Applying Compensation Map Data

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Purpose

This article is written showing one method to interpret compensation error data for a coordinate measuring machine for any position in the measuring volume. Understanding the method used for error correction and can be useful for developing calibration tools or simply to understand the significance of the data.

Description

The compensation map is a table of data for each axis containing a relative measurement of error at specific points along the axis. Each sample position will have rotational measurements around the X, Y, and Z axis (called Rx, Ry, and Rz) and linear measurements parallel to the three axis (Lx, Ly, and Lz). A typical CMM has three axis therefore a typical compensation map will have a three tables of six parameters for a total of eighteen parameters. The following is an example of a compensation map table for the X, Y, and Z axis (linear values in mm, angular in mm/m):

X Axis

Position	Lx	Ly	Lz	Rx	Ry	Rz
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100.0000	0.0050	0.0100	0.0150	0.0200	0.0250	0.0300
200.0000	0.0100	0.0200	0.0300	0.0400	0.0500	0.0600
300.0000	0.0150	0.0300	0.0450	0.0600	0.0750	0.0900
400.0000	0.0200	0.0400	0.0600	0.0800	0.1000	0.1200

Y Axis

Position	Lx	Ly	Lz	Rx	Ry	Rz
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
200.0000	0.0030	0.0400	0.0060	0.0070	0.0080	0.0090
400.0000	0.0060	0.0800	0.0120	0.0140	0.0160	0.0180
600.0000	0.0090	0.1200	0.0180	0.0210	0.0240	0.0270
800.0000	0.0120	0.1600	0.0240	0.0280	0.0320	0.0360

Z Axis

Position	Lx	Ly	Lz	Rx	Ry	Rz
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-50.0000	0.0130	0.0110	0.0120	0.0130	0.0140	0.0150
-100.0000	0.0260	0.0220	0.0240	0.0260	0.0280	0.0300
-150.0000	0.0390	0.0330	0.0360	0.0390	0.0420	0.0450
-200.0000	0.0520	0.0440	0.0480	0.0520	0.0560	0.0600

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The error values are always relative to one position in the machine volume. Often the XYZ zero is used as the reference point but any arbitrary position can be used.

There are many variations to the naming convention of the compensation map data. The names Roll, Pitch, Yaw, Horizontal Straightness, Vertical Straightness, and Scale Error are frequently used but can be ambiguous in some cases so using more specific label names is preferred.

The individual parameter entries combined with the axis have standardized names:

Axis	Parameter	Description	DEA	ISO 230	VDI 2617
X Axis	Lx	Scale	LXX	XX	XtX
	Ly	Horz. Straightness	LXY	YX	XtY
	Lz	Vert. Straightness	LXZ	ZX	XtZ
	Rx	Roll	RXX	AX	XrX
	Ry	Pitch	RXY	BX	XrY
	Rz	Yaw	RXZ	CX	XrZ
Y Axis	Lx	Horz. Straightness	LYX	XY	YtX
	Ly	Scale	LYY	YY	YtY
	Lz	Vert. Straightness	LYZ	ZY	YtZ
	Rx	Pitch	RYX	AY	YrX
	Ry	Roll	RYY	BY	YrY
	Rz	Yaw	RYZ	CY	YrZ
Z Axis	Lx	Horz. Straightness*	LZX	XZ	ZtX
	Ly	Vert. Straightness*	LZY	YZ	ZtY
	Lz	Scale	LZZ	ZZ	ZtZ
	Rx	Pitch*	RZX	AZ	ZrX
	Ry	Yaw*	RZY	BZ	ZrY
	Rz	Roll	RZZ	CZ	ZrZ

These names assume a kinematic order of YXZ.

Kinematic Chain

The kinematic chain describes the order that the axis are physically connected to each other. In order to interpret the compensation data properly it is necessary to apply the correction data from the compensation map in this order. For a typical CMM where the Y axis is front to back and moves along the workpiece table, X from left to right and is connected to the Y axis, and Z is vertical and connected to the X axis the kinematic chain would be YXZ.

The common axis convention for vertical arm machines is YXZ or XYZ. For horizontal arms it is usually XZY. These have become defacto axis conventions but any axis convention is possible.

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Data Interpolation

The data in the compensation tables is provided at specific points along the axis. In almost all cases it is necessary to get tables values at positions other than those listed in the compensation map. In order to have a correction value for any position along the axis it is necessary to interpolate the table data.

Data extraction is done by using a linear interpolation between adjacent map steps. Methods such as using a high order interpolating or approximating spline are never used primarily due to the performance hit from the additional calculation overhead.

