Machine tool and motion error standardized definitions for simplified error modeling

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Abstract

Error models for the purposes of understanding and correcting machine motion errors have been used for many years. Most of these models have been developed to define and improve the behavior of specific laboratory devices or commercial products. The adaptation of Error Modeling for general use in factory applications requires the incorporation of a wide variety of machine configurations. Some of these machines and their errors are described in ISO and ANSI Standards.

Limitations of the current number of machine configurations defined in these Standards reduce the effective application of standardization when new configurations are developed. Also, the measurement of a machine is often limited to a few errors by the instrumentation available. This paper proposes more generalized methods for naming machines and their errors, as well as error sign conventions, to permit a wider application of models. These generalized methods also facilitate communication of the wide variety of error measurements necessary for comprehensive diagnostics and corrections. The research funding to create these conventions has been provided to Independent Quality Labs, Inc. (IQL) by the US Army Research Laboratories in Aberdeen, MD.

1 Machine classes and sub-classes

Machine Classes have been defined in the Draft Standard ASME B5.59 [1] as: Turning Machine, NC Turning Machine, Turning Center, Milling Machine, NC Milling Machine, and Milling Center. Machine kinematic arrangements (axis stacking) have been defined in ANSI/ASME B5.54 [2] and a variety of machine-specific ISO Standards.

1.1 Machine classes

IQL has simplified these definitions by adopting machine classifications according to function and orientation of material and/or material working device (tool). Classifications include Vertical, Horizontal and Universal Machining Centers, Turning Centers, Grinding Centers and Welding Centers. The classifications for Machine and NC have been dropped to simplify the list. The term "Centers" is used for all classes since the majority of machines which have been modeled include some type of automatic part loading, tool or part position sensor. Additional Classes can easily be added as other working devices are developed.

1.2 Machine sub-classes

The identification of machine errors requires a complete definition of the kinematic arrangement of machine motion axes. In order to accommodate the classification for Universal Turning Centers, where the material is transferred from one Work Spindle to another, the previous IQL method [3] that defined arrangements from the material to the tool, was abandoned. Upon suggestion from Dr. Thomas Charlton, the proposed IQL approach defines kinematic chains (axis stack) working from a fixed point on the earth through multiple chains to the material and/or the tool. The Draft Standard ASME B5.59 [1] Roll, Pitch and Yaw definitions for Angular Errors required the definition of the Axis Rail or Way Plane to fully describe the error. The resulting proposed Machine Sub-Class definitions start at the earth and proceed upward to the material or tool, describing the plane of the ways, for each kinematic chain (axis stack). Axes with no apparent Way Plane are defined using the Way Plane of the preceding Axis.

The simplest example is the Sub-Class definition for the Vertical Machining Center with a Moving Gantry (Figure 1).

