikely. The risk associated with basing an error budget on this approach is one of making the machine unnecessarily expensive. Alternatively, if all of the errors are assumed to be uncorrelated, the rms sums of the directional errors can be used to establish a lower bound overall error. In this case, however, the predicted error would be overly optimistic, since many of the errors cannot be assumed to be uncorrelated, and some are dependent on common sources.

In our 1989 CIRP paper [2] we proposed a combinatorial rule, originally suggested by Hocken [3], that predicted an overall system error value based on the means of the upper (arithmetic sum) and lower (rms) bounds. While admittedly arbitrary, the proposed methodology appeared to yield results reasonably consistent with actual accuracies measured on existing precision machine tools. In this paper, we compare our original predicted results using Hocken's rule with actual measured parametric error values and overall accuracy for a recently completed precision CNC measuring machine.

The Certification of Process Gauge

The Certification of Process (COP) Gauge, so named because of its intended application, is illustrated in Figure 1. The instrument is to be applied to the continuous path scanning inspection of inner and outer surfaces of hemispherical shells and other axisymmetric parts, with diameters of up to 400 mm. The required measurement accuracy, including all machine and process errors, is 750 nm. The machine is configured with three linear axes and one rotary axis. An independent horizontal axis (y-axis) transports a rotary table (c-axis) upon which the part is mounted. A 400 mm diameter hole through the center of the rotary table provides access to the lower surface of the part by a probe mounted from a vertical linear axis (lower z-axis). A similar vertical axis (upper z-axis) is used to probe the upper surface of the part. The upper and lower z-axes have travels of 250 and 450 mm respectively, and the y-axis has a travel of 600 mm. The base is a substantial block of granite, supported at three points. A super invar bridge supports the upper z-axis assembly, and super invar is used extensively for mounting of components within the metrology loop of the machine. All of the bearings are externally pressurized air, and the slides are actuated by capstan drives. The rotary table is driven directly by a large diameter dc torque motor.

Position feedback for the linear axes is provided by Zygo laser interferometers operating at 2.5 nm resolution. The z-axis interferometers are located along the centerlines of the rams, resulting in an Abbe offset of 65 mm to the probe tips. The z-axis retroreflectors are located nearly at the ends of the rams, thereby minimizing the effects of temperature changes on the rams in the z-direction. Two interferometers, located in line with the rotary table axis, are used for y-slide position feedback. Position information from the two interferometers is used to calculate actual position at the probe tips in compliance with the Abbe principle [4]. All of the laser interferometer beam paths are contained in evacuated (50 mTorr) extendible welded metal bellows. The probes used for gauging a part surface are air bearing LVDT's inclined at a 45 degree angle.

COP Gauge Error Budget

The error budget for the COP Gauge is tabulated in Table 1. The budget is based on a single scanning measurement of a 250 mm diameter disc, over 90 degrees of arc, using the upper z-axis and the y-axis. Final testing of the lower z-axis is not yet complete. All individual error values shown are p-v, over the time period expected for a single measurement. No values are shown for the rotary table, since the final testing did not include the effects of rotary table errors. The values shown in the first column are those originally predicted.. The second column values reflect actual parametric accuracy testing of the machine. In each case, the overall error value is based on the vector sum of the means of the directional (y and z) arithmetic sum and rms errors.

Actual overall accuracy was evaluated by scanning 90 degrees of a 250 mm diameter precision disc, with a combined size and figure accuracy of less than 100 nm. Output data was digitally filtered, with a spatial frequency cutoff of 8 mm. The results of a typical scan are shown in Figure 2, indicating that the combined error of the machine and test artifact is approximately 470 nm under these conditions.

Analysis of Results

The most relevant comparison to make to assess the validity of our error budgeting methodology and the proposed combinatorial rule is between the predicted disk check accuracy using measured parametric error values (Table 1, column 2), and the actual overall error as tested. The results are in remarkably close agreement. The predicted disc check accuracy is approximately 540 nm, which agrees with the measured value of 470 nm within 15%. In addition to being close, the predicted accuracy value is also well-behaved, in the sense that it is comfortably conservative.

One can also note that the original prediction (column 1) also agrees fairly well with the measured accuracy. This is particularly true if we observe that the largest contributor to the difference comes from our inability to accurately predict (at least at the time, in 1989) transient thermal deformations. If we substitute the measured thermal error values for an inspection cycle, as tabulated in column 3, the predicted value drops from 708 nm to 471nm--which agrees unreasonably closely with the measured value of 470 nm. It is also interesting to note here that the error budgets based on predicted and measured parametric error values agree fairly closely, even though individual error value entries differ significantly.