The dimensions of the map data should always be greater than the working axis of the machine. When trying to extract a compensation value from a position outside of the compensation map dimensions two methods are commonly used:

1) Use last value of map.

2) Use zero.

Using the last value of the map data causes the least amount of disruption and is relatively easy to implement. Returning zero for the map data when the position is outside the map dimensions is easier to implement but will appear as a noticeable step if measurements are performed over this transition. There is no set rules for this behavior and it depends on the vendor so it is always better to have a map extend slightly beyond the dimensions of the CMM.

Some compensation maps will always have one corner inside the measurement volume of the CMM (standard DEA maps for example). The corner inside the CMM volume is always the zero point so there is no sudden transition when moving beyond this point. In addition the distance from the edge of the CMM is usually small (typically 1 mm).

Application of Compensation Parameters

The compensation of the machine errors does not change the physical shape of the machine but instead calculates the linear XYZ offset of the CMM's probe stylus. The offsets change throughout the entire volume of the machine. The process begins with the raw scale positions then is offset by corrections based on the error map data.

For this example the input X, Y, Z position for the CMM coordinate is 200, 600, -150. The CMM's kinematic order is assumed to by YXZ. From the previous compensation error map data the errors at this specific XYZ location is shown in the following table:

Axis	Position	Lx	Ly	Lz	Rx	Ry	Rz
Y	600.0000	0.0090	0.1200	0.0180	0.0210	0.0240	0.0270
X	200.0000	0.0100	0.0200	0.0300	0.0400	0.0500	0.0600
Z	-150.0000	0.0390	0.0330	0.0360	0.0390	0.0420	0.0450

Correction Y Axis Linear

The linear errors from the compensation map Y axis data at position 600 mm is added to the X, Y, and Z axis.

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Correction Y Axis Angular

The correction for the angular error from angles Rx, Ry, and Rz is done using the position of the X and Z axis as the length components. Illustration 1 shows the effect from the angular correction from the Y axis data based on the X and Z axis positions.
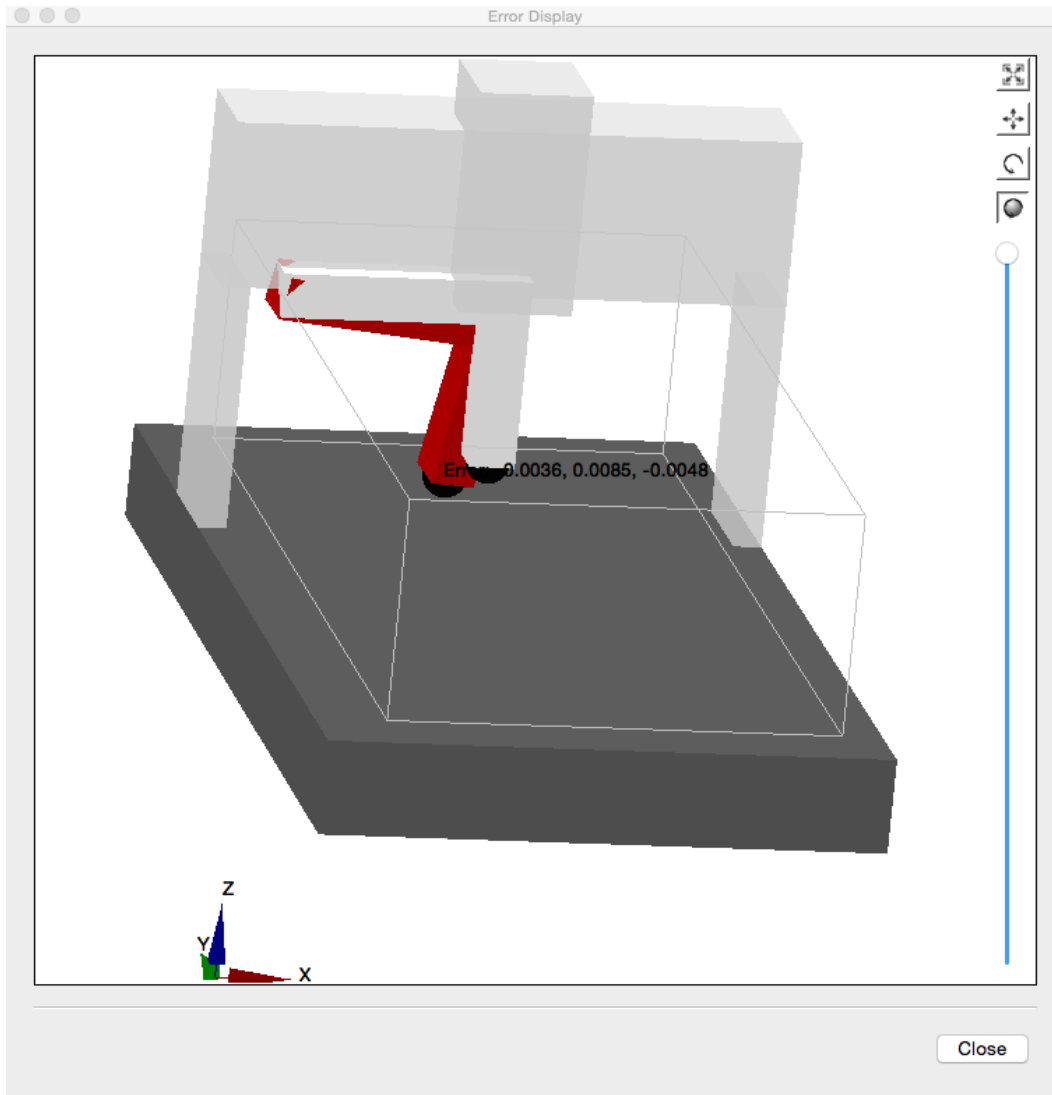