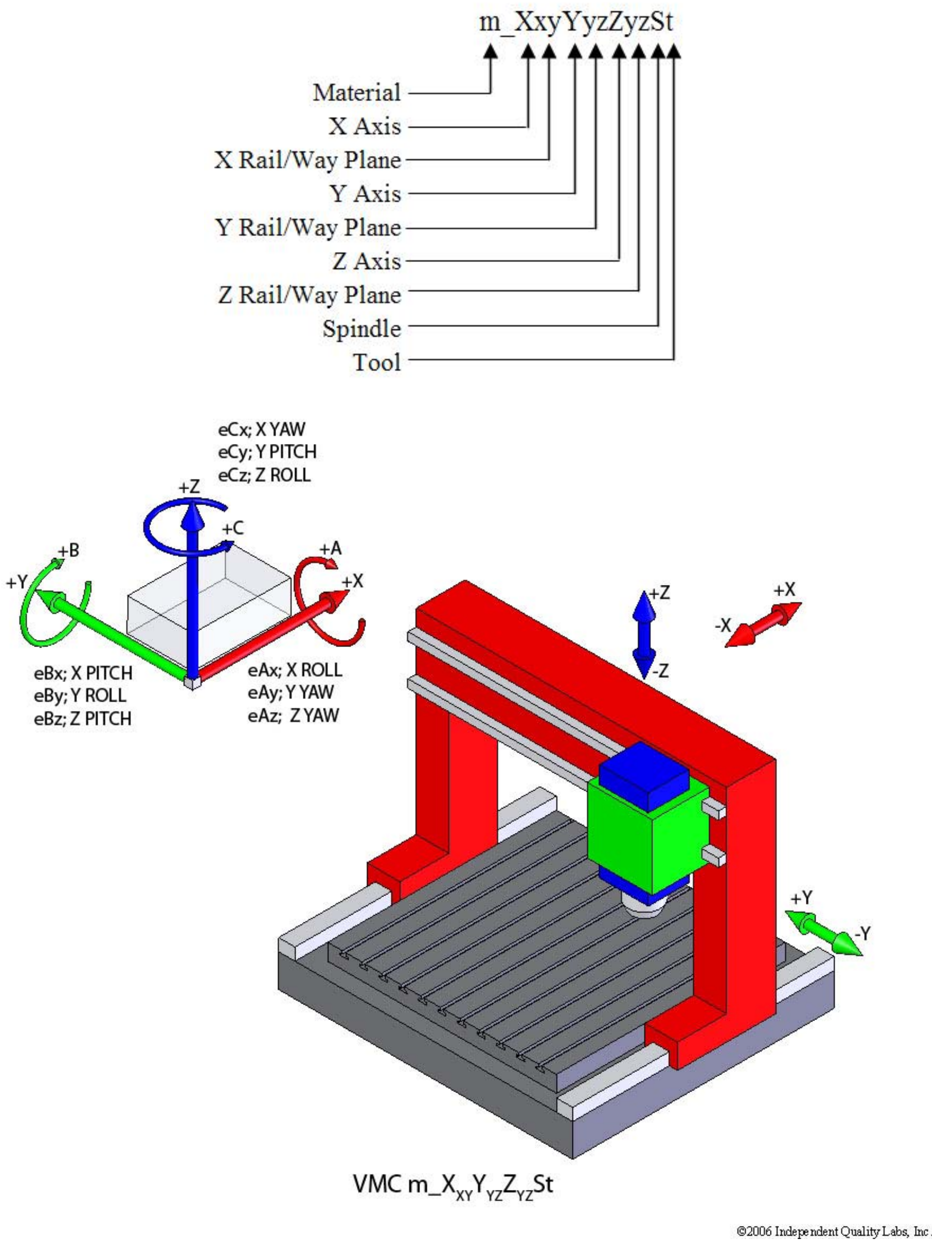


Figure 1: Vertical Machining Center.

The more complicated example, which prompted the revision in definitions, is the Universal Turning Center (Figure 2).