It is difficult to draw any absolute conclusions from this exercise, nor was that our intent. One can, for example, come up with any number of pathological cases (for example, having to do with the rate of change of error sources) that would render the proposed combinatorial rule less accurate. One could just as easily dismiss our method as invalid, on the grounds that it is not mathematically defensible. We have not tried to defend the method as an absolute method for predicting accuracy, nor do we advocate its use. We have merely tried to observe that we have tested an estimating technique that appears to work reasonably well as a tool for implementing an error budget during the design phase of a precision motion control system, and that our predicted results agree reasonably closely with actual accuracies obtained. Conclusions beyond this point are left as an exercise for the reader.

References

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2. Thompson, D. C., 1989, "The Design of An Ultra-Precision CNC Measuring Machine", 39th CIRP General Assembly, August 1989.
3. Hocken, R. J., Telephone Conversation, August 17, 1988.
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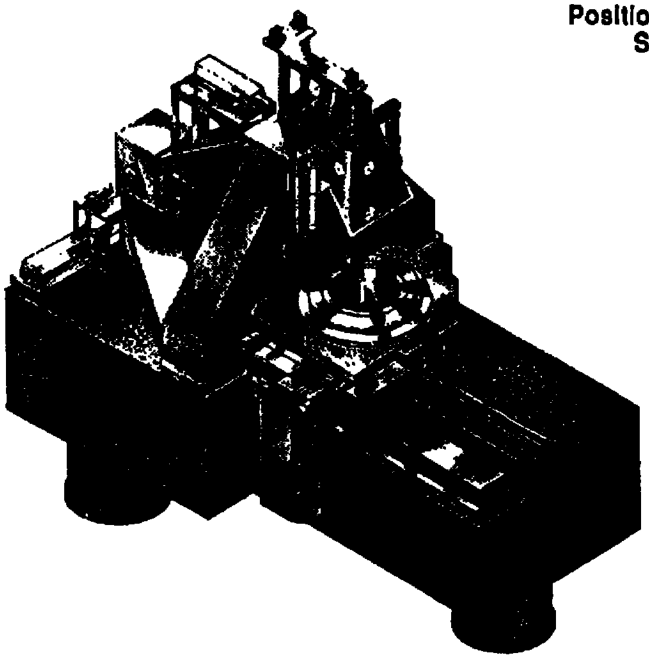
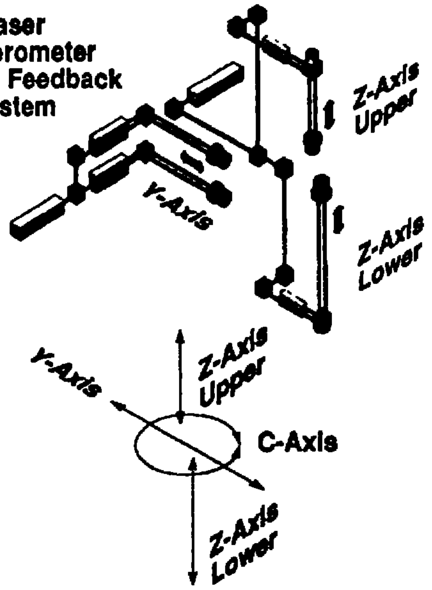
TABLE 1: PREDICTED DISK CHECK ACCURACY

	P-V Magnitude (nm)			
	With Predicted Error Values		With Measured Error Values	
	Y	Z	Y	Z
LASER INTERFEROMETER				
Frequency stability	15.0	22.5	15.0	22.5
Resolution	2.5	2.5	2.5	2.5
Index of refraction	12.5	20.0	12.5	20.0
Optical electronic factors	5.0	5.0	5.0	5.0
MACHINE GEOMETRY				
Y-slide straightness		100.0		55.0
Y-slide pitch			62.0	
Upper z-slide straightness	100.0		300.0	
Upper z-slide pitch		25.0		170.0
Squareness				
Upper z-slide to y-slide	75.0	75.0	25.0	25.0
THERMAL EFFECTS				
0.05 degree C gradient--x-direction				
0.05 degree C gradient--y-direction				
0.05 degree C gradient--z-direction	300.0	240.0		
0.05 degree C overall change				
Measured			50.0	50.0
Part	120.0	120.0	50.0	50.0
LVDT				
Electronic noise	25.0	25.0	7.0	7.0
Linearity	25.0	25.0	10.0	10.0
PROBE TIP				
Size	18.0	18.0	10.0	10.0
Contour	50.0	50.0	25.0	25.0
GAUGING FORCE	25.0	25.0	25.0	25.0
MASTERING	50.0	50.0	50.0	50.0
DATA ACQUISITION	25.0	25.0	25.0	25.0
TEST ARTIFACT (DISK) ACCURACY	65.0	65.0	65.0	65.0
Arithmetic Sum:	913.0	893.0	739.0	617.0
*RMS Sum:	105.1	91.8	95.2	62.8
Mean ((EA+ER)/2:	509.0	492.4	417.1	339.9
Predicted Maximum Error:				
((EMY2+EMZ2)1/2)		**708.2**		**538.1**

*Assumes a uniform probability density for each error about its mean value





Physical Characteristics

Slide Travels: Upper Z = 10.00 In.
Lower Z = 18.00 In.
Y = 24.00 In.

Overall Dimensions: Height = 123.50 (10'3.5")
Width = 78.00 (6'6")
Depth = 132.00 (11'0")

Figure 1: Certification of Process (COP) Guage

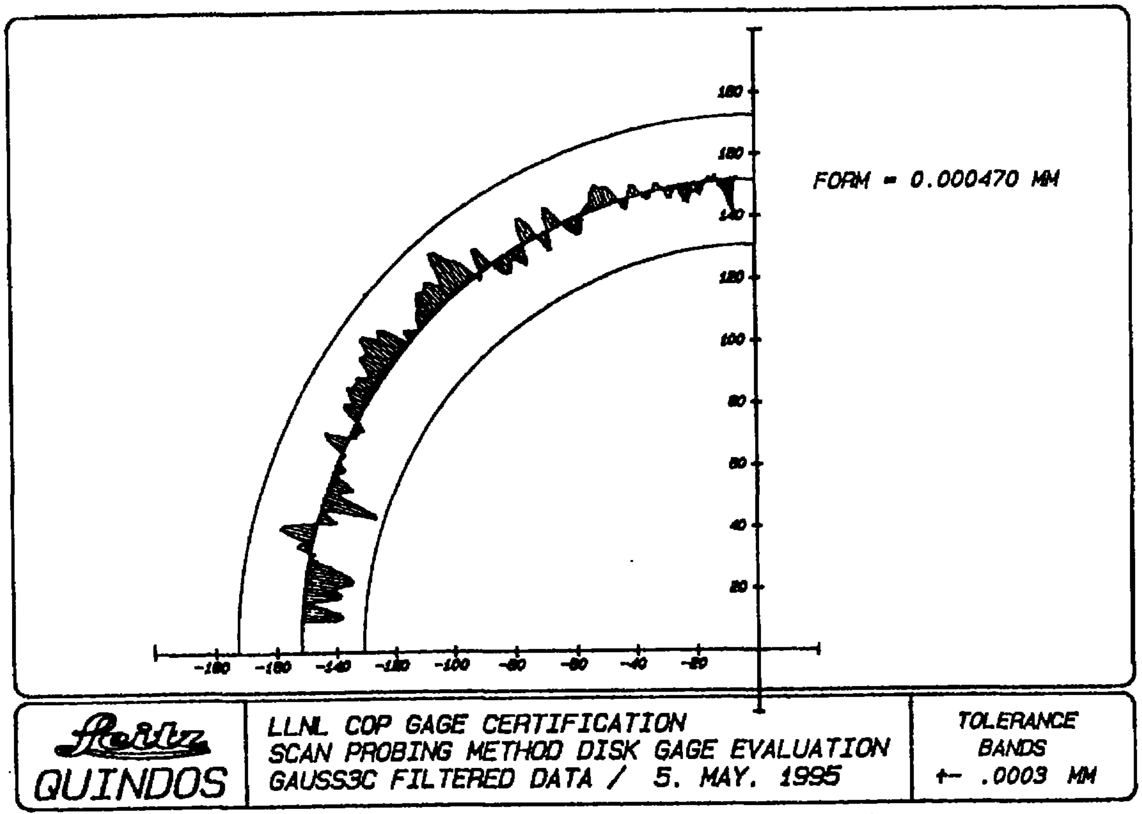


Figure 2: Results from 90° scan of 250mm diameter cylindrical disk