

CMM Error Simulator Users Guide

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Introduction

The CMM Error Simulator utility was written to provide unbiased CMM measurement results in order to assist in the development of tools and procedures necessary for efficient calibration of coordinate measuring machines. Developing methods to extract specific machine errors from measurements require accurate test data so that methods can be evaluated properly. Using a real CMM can be problematic as measurement noise can bias the results. Using a real CMM for this task by introducing errors into a CMM compensation map adds error into the testing process. Coordinate measuring machines must have physical errors to be evaluated properly.

In addition to providing test data for tool development the CMM Error Simulator was also designed to perform automatic comparison testing for different measurement strategies. This can be used to compare performance test standards or to simply evaluate a chosen measurement pattern. Manually testing all combinations of machine errors can be a very long process so automating this makes sense.

The CMM Error Simulator utility can duplicate a variety of machine error conditions from various vendors and axis configurations. This includes vertical and horizontal arm coordinate measuring machines in one of the four common kinematic chain orders. For kinematic axis orders that are typically associated with horizontal arm CMM's it is possible to introduce errors due to tower deflection.

The measurements tests can use variables allowing for dynamic adjustments between different configurations of machines without having to change any of the data. If setup as intended no changes to any measurement should be required to run any measurement test even if the machine configuration changes significantly.

This utility is cross platform and can be compiled to run on GNU/Linux, OSX, and Windows.

Overview

The CMM Error Simulator uses a single dialog window to the main interface. There are no menu or other non-visual controls. The machine and measurements are automatically stored in the *.errorsimulator* sub folder of the users home folder regardless of the operating system the program is run on. The naming convention of a dot followed by the name of the application is typical for unix based applications.

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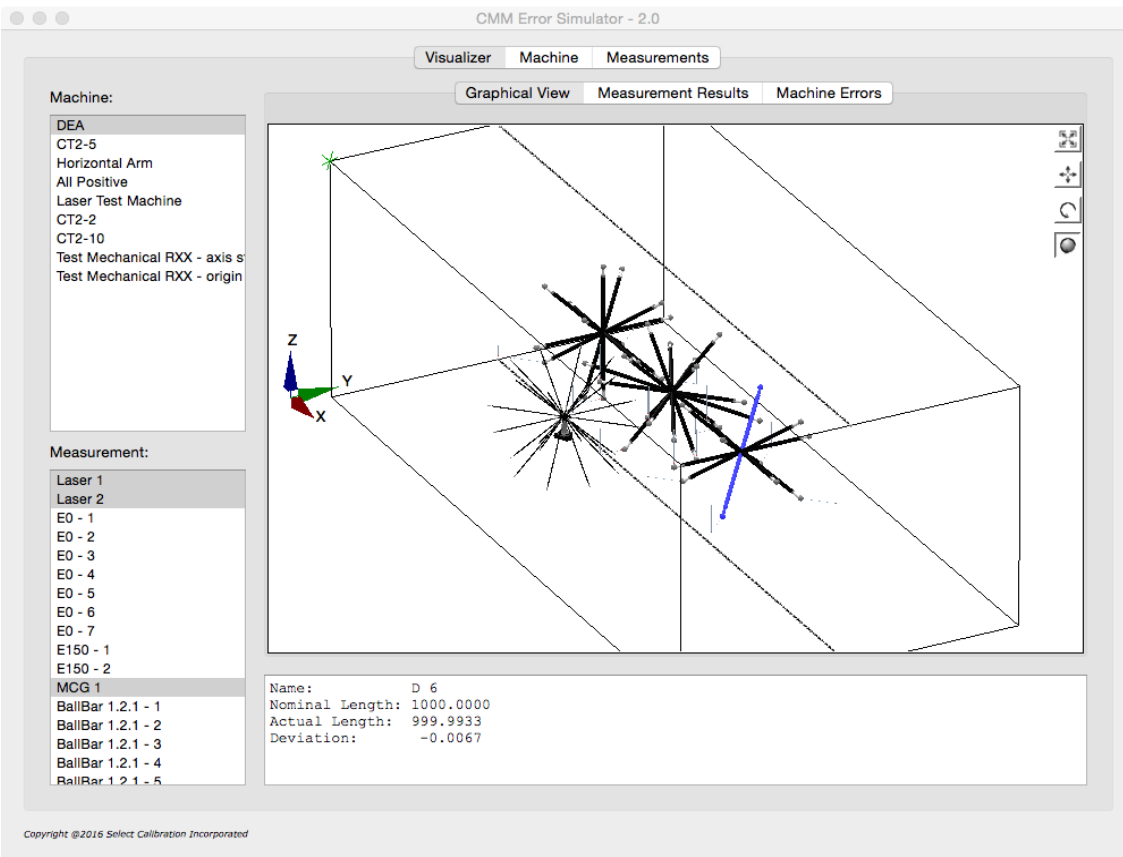