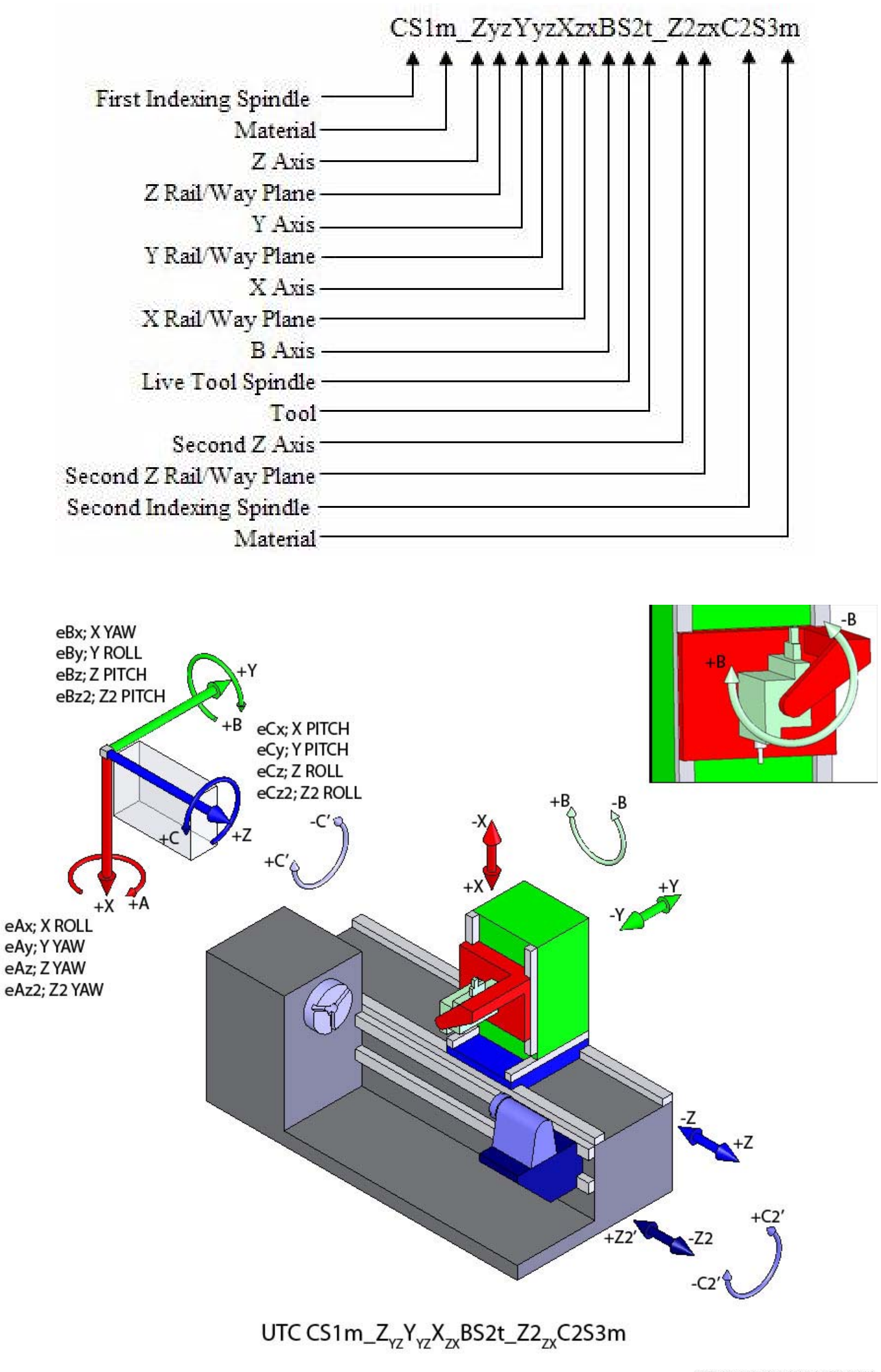


Figure 2: Universal Turning Center.

2 Machine error definitions

Machine Errors have many properties including motion axes, error source, method of analysis, direction, and sign. To accommodate these properties, IQL has developed the following terminology:

2.1 Parametric Error Names (PENs)

Errors are defined by Test Classes and Test Properties in the Draft Standard ASME B5.59-2 [1]. Tests Classes such as Axis Acceleration, Angular, Motion, and Positioning, and Test Properties such as Circular, Line and Point Tests are considered. The ISO Draft 230 [4] defines Linear, Positional and Angular deviations using these terms:

For Linear Axes Motion:

EXZ: Linear Deviation	EAZ: Pitch Angular Deviation
EYZ: Linear Deviation	EBZ: Yaw Angular Deviation
EZZ: Linear Deviation	ECZ: Roll Angular Deviation

For Angular Axes Motion:

EXC: Radial Error	EAC: Tilt Error
EYC: Radial Error	EBC: Tilt Error
EZC: Axial Error	ECC: Positioning Deviation

The methods of naming errors provided by these Standards are inadequate to clearly describe all the errors present in a comprehensive model of machine performance. IQL has developed and successfully utilized Locus™ PEN definitions of Machine Errors to describe a large number of Quasi-static, Thermal and Dynamic Errors in machines by extending and modifying the ISO Draft 230 [4] definitions. Locus™ PEN definitions use a combination of error description, direction and motion axis (axes) terms as follows:

Error Prefix Characters:

Error Types - considering Class, Properties and Method of Analysis

e – Bandwidth of the Bi-directional Averages

eb – Average Reversal Error

ebs – Dynamic Step Reversal

ei – Dynamic Interpolation Error

el – Location Error

ep – Periodic Error

er – Calculated Repeatability

es – Dynamic Step Error

et – Motion Axis Thermal Drift

etve – Environmental Thermal Drift

Direction Characters:

Error Direction - using the Part Coordinate System

eX, eY and eZ – Indicate the directions of linear displacement errors such as Linear Displacement Accuracy, Straightness, and Spindle Radial and Axial Average Errors.

eA, eB and eC – Indicate the directions of angular errors Roll, Pitch and Yaw, Angular Displacement Accuracy, Squareness, Parallelism and Spindle Tilt. A, B and C represent the directions of the errors.

Note: Roll is defined as rotation about the linear guide, Pitch is rotation about an axis in the plane of the linear guide and Yaw is rotation about an axis perpendicular to the plane of the linear guide.

Motion Characters:

Motion Axes - using the ISO-841 [5] Axis Standard and Locus™ PEN Spindle definitions

Linear Axes: X, Y, and Z, with parallel linear axes U, V and W. Machines with many parallel axes the definitions may be indexed by adding a number to the letter (e.g. X1, X2...).