Illustration 1: Calculation of XYZ offset from Y angular errors Rx, Ry, Rz using the X and Z position for length.

Correction X Axis Linear

The linear errors from the compensation map X axis data at position 400 mm is added to the X, Y, and Z axis.

Correction X Axis Angular

The correction for the angular error from angles Rx, Ry, and Rz is done using the position of the Z

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axis as the length component. Illustration 2 shows the effect from the angular correction from the X axis data based on the Z axis position.
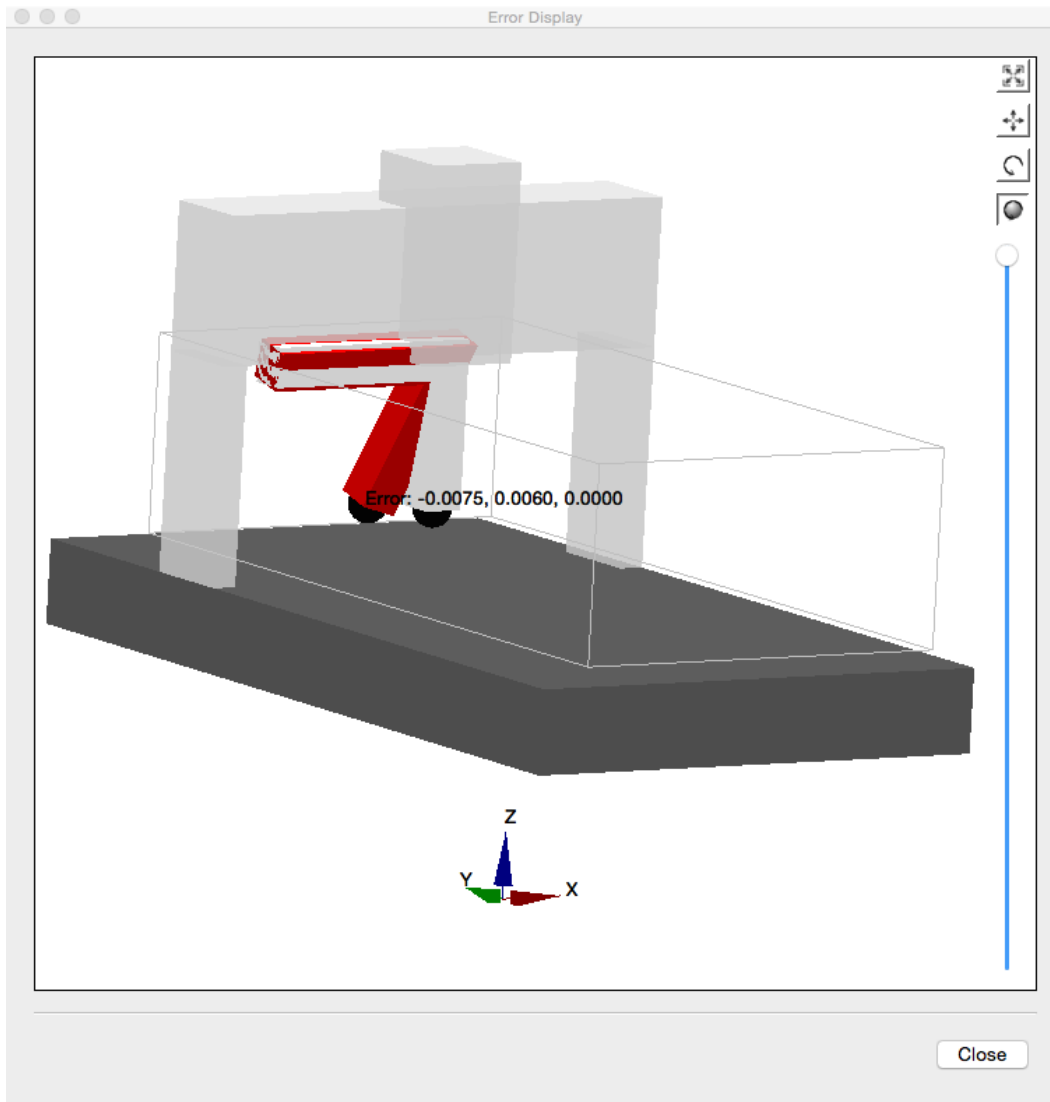