Illustration 1: Main view from the Visualizer Tab of the CMM Error Simulator program showing a graphical view of various measurements inside the volume of a selected machine.

Visualizer Tab

This view shows the results from combining a selected machine and one or more measurements. All results can be accessed from this view of the CMM error simulator program.





Graphical View

This view shows a graphical 3D representation of the measurement volume for the active machine and all selected measurements. Items displayed inside the graphical view can be selected with a left mouse click which will report a summary of the selected item in the section below the model display. The selected measurement item will be highlighted in this view of the data.

Graphical View 3D Controls

The 3D model display is not fixed and can be manipulated in a variety of ways. The model volume is based on the dimensions of the selected machine and is displayed as a wire frame. The model is displayed with the idea of a projection frustum to mimic the relative size of objects based on the relative distance of the viewer. This provides a slightly more realistic rendering of the volume of the data.

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<i>Image</i>	<i>Description</i>
	Scale to fit. Adjusts the scale of the OpenGL Projection matrix to fit the visible data into the display viewport.
	Pan Mode. When enabled a right mouse button click and drag will move the position of the displayed model. For systems with a single mouse button use Ctrl + Mouse.
	Rotate 2D Mode. When enabled a right mouse button click and drag will rotate the model around the center of the viewport. For systems with a single mouse button use Ctrl + Mouse.
	Rotate 3D Mode. When enabled a right mouse button click and drag will rotate the model around the click position on the displayed model. For systems with a single mouse button use Ctrl + Mouse.

OpenGL

The graphical view of the measurement data is drawn using OpenGL. Starting with version 2.0 of the CMM Error Simulator utility a newer base class for rendering 3D data is used. The computer must have at least OpenGL version 2.x or higher in order to run this utility program with a functional 3D view of the measurement data.

Using the newer base class solves a number of problems such as the opaque (or nonexistent) zoom window. The newer OpenGL widget is also more suitable for using modern features such as vertex shaders. The CMM Error Simulator utility will be eventually updated with the newer OpenGL features and methodologies and moving to the new widget is the first step.

The advantage of the older OpenGL base class was compatibility with legacy systems. Version 1.x of the CMM Error Simulator utility would work on computers that only supported OpenGL 1.x.

Running the CMM Error Simulator program on computers that only support OpenGL 1.x the 3D view is replaced with an information window. An example of this information window is shown in illustration 2.

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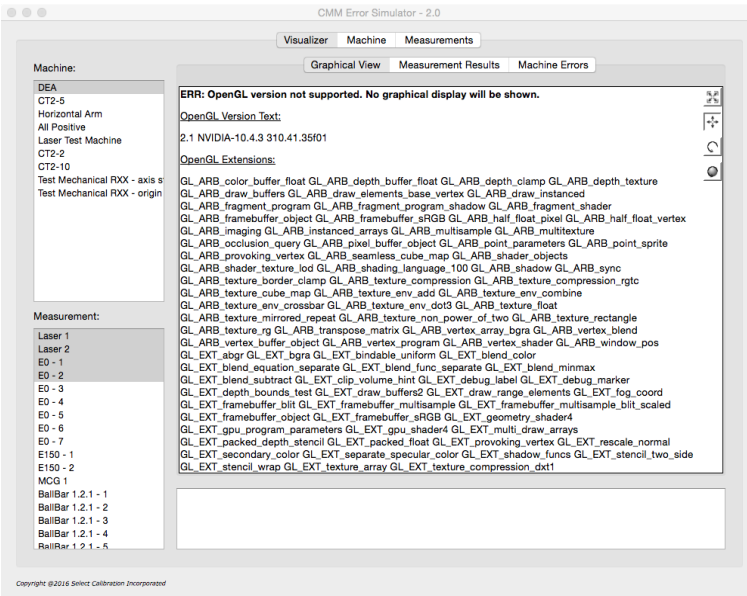


Illustration 2: Information screen that is displayed with unsupported OpenGL versions.