Rotary Axes: A, B and C parallel to X, Y and Z, with additional parallel rotary axes D and E. Machines with many parallel rotary axes may also be indexed by adding a number to the letter (e.g. A1, A2...).

Spindle Axes: S, S1, S2, etc., generally parallel to Z or with a subscript x, y, or z for the axis about which they rotate (e.g. Sx, Sy…).

Turret or Indexing Axes: I, I1, I2 etc., with a subscript x, y, or z for the axis about which they rotate (e.g. Ix, Iy...).

2.2 Machine error definitions

Using the error and motion axis definitions from above, Machine Errors can now be defined as:

eXx, eXy, eXz, etc. – Indicating that a single axis is moving to produce the error in the direction of motion.

eAyz, eBzx, eCxy – Indicating that two axes are moving to produce the error. It is important to note the order of the motion axes to assure that the sign of Squareness and Parallelism Errors meet the criteria for the Plus direction (greater than 90 degrees) defined in the ISO Draft 230 [4] methods. This requires the proper utilization of Primary, Secondary and Tertiary plane and axis designations as shown in Figure 3.

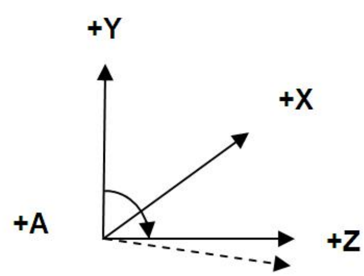


Figure 3: eAyz squareness.

Other multi-axis Locus™ PENs include:

Parallelism between two linear axes
eAzw – Parallelism
eBzw – Parallelism

Squareness between linear and rotary axes
eAyc – Squareness
eBxc – Squareness

Squareness between two rotary axes
eAbc – Squareness
eBca – Squareness

Parallelism between linear and rotary axes
eAzc – Parallelism
eBzc – Parallelism

Parallelism between two rotary axes
eAc1c2 – Parallelism
eBc1c2 – Parallelism

3 Machine error sign conventions

Sign conventions for axes motion has been established by ISO 841 [5] using the Right Hand Rule. The conventions are based on the need to create machine motion programs which place the Tool in relation to the Part (Material), regardless of the kinematic arrangement of machine motion axes (See 1.2 above). Locus™ PEN sign convention uses the same logic to simplify diagnosis of Part Errors regardless of the machine arrangement. This rule is also consistent with the current ISO Draft 230 [4]. The sign of Error Data taken on machines where the part is carried by one or more motion axes is reversed from the direction of the motion axis which is designated with a prime ('). Figure 4 illustrates this convention.

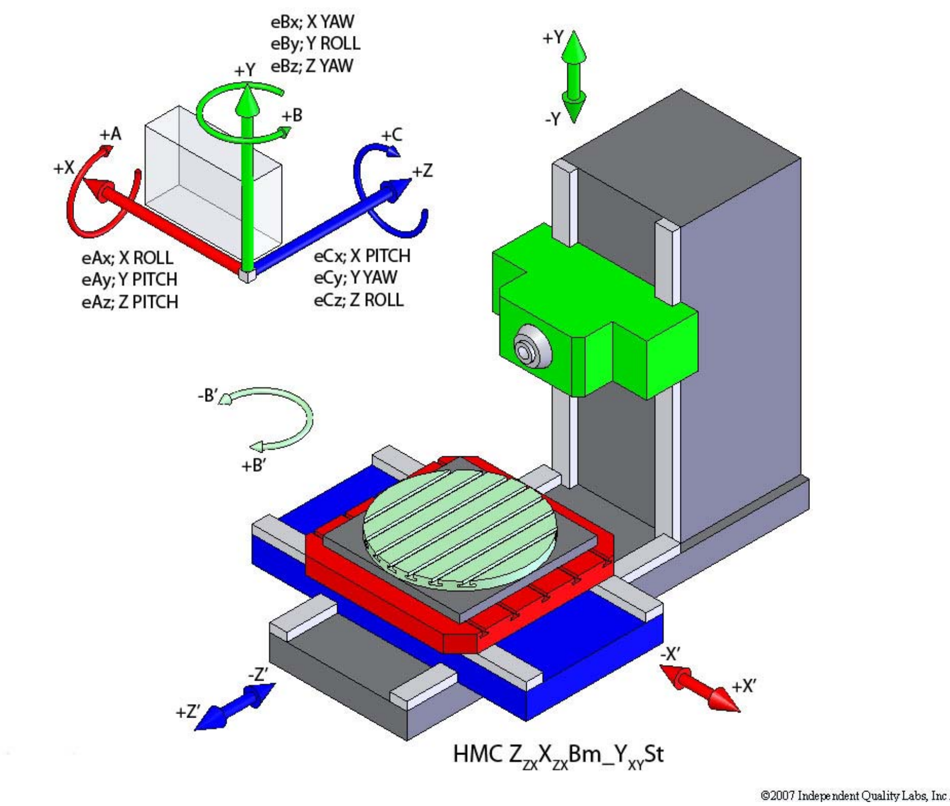
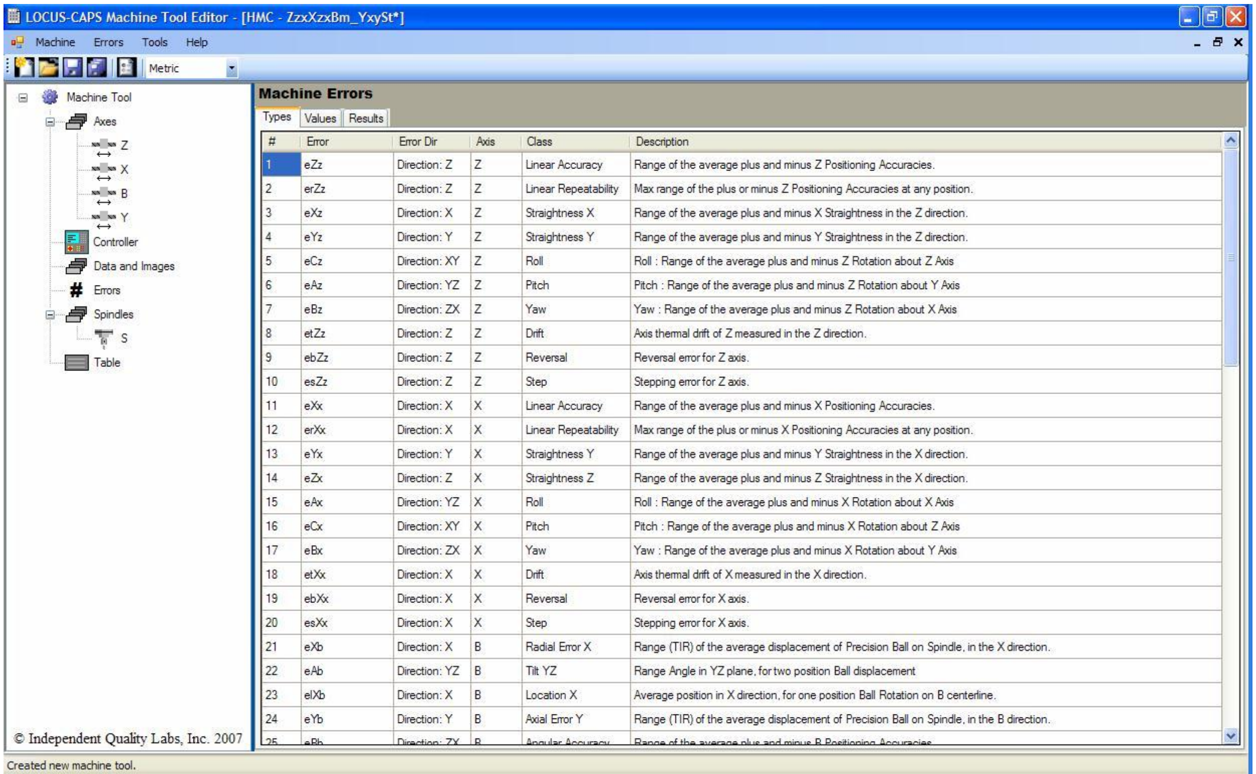


Figure 4: Horizontal Machining Center.

4 Conclusion

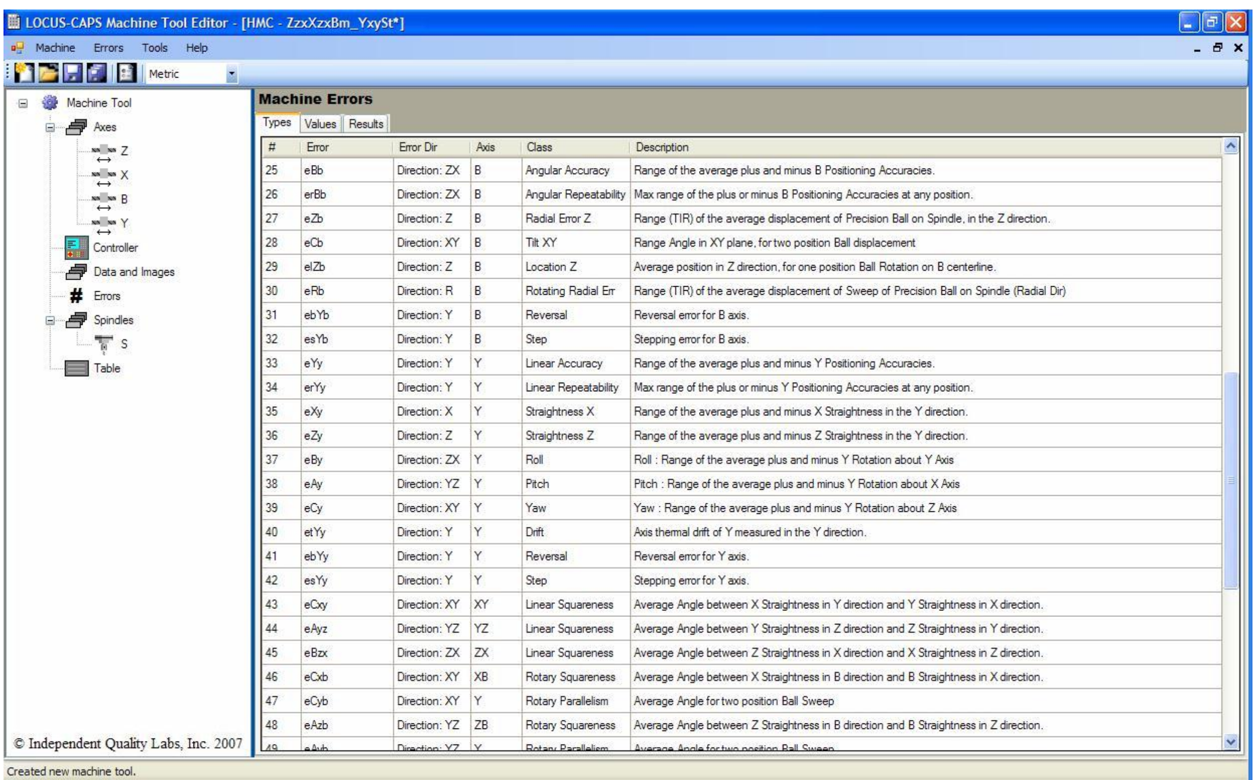
The use of Locus™ Machine Sub-Class Names and Parametric Error Names (PENs) has allowed the creation of an application which will create complete PEN Lists for machine errors, simply from the Sub-Class Name (Figures 5a, b, and c). These lists provide the foundation on which to build tools for Machine Modeling as well as Error Diagnostics and Correction. Test instrumentation and artifacts, with the corresponding test procedures can be easily identified and organized using the PEN List.

Machine Sub-Class Names and Parametric Error Names should be considered to extend the utilization of current National and International Standards. These extensions will simplify the interchangeability of data between the developers of Machine Metrology Software and Instrumentation.



#	Error	Error Dir	Axis	Class	Description
1	eZz	Direction: Z	Z	Linear Accuracy	Range of the average plus and minus Z Positioning Accuracies.
2	erZz	Direction: Z	Z	Linear Repeatability	Max range of the plus or minus Z Positioning Accuracies at any position.
3	eXz	Direction: X	Z	Straightness X	Range of the average plus and minus X Straightness in the Z direction.
4	eYz	Direction: Y	Z	Straightness Y	Range of the average plus and minus Y Straightness in the Z direction.
5	eCz	Direction: XY	Z	Roll	Roll : Range of the average plus and minus Z Rotation about Z Axis
6	eAz	Direction: YZ	Z	Pitch	Pitch : Range of the average plus and minus Z Rotation about Y Axis
7	eBz	Direction: ZX	Z	Yaw	Yaw : Range of the average plus and minus Z Rotation about X Axis
8	etZz	Direction: Z	Z	Drift	Axis thermal drift of Z measured in the Z direction.
9	ebZz	Direction: Z	Z	Reversal	Reversal error for Z axis.
10	esZz	Direction: Z	Z	Step	Stepping error for Z axis.
11	eXx	Direction: X	X	Linear Accuracy	Range of the average plus and minus X Positioning Accuracies.
12	erXx	Direction: X	X	Linear Repeatability	Max range of the plus or minus X Positioning Accuracies at any position.
13	eYx	Direction: Y	X	Straightness Y	Range of the average plus and minus Y Straightness in the X direction.
14	eZx	Direction: Z	X	Straightness Z	Range of the average plus and minus Z Straightness in the X direction.
15	eAx	Direction: YZ	X	Roll	Roll : Range of the average plus and minus X Rotation about X Axis
16	eCx	Direction: XY	X	Pitch	Pitch : Range of the average plus and minus X Rotation about Z Axis
17	eBx	Direction: ZX	X	Yaw	Yaw : Range of the average plus and minus X Rotation about Y Axis
18	etXx	Direction: X	X	Drift	Axis thermal drift of X measured in the X direction.
19	ebXx	Direction: X	X	Reversal	Reversal error for X axis.
20	esXx	Direction: X	X	Step	Stepping error for X axis.
21	eXb	Direction: X	B	Radial Error X	Range (TIR) of the average displacement of Precision Ball on Spindle, in the X direction.
22	eAb	Direction: YZ	B	Tilt YZ	Range Angle in YZ plane, for two position Ball displacement
23	elXb	Direction: X	B	Location X	Average position in X direction, for one position Ball Rotation on B centerline.
24	eYb	Direction: Y	B	Axial Error Y	Range (TIR) of the average displacement of Precision Ball on Spindle, in the B direction.

Figure 5a: Errors 1-24.



#	Error	Error Dir	Axis	Class	Description
25	eBb	Direction: ZX	B	Angular Accuracy	Range of the average plus and minus B Positioning Accuracies.
26	erBb	Direction: ZX	B	Angular Repeatability	Max range of the plus or minus B Positioning Accuracies at any position.
27	eZb	Direction: Z	B	Radial Error Z	Range (TIR) of the average displacement of Precision Ball on Spindle, in the Z direction.
28	eCb	Direction: XY	B	Tilt XY	Range Angle in XY plane, for two position Ball displacement
29	elZb	Direction: Z	B	Location Z	Average position in Z direction, for one position Ball Rotation on B centerline.
30	eRb	Direction: R	B	Rotating Radial Err	Range (TIR) of the average displacement of Sweep of Precision Ball on Spindle (Radial Dir)
31	ebYb	Direction: Y	B	Reversal	Reversal error for B axis.
32	esYb	Direction: Y	B	Step	Stepping error for B axis.
33	eYy	Direction: Y	Y	Linear Accuracy	Range of the average plus and minus Y Positioning Accuracies.
34	erYy	Direction: Y	Y	Linear Repeatability	Max range of the plus or minus Y Positioning Accuracies at any position.
35	eXy	Direction: X	Y	Straightness X	Range of the average plus and minus X Straightness in the Y direction.
36	eZy	Direction: Z	Y	Straightness Z	Range of the average plus and minus Z Straightness in the Y direction.
37	eBy	Direction: ZX	Y	Roll	Roll : Range of the average plus and minus Y Rotation about Y Axis
38	eAy	Direction: YZ	Y	Pitch	Pitch : Range of the average plus and minus Y Rotation about X Axis
39	eCy	Direction: XY	Y	Yaw	Yaw : Range of the average plus and minus Y Rotation about Z Axis
40	etYy	Direction: Y	Y	Drift	Axis thermal drift of Y measured in the Y direction.
41	ebYy	Direction: Y	Y	Reversal	Reversal error for Y axis.
42	esYy	Direction: Y	Y	Step	Stepping error for Y axis.
43	eCxy	Direction: XY	XY	Linear Squareness	Average Angle between X Straightness in Y direction and Y Straightness in X direction.
44	eAyz	Direction: YZ	YZ	Linear Squareness	Average Angle between Y Straightness in Z direction and Z Straightness in Y direction.
45	eBzx	Direction: ZX	ZX	Linear Squareness	Average Angle between Z Straightness in X direction and X Straightness in Z direction.
46	eCxb	Direction: XY	XB	Rotary Squareness	Average Angle between X Straightness in B direction and B Straightness in X direction.
47	eCyb	Direction: XY	Y	Rotary Parallelism	Average Angle for two position Ball Sweep
48	eAzb	Direction: YZ	ZB	Rotary Squareness	Average Angle between Z Straightness in B direction and B Straightness in Z direction.

Figure 5b: Errors 25-48.

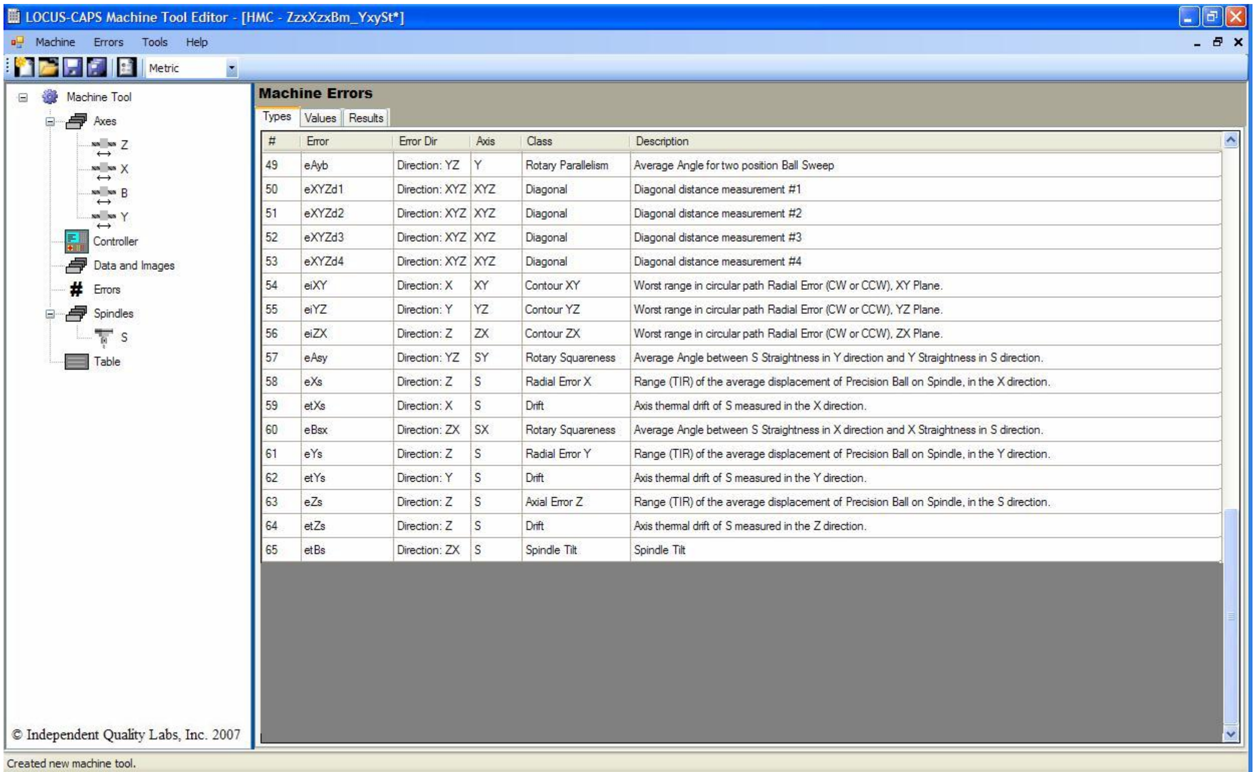


Figure 5c: Errors 49-65.

References

[1] The American Society of Mechanical Engineers, *ASME Draft B5.59-1: Data Specification for Machine Tool Performance Tests*, and *ASME Draft B5.59-2: Data Specification for Properties of Machine Tools for Milling and Turning*, The American Society of Mechanical Engineers: New York, 2006.

[2] The American Society of Mechanical Engineers, *ANSI/ASME B5.54-1992: Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers*, The American Society of Mechanical Engineers: New York, 1993.

[3] Callaghan, R. *Methods for Establishing Machine Tool Performance Specifications from Part Tolerance Requirements*, Lamdamap Sixth International Conference and Exhibition on Laser Metrology , Machine Tool, CMM and Robot Performance, July 15-18, The University of Huddersfield, UK, 2003.

[4] International Organization for Standardization, *International Standard Committee Draft ISO/CD 230/1.4: Test code for machine tools - Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*, International Organization for Standardization: Geneva, 2006.

[5] International Organization for Standardization, *International Standard ISO 841: Industrial automation systems and integration — Numerical control of machines — Coordinate system and motion nomenclature*, 2^{nd} ed. International Organization for Standardization: Geneva, 2001.