Illustration 2: Calculation of XYZ offset from X angular errors Rx, Ry, Rz using the Z position for length.

Correction Z Axis Linear

The linear errors from the compensation map Z axis data at position -200 mm is added to the X, Y, and Z axis.

Correction Z Axis Angular

The correction for the angular error from angles Rx, Ry, and Rz is done using only the probe offset. Illustration 3 shows the effect from the angular correction from the Z axis data based only on the offset of the probe.
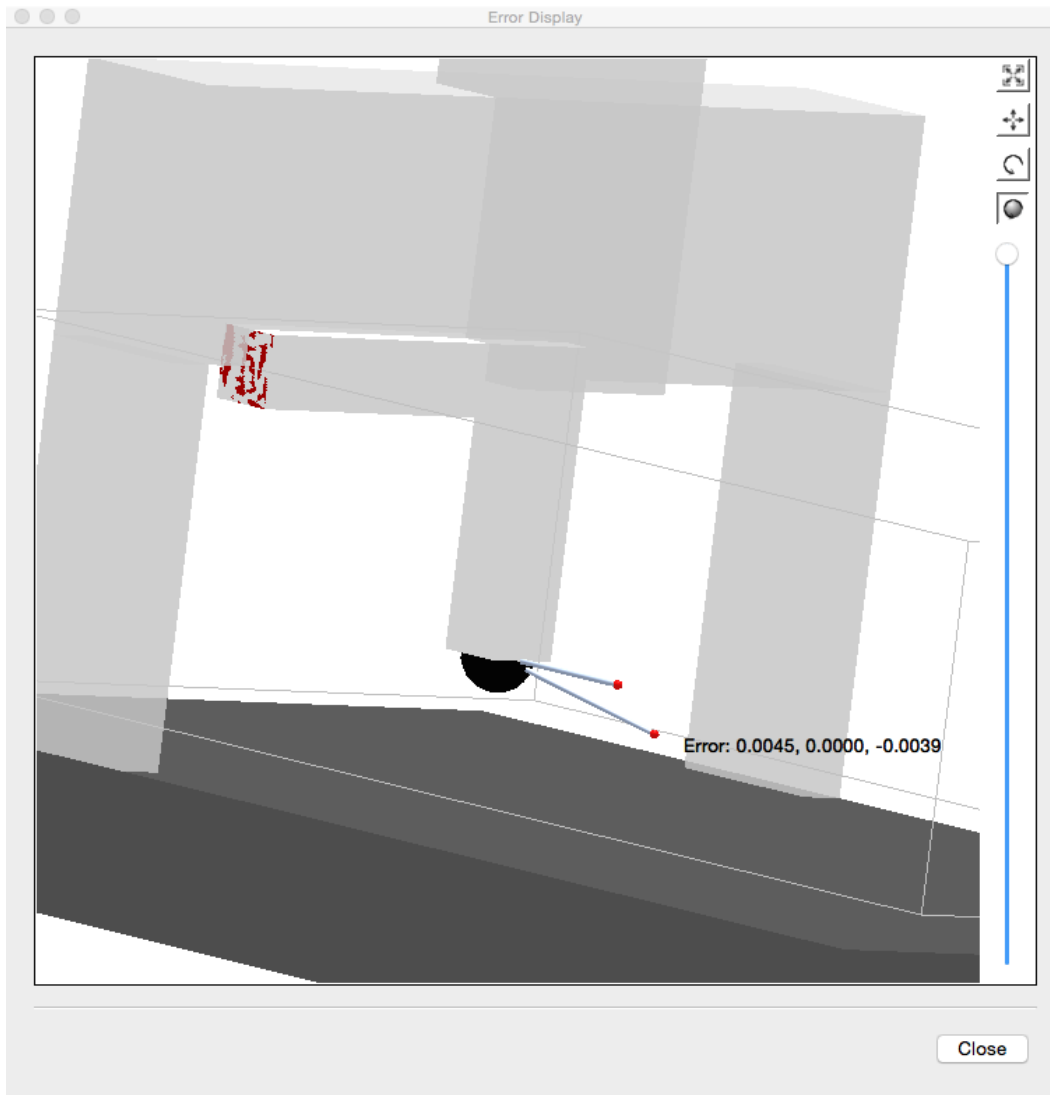
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Illustration 3: Calculation of XYZ offset from Z angular errors Rx, Ry, Rz using the probe offset for length.