Measurement Results

This view of the Visualizer Tab shows the text result of all selected measurements. Depending on the type of data some measurements are combined into a single table such as the ball bar data. Measurements that consist of more than one measured value are reported as a group for each selected measurement.

The following is a partial example of the measurement of a Renishaw Machine Checking Gauge as displayed in this view:

MCG Measurement

```
-----
Name:           MCG 1
Probe Offset:   0.0000, 0.0000, -50.0000
Center Position: 500.0000, 1000.0000, -500.0000
```

Elevation	Azimuth	Length	Error
-45.0006	0.0010	499.9979	-0.0021
-45.0002	45.0015	500.0013	0.0013
-44.9998	90.0010	500.0019	0.0019
-44.9997	135.0007	500.0001	0.0001
-44.9997	180.0008	500.0004	0.0004
-44.9995	225.0004	500.0021	0.0021
-44.9998	269.9997	500.0011	0.0011
-45.0004	314.9998	499.9978	-0.0022
-0.0004	0.0008	499.9988	-0.0012
...			
45.0005	180.0008	499.9979	-0.0021

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45.0002	225.0011	500.0005	0.0005
44.9999	270.0008	500.0019	0.0019
44.9997	315.0007	500.0012	0.0012

Max Length Error: 0.0034

Min Length Error: -0.0024

Measurement Results – Save Text

The *Save Text* option will create an output text file of all the currently displayed results. The output file contains everything that is displayed from this view of the data.

Measurement Results – Export Measurements

The *Export Measurements* option will create one or more measurement files containing data suitable for external testing. For ball bar measurements a single file is created with each measurement result shown as a specific entry in the file. For all other measurements one or two output files are created containing the measurement data.

The output format of all files is suitable for Select Calibration Incorporated and matches the current revision of all related measurement software.

All displayed measurement data is shown without the addition of the probe offset. All exported measurement data files include the probe offset automatically. The addition of the probe offset mimics the effect from a measurement on an actual CMM.

Measurement Results – Evaluation Report

The *Evaluation Report* option will create a single file containing an extensive comparative set of results from all selected measurements.

The number of available errors from the active machine determines the total size of the output file. Each error from the active machine is combined in every possible configuration producing a series of measurement results for each unique combination. This function was used to perform a comparison of the ASME B89.4.1:1997 and ISO/IEC 10360-2:2009 or ASME B89.4.10360-2:2008 performance test standards.

Machines with all error parameters active will produce an output file containing 65535 measurement result lines. This process can take some time to complete. A progress dialog and the option to cancel the process will automatically appear when using this function.

Machine Errors

This view shows the calculated errors of the active machine. The errors are displayed in the form of a typical CMM error map. An example of this data is shown below:

Selected Machine: CT2-5

Squareness

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YZ: 0.0050
 XY: 0.0050
 ZX: 0.0050

X Axis Data

Pos	Lx	Ly	Lz	Rx	Ry	Rz
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100.0	0.0000	-0.0001	0.0001	0.0005	0.0005	0.0005
200.0	0.0000	-0.0002	0.0002	0.0010	0.0010	0.0010
300.0	0.0000	-0.0003	0.0003	0.0015	0.0015	0.0015
400.0	0.0000	-0.0003	0.0003	0.0020	0.0020	0.0020
500.0	0.0000	-0.0002	0.0002	0.0025	0.0025	0.0025
600.0	0.0000	-0.0001	0.0001	0.0030	0.0030	0.0030
700.0	0.0000	0.0000	-0.0000	0.0035	0.0035	0.0035
800.0	0.0000	0.0003	-0.0003	0.0040	0.0040	0.0040
900.0	0.0000	0.0005	-0.0005	0.0045	0.0045	0.0045
1000.0	0.0000	0.0008	-0.0008	0.0050	0.0050	0.0050

