Ballbar Length Calibration

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Purpose

This article shows one method to calibrate a fixed length ballbar resulting in a nominal length and measurement uncertainty with a confidence level of 95%. A ballbar can be used to verify the geometry of a CMM where a calibrated ballbar can be used to verify geometry and scales.

Using a calibrated ballbar without performing a Linear Displacement Accuracy (LDA) test does not conform to the ASME B89.4.1:1997 standard but it does eliminate an obvious hole when the LDA test is omitted as is commonly done when performing an interim check of a CMM.

There are service companies that only run the length repeatability check of a CMM using a non-calibrated ballbar as a yearly certification/calibration of a CMM. This not only ignores the requirements of ASME B89.4.1:1997 but the intent of the standard at the same time. This kind of yearly certification/calibration should be avoided.

Ballbar Requirements

A ballbar is easy to manufacture by anyone with even modest manufacturing ability or access to manufacturing facilities. This result is a wide variety of ballbar's in the field with some exceptional while others have an array of problems.

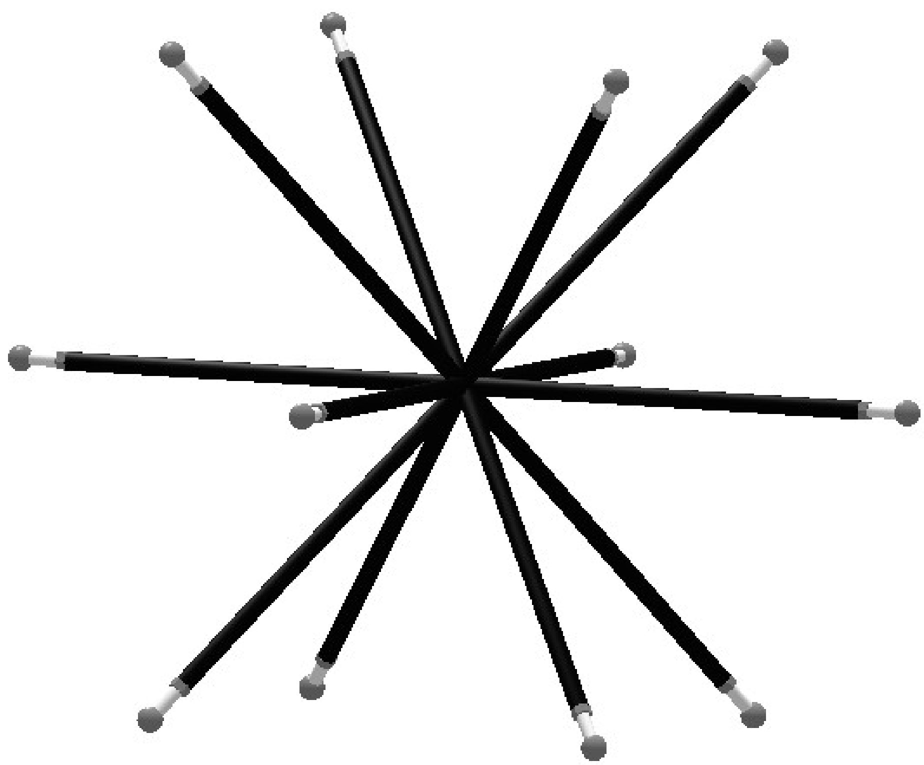

Illustration 1: Typical ballbar in the six orientations commonly used for squareness checks of a CMM.

Ballbar Length Calibration

A reliable ballbar is one that has the following characteristics:

- Shaft with a known expansion coefficient (steel or Invar).
- Ballbar spheres with a minimum form error (grade 25 or better).
- Sufficiently stable base.
- Sufficiently stable ballbar support system.

The following provide further details on each of the listed requirements shown above.

Ballbar Shaft

The shaft that holds the two ballbar spheres should be made from a stable material such as steel or Invar. The advantage Invar has is that the Coefficient of Thermal Expansion (CTE) is virtually zero which reduces the measurement uncertainty when used in environments that are not ideal. If using steel the typical CTE is 12 um/m/°C and, unless the CTE of the ballbar shaft is calibrated, a reasonable expansion uncertainty would be +/- 10% of the CTE (+/- 1.2 um/m/°C for material with a CTE of 12 um/m/°C).

Material such as aluminum should never be used for a ballbar shaft. The expansion coefficient of aluminum is around 22 – 24 um/m/°C and this material has good thermal conductivity and can change temperature (and therefore length) very rapidly.

It is assumed that temperature compensation is used when performing ballbar measurements in which case Invar is the better choice for the ballbar shaft material. If temperature compensation is not used then Steel is the better option as the expansion coefficient of steel is closer to that of a typical CMM axis scale as opposed to Invar.

The choice of material has an impact on the final measurement uncertainty where Invar is a better choice from that point of view. For classic CMM's without temperature compensation, in less than ideal environments, steel is probably a better, practical, choice.

Ballbar Spheres

The quality of the spheres of the ballbar is critical. The length measurement of the ballbar is the 3D distance between the center of the two spheres. With a poor sphere quality the measurement uncertainty will increase as finding the center of a non-perfect sphere is difficult and subjective.

A typical steel probe calibration sphere used on a CMM is grade 10 (form error 0.00025 mm) where a typical ceramic probe calibration sphere is grade 5 (form error 0.00013 mm). Often tooling ball spheres are used for a ballbar manufactured in-house for interim checks of CMM's. These spheres have a typical grade of 200 (form error 0.005 mm) and should be avoided if possible.

Most ballbar programs cannot handle measuring spheres of two vastly different sizes so both spheres should have the same nominal size at a minimum. When measuring a ballbar it is a good idea to monitor both the size and form of the measured spheres and throw out lengths where either result exceeds some established tolerance so having the two ballbar spheres with matched diameters is a good idea. Monitoring the sphere form error should always be done regardless of the situation where monitoring the diameter is supplemental information and can be done if practical.

Based on previous testing the impact on the position of the sphere center relative to the sphere form error when measured with eight points (the typical measurement pattern used by MeasureDirect for a ballbar) is 1:0.5375. A form error of 1 um would therefore represent a potential shift in position of only 0.54 um. This relationship between form error and position shift is linear so this can be scaled up or down easily. This position shift uncertainty is combined twice since there are two spheres and assuming both spheres have similar form errors.

Note: The relationship of 1:0.5375 only applies to spheres measured with eight points.

The final calibration length reported in this article is for a custom manufactured ballbar using tooling ball spheres on a steel shaft. The measured results showed an average sphere form error of 0.0035 mm which is reasonable considering the expected max form error is 0.005 mm for a grade 200 sphere and only eight points on the sphere are sampled.

Stable Base

The base supports the ballbar. If the base is not stable each sphere will be a moving target to the CMM.

If the ballbar system is dedicated to a particular CMM then using a large, heavy base is a good idea. If the ballbar system is meant to be moved from machine to machine keeping the size and weight down to something reasonable is preferred.

Using a heavy base is not necessary if the design is good. A small flat plate is probably the worst setup unless it is bolted to the CMM table prior to use.

Ballbar Support

The most common problem seen with a typical ballbar is the ballbar shaft support. Often this is a single, centrally located, clamp on the ballbar shaft. When the length of the ballbar approaches 1000 mm this centrally located support doesn't hold the ballbar very well and gets exponentially worse as the length increases.

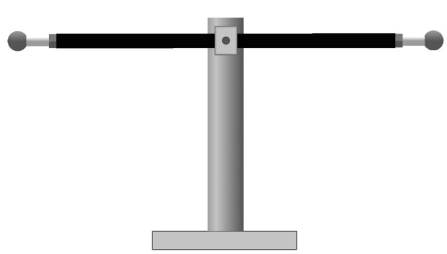

Illustration 2: Centrally clamped ballbar shaft.

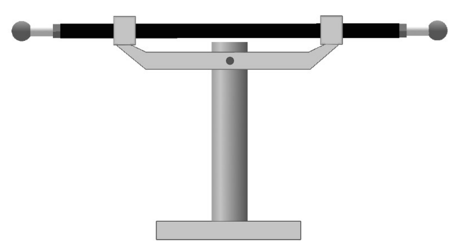

Illustration 3: Dual clamped ballbar shaft support system.

There are many factors at play in deciding what kind of design should be used to support the ballbar system but, in the author's opinion, any ballbar with a length over 750 mm should have two support points instead of a single, centrally located, support.

Illustration 4: Example of one end of a two point ballbar shaft support.

Illustration 4 shows a system where each end of the shaft is supported by an elaborate kinematic sphere system. It is not known if this kind of elaborate system is necessary but the idea is definitely correct.

Calibrated Length

The calibrated length of the ballbar is easy to determine using a CMM; it is simply the average length from a series of measurements performed on the machine. The position and orientation of the ballbar must be changed between each measurement to cover all axis of the machine at a minimum. Preferably measurements are run randomly throughout the volume of the machine until a standard distribution of the data is seen as shown in illustration 5.

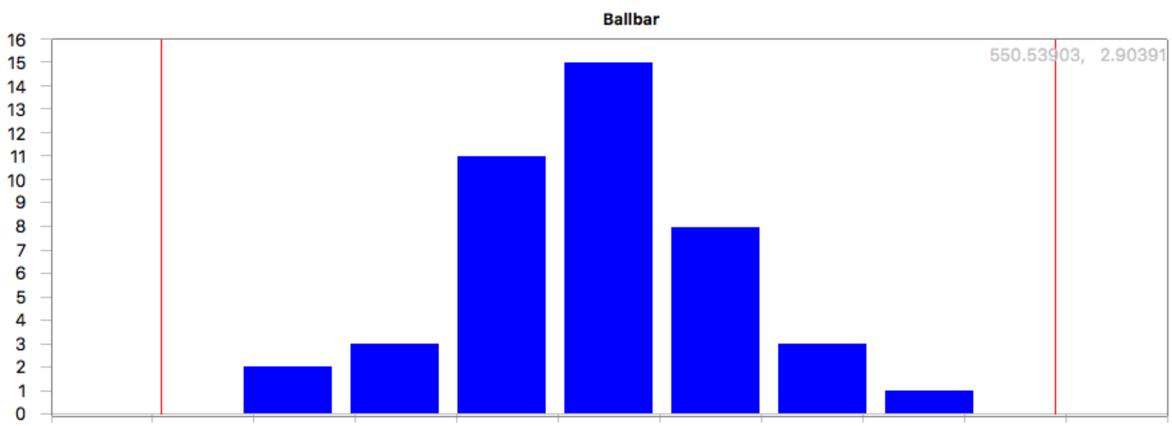

Illustration 5: Standard distribution of ballbar length measurement data.

The machine used to calibrate the length of the ballbar should itself be calibrated using a laser or some other certified length standard in order to establish the scales of each axis. The machine should also not have obvious geometry errors as this can bias the calibrated length of the ballbar if ignored.

The use of a laser or certified length standard to establish the axis scales is necessary otherwise no traceability is possible.

Measurement Uncertainty

The calibrated length of the ballbar should not be used without consideration of the measurement uncertainty. The measurement uncertainty provides a realistic estimation of measurement error when using this equipment to evaluate other machines. If done properly it should be traceable back to the SI units.

The measurement uncertainty of the ballbar is based on the following sources of error:

- The CMM uncertainty used to establish the calibrated length.
- The impact of the environment on the known length of the ballbar.
- Grade of the ballbar spheres.

The following provide further details on each of the listed uncertainty sources shown above.

CMM Uncertainty

The CMM uncertainty is the potential measurement error of the CMM used to establish the calibrated distance between the two spheres. The uncertainty is the higher value of the specifications or the strict acceptance limit from the last calibration using a standard such as ASME B89.4.10360-2 or equivalent.

The CMM probing must be configured the same as that used during the last calibration. If, for example, the probe configuration for the last calibration was a Renishaw SP25 with a 5x30 mm stylus then this should been used for the calibration of the ballbar. If this is not done the difference between the probing systems must be considered and included in the uncertainty calculations.

The CMM environment must be comparable to the environment recorded during the last calibration. If the environment has changed by an amount more than permitted by the specifications of the CMM then the results are questionable (and not addressed by this article). Ideally the calibration of the ballbar is done immediately following the calibration of the CMM; preferably the same day if possible.

The calibration of the ballbar in this article was based on measurements from a Global Status 12.22.10 CMM. The specifications of this particular CMM is 4+4L um (L in meters) where the strict acceptance limit was found to be 5.1+4.7L um (L in meters) based on the ASME B89.4.10360-2 performance test.

The CMM uncertainty budget data, in this case, covers all subcomponents such as the calibration sphere, probing, scale resolution, and environment factors that had an impact on the CMM. The CMM is treated as a combined unit consisting of all the sub-components that would normally be associated with CMM measurement uncertainty.

CMM Uncertainty Budget Data

Uncertainty Item	*Type*	*Expression*	*Type*	*Distribution*	*Sensitivity*	*Comments*
CMM						
Specification or Strict Acceptance	Length Dependent	0.0051+0.0047L/1000	B	Rectangular	1.0	Uncertainty of the CMM from strict acceptance limit.

Ballbar Uncertainty

The ballbar uncertainty, from a calibration point of view, consists of the unknown shaft expansion coefficient, error in temperature measurement of the ballbar, and the impact from the quality of the calibration spheres.

In this example the ballbar under test is using standard fixture tooling balls mounted on a Steel shaft. Temperature compensation is used during the measurement of the ballbar. The expansion error of the ballbar shaft is dependent on the uncertainty of the thermometer used for this measurement.

Ballbar Uncertainty Budget Data

Uncertainty Item	*Type*	*Expression*	*Type*	*Distribution*	*Sensitivity*	*Comments*
Ballbar						
Expansion Error	Length Dependent	CTEc * 0.1	B	Rectangular	1.0	Steel shaft, 12 um/m/˚C. 10% Uc.
Environment Error	Length Dependent	UTt * CTEc	B	Normal	1.0	Temperature measurement uncertainty of ballbar.
Ballbar Sphere1 Form	Constant	0.005	B	Rectangular	0.54	Ballbar uses tooling ball spheres grade 200. Form error from 8 point sphere impact on location is 1:0.5375
Ballbar Sphere2 Form	Constant	0.005	B	Rectangular	0.54	Ballbar uses tooling ball spheres grade 200. Form error from 8 point sphere impact on location is 1:0.5375

Thermometer Uncertainty Budget Data

Uncertainty Item	*Type*	*Default Value*	*Type*	*Distribution*	*Sensitivity*	*Comments*
Thermometer						
Sensor Resolution	Constant	0.01 C	B	Step	1.0	Resolution of the thermometer.
Specification	Constant	0.10 C	B	Rectangular	1.0	Specification of the thermometer.

Ballbar Length

The ballbar length is the average of a series of measurements performed on the CMM. The following is a measurement summary of the results:

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Minimum Length: 787.6309 mm
Maximum Length: 787.6435 mm
Mean Length:    787.6377 mm
Length Range:     0.0126 mm
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The Mean Length listed in the above table represents average of all measurements of the ballbar and is considered to be the calibrated length.

Ballbar Uncertainty

The following is the output from the uncertainty budget editor when using the uncertainty entries desribed above.

Budget Definition - Ballbar Calibration

Thermometer Component Variable

Source	Value	Expression	Type	Sensitivity	Distribution	Distribution Divisor
Sensor Resolution	Constant	0.01	Type B	1.000000	Step	3.464102
Specification	Constant	0.1	Type B	1.000000	Rectangular	1.732051

Ballbar Component

Source	Value	Expression	Type	Sensitivity	Distribution	Distribution Divisor
Expansion Error	Length Dependent	CTEc * 0.1	Type B	1.000000	Rectangular	1.732051
Environment Error	Length Dependent	UTt * CTEc	Type B	1.000000	Normal	1.000000
Sphere1 Form	Constant	0.005	Type B	0.540000	Rectangular	1.732051
Sphere2 Form	Constant	0.005	Type B	0.540000	Rectangular	1.732051

CMM Component

Source	Value	Expression	Type	Sensitivity	Distribution	Distribution Divisor
Strict Acceptance	Length Dependent	0.0051+0.0047*L/1000	Type B	1.000000	Rectangular	1.732051

Global Variables

CTEm	0.010000
Sr	0.000100
Td	0.000000
Tr	2.000000
Tg	0.000000
Sdev	0.000000

Ballbar Length Calibration

Budget Data - Ballbar Calibration

	Position (mm)	0.0	98.4	196.8	295.1	393.5	491.9	590.2	688.6	787.0	885.4	983.8
Thermometer Component	**Variable**											
Export Variables	UTt	0.05781	0.05781	0.05781	0.05781	0.05781	0.05781	0.05781	0.05781	0.05781	0.05781	0.05781
Source	Sensor Resolution	0.00289	0.00289	0.00289	0.00289	0.00289	0.00289	0.00289	0.00289	0.00289	0.00289	0.00289
	Specification	0.05774	0.05774	0.05774	0.05774	0.05774	0.05774	0.05774	0.05774	0.05774	0.05774	0.05774
Ballbar Component												
Local Variables	CTEc	0.01200	0.01200	0.01200	0.01200	0.01200	0.01200	0.01200	0.01200	0.01200	0.01200	0.01200
Source	Expansion Error	0.00000	0.00007	0.00014	0.00020	0.00027	0.00034	0.00041	0.00048	0.00055	0.00061	0.00068
	Environment Error	0.00000	0.00007	0.00014	0.00020	0.00027	0.00034	0.00041	0.00048	0.00055	0.00061	0.00068
	Sphere1 Form	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156
	Sphere2 Form	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156	0.00156
CMM Component												
Local Variables	L	0.00000	98.3750	196.750	295.125	393.500	491.875	590.250	688.625	787.000	885.375	983.750
Source	Strict Acceptance	0.00000	0.00032	0.00068	0.00111	0.00158	0.00210	0.00268	0.00331	0.00400	0.00473	0.00552
Uncertainty												
	Combined	0.00220	0.00223	0.00232	0.00248	0.00274	0.00309	0.00352	0.00404	0.00463	0.00529	0.00602

Uncertainty Expression

Uc(K=1): 0.00221-0.00028L+0.00425L^2 mm (L is length in meters)
Uc(K=2): 0.00441-0.00057L+0.00850L^2 mm (L is length in meters)

For a ballbar length of 787 mm the standard uncertainty is estimated to be 0.00463 mm.

Final Calibrated Length Result

The calibrated length of the ballbar described in this article is:

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787.6377 +/-0.0093 mm (k=2)
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The measurement uncertainty of the length is shown with a confidence level of 95% (k=2).

Using the Calibrated Ballbar

The use of the calibrated ballbar is no different than the non-calibrated counterpart with the exception that the average ballbar length on the test machine should be within the allowed range of the calibrated ballbar length of 787.6377 +/-0.0093 mm in this case. If the average ballbar length is outside the range then the axis scales should be checked using a certified artifact such as a step gauge or laser.

The problem using a non-calibrated ballbar is the length range could be very small and yet the scale errors could be in the mm range. As mentioned earlier a certification/calibration using a non-calibrated ballbar without a Linear Displacement Accuracy test should be avoided for this reason.

Revision History

Revision	*Date*	*Reason*
1	Apr 16, 2022	Initial Release