Combined Correction

The correction from the individual steps is combined into a single set of XYZ offsets. The combined offset represents the correction at the center of the probe stylus based on the errors described in the compensation table.

Squareness Correction

The three axis must be orthogonal to each other. The three axis are split into three sets of 2D squareness errors XY, YZ, and ZX.
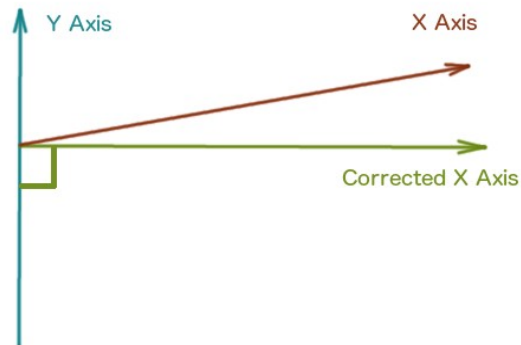
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Illustration 4: Example of the squareness error between the X and Y axis.

There are two known methods that are used to correct for squareness errors in machines:

Correction By Adjusting Straightness

This method changes the straightness of the axis by adding a gradient to the straightness data. For each position along the axis an offset in an orthogonal direction is added.

Correcting squareness using the straightness data has the following problems:

- Several options exist for applying squareness corrections.

- Large squareness errors can introduce a scaling error.

Using the XY squareness as an example the straightness data can be offset in the X axis based on the Y position, in the Y axis based on the X position, or by combining the two methods at the same time and using half the error along each axis.

Squareness correction by adding an offset in an orthogonal direction to an axis ends up scaling the axis. Since the angular errors are small the scaling error is minimal but it always exists. The amount of scaling error is $Err = Length / \cos(SQ_{err}) - Length$.

There is only one family of compensation maps that use this method for squareness adjustment. The map format is common and switching the method used for squareness correction will likely break many of the existing compensation editors and utilities which is a good reason to continue to use this method.

Correction By Adjusting Angular

This method is the preferred method for interpreting squareness errors. The squareness error is applied as a constant to all angular data. From the example shown in illustration 4 the squareness correction would be applied equally to all parameters of RYZ.

Compensation maps that have separate squareness correction entries will internally correct the squareness by this method.

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Vendor Specific Methods

All vendors that provides geometric compensation to their CMM product lines are sufficiently similar that a generic implementation would cover the majority. Some differences that have been observed are listed below:

- Rotation point for Z axis of a horizontal arm calculated from opposite end of zero point. This makes sense since the mechanical rotation and the software rotation point would be the same. Not all vendors do this.

- Arbitrary rotation point for all axis inside measurement volume. Some vendors calculate all rotation values from a point other than the map zero point. One advantage of this method is that the software corrections are smallest at the rotation point and grow as you move toward the edges of the machine volume.

- Rotation signs. Most vendors use the standard rule of counter clockwise representing a positive angular rotation but not all.

- Linear signs. Most vendors use linear correction signs that are the same as the error calculated from a measurement of 'laser – machine' (i.e. laser shows 100.010, machine says 100.000, then error is 0.010). Ths is not true for all vendors.

In order to better understand a vendor specific implementation it is necessary to perform tests to determine the amount of compensation calculated for various points in the machine volume and reproduce those corrections precisely. The preferred method is to have the option of driving the machine to a specific location in the machine volume and switch on/off the compensation comparing the difference in position. Methods that involve measuring an artifact (i.e. measure the location of a calibration sphere with compensation on and off) can be error prone since the correction value will be opposite to the shift in the sphere position. This method can be used but should be carefully reviewed for mistakes.

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Revision History

Revision	Date	Reason
1	June 10, 2015	Initial Release
2	Dec 8, 2019	Document review and update.

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