Y Axis Data

Pos	Lx	Ly	Lz	Rx	Ry	Rz
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100.0	0.0003	0.0000	-0.0003	0.0005	0.0005	0.0005
200.0	0.0006	0.0000	-0.0006	0.0010	0.0010	0.0010
300.0	0.0008	0.0000	-0.0008	0.0015	0.0015	0.0015
400.0	0.0009	0.0000	-0.0009	0.0020	0.0020	0.0020
500.0	0.0011	0.0000	-0.0011	0.0025	0.0025	0.0025
600.0	0.0011	0.0000	-0.0011	0.0030	0.0030	0.0030
700.0	0.0011	0.0000	-0.0011	0.0035	0.0035	0.0035
800.0	0.0011	0.0000	-0.0011	0.0040	0.0040	0.0040
900.0	0.0010	0.0000	-0.0010	0.0045	0.0045	0.0045
1000.0	0.0009	0.0000	-0.0009	0.0050	0.0050	0.0050
1100.0	0.0007	0.0000	-0.0007	0.0055	0.0055	0.0055
1200.0	0.0004	0.0000	-0.0004	0.0060	0.0060	0.0060
1300.0	0.0002	0.0000	-0.0002	0.0065	0.0065	0.0065
1400.0	-0.0002	0.0000	0.0002	0.0070	0.0070	0.0070
1500.0	-0.0006	0.0000	0.0006	0.0075	0.0075	0.0075
1600.0	-0.0010	0.0000	0.0010	0.0080	0.0080	0.0080
1700.0	-0.0015	0.0000	0.0015	0.0085	0.0085	0.0085
1800.0	-0.0020	0.0000	0.0020	0.0090	0.0090	0.0090
1900.0	-0.0026	0.0000	0.0026	0.0095	0.0095	0.0095
2000.0	-0.0033	0.0000	0.0033	0.0100	0.0100	0.0100

Z Axis Data

Pos	Lx	Ly	Lz	Rx	Ry	Rz
-----	----	----	----	----	----	----

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-1000.0	0.0008	-0.0008	0.0000	-0.0050	-0.0050	-0.0050
-900.0	0.0005	-0.0005	0.0000	-0.0045	-0.0045	-0.0045
-800.0	0.0003	-0.0003	0.0000	-0.0040	-0.0040	-0.0040
-700.0	0.0000	-0.0000	0.0000	-0.0035	-0.0035	-0.0035
-600.0	-0.0001	0.0001	0.0000	-0.0030	-0.0030	-0.0030
-500.0	-0.0002	0.0002	0.0000	-0.0025	-0.0025	-0.0025
-400.0	-0.0003	0.0003	0.0000	-0.0020	-0.0020	-0.0020
-300.0	-0.0003	0.0003	0.0000	-0.0015	-0.0015	-0.0015
-200.0	-0.0002	0.0002	0.0000	-0.0010	-0.0010	-0.0010
-100.0	-0.0001	0.0001	0.0000	-0.0005	-0.0005	-0.0005
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

This data is generated based on the increment values shown at the top of the Machine Error display of the data. The data can be viewed with any desired increment by editing the fields and pressing the *Update* button.

This data is provided to show the end result of all machine errors. This data is not used for calculation of the measurement errors therefore the input map increments have no affect on any calculated measurement result.

Machine Tab

This view is for managing all available simulated coordinate measuring machines.

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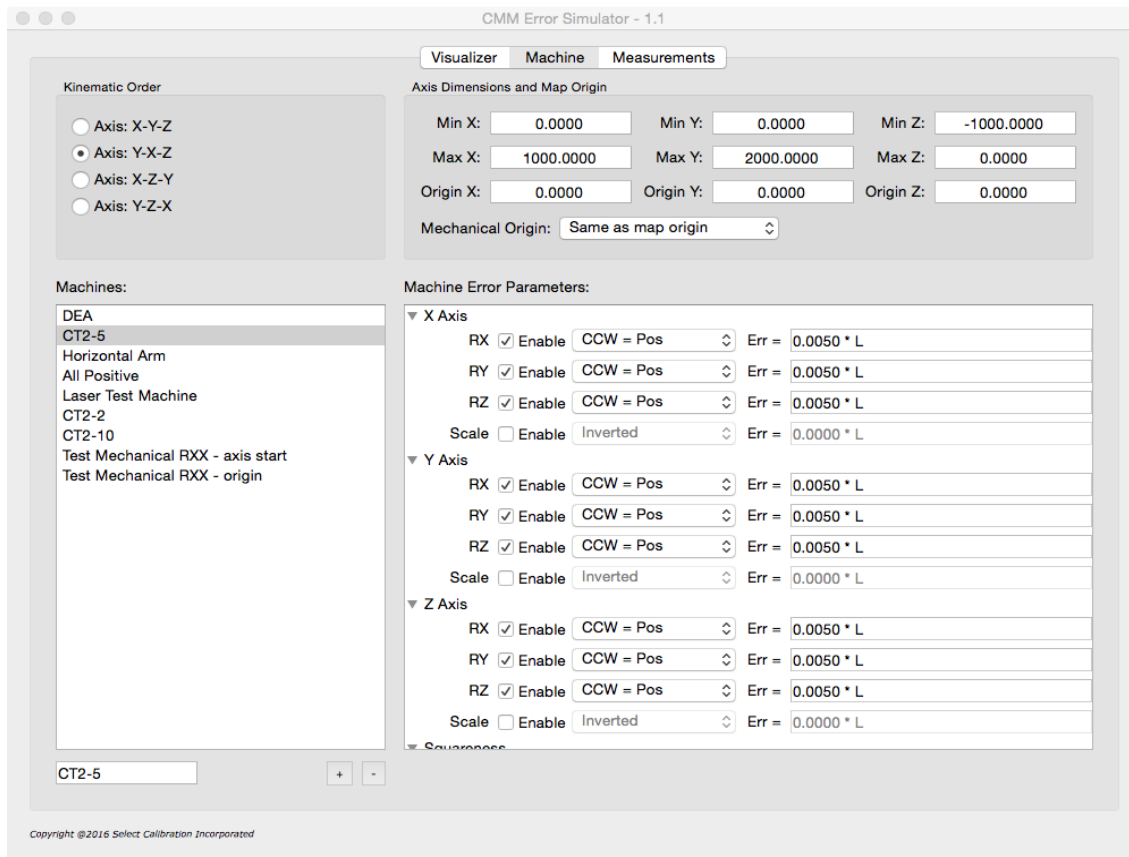


Illustration 3: View from the Machine tab of the CMM Error Simulator program.

Machine Management

New machines can be created by pressing the '+' button at the bottom of the list of machines. Existing machines can be removed by selecting one or more machines then pressing the '-' button.

All machines are added with a unique name of Untitled (or Untitled – n). To change the name of an existing machine an editor for the name field is available at the bottom of the machine list.

All machine names must be unique. Names that are entered which already exist will use the closest unique name possible (or will be ignored).

Kinematic Order

The kinematic order defines how the axis of a machine is connected to each other. Four kinematic orders are supported by the CMM Error Simulator utility and described in the following table:

<i>Kinematic Order</i>	<i>Description</i>
X-Y-Z	The axis of the simulated CMM has the X as the first axis, the Y connected to the X, and the Z connected to the Y. This configuration is assumed to be a vertical arm CMM.

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<i>Kinematic Order</i>	<i>Description</i>
Y-X-Z	The axis of the simulated CMM has the Y as the first axis, the X connected to the Y, and the Z connected to the X. This configuration is assumed to be a vertical arm CMM.
X-Z-Y	The axis of the simulated CMM has the X as the first axis, the Z connected to the X, and the Y connected to the Z. This configuration is assumed to be a horizontal arm CMM.
Y-Z-X	The axis of the simulated CMM has the Y as the first axis, the Z connected to the Y, and the X connected to the Z. This configuration is assumed to be a horizontal arm CMM.

Axis Dimensions and Map Origin

This section defines the limits of the CMM machine axis. The origin entries define the mathematical rotation zero point for this machine.

The machine origin option allows for placing the mechanical rotation point at positions other than the mathematical rotation point. The default is to use the same position as the mathematical rotation point but this can be to different positions in the machine volume if required.

Illustration 4 shows an example for the mechanical rotation point. In most cases this option can be ignored but when specifically testing for the effect from having the compensation applied from one end of an axis and compensating from the other this feature is invaluable.

The list of possible axis combinations is suitable for generic testing. Not every possible axis combination is available or even technically required.

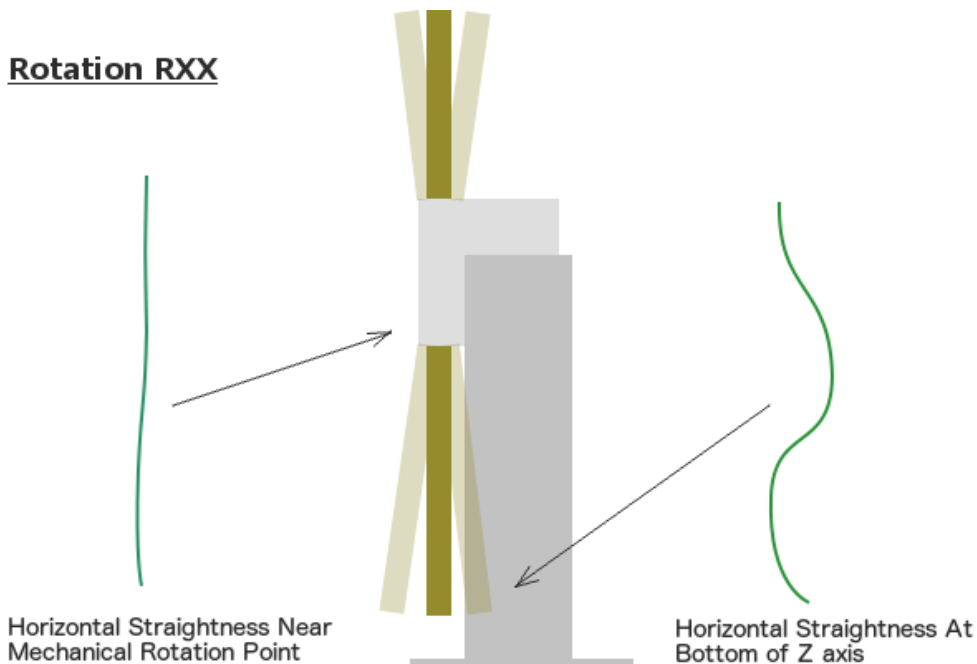


Illustration 4: Example of the effect of rotation error RXX at different points in the X axis affecting the Y axis straightness.

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The options are listed based on the sign of the axis. The mechanical rotation is always assumed to be at either end of a machine axis. For example, the option '*Axis positions -X +Y +Z*' will place the mechanical origin at the negative end of the X axis and the positive ends of the Y and Z axis.

Machine Error Parameters

The X, Y, and Z machine axis can have up to four error parameters. For horizontal arm CMM's an additional D axis is added and allows a single entry for an expression suitable to describe the tower deflection.

All parameters are entered as a constant or formula expression. The following are examples of different expressions that can be used to describe machine axis errors:

$$E_r=0.005$$

$$E_r=0.005*L$$

$$E_r=0.005+0.002*L+0.003*L^2-0.004*L^3$$

The first example is a constant. This value will be applied evenly to all data of the simulated CMM. The second example is a gradient with the variable 'L' substituted for the actual position in the machine volume. The third example is in the form of a polynomial with coefficients. The resulting shape from this expression is complex.

Using a constant for angular data is equivalent to adding a squareness error. The affected axis and rotation direction can be precisely controlled using constants.

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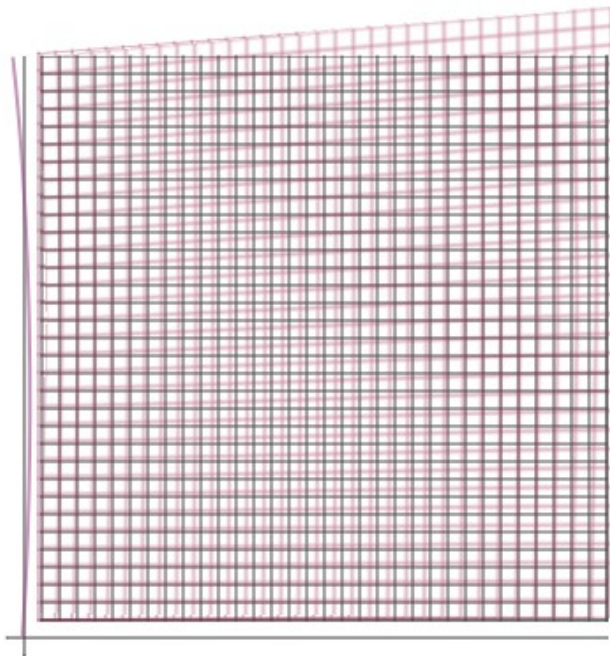


Illustration 5: Interpretation of machine error for rotation around Z axis (viewer).

The interpretation of the machine error is a description of what the physical machine characteristics are. A machine error with a counter clockwise positive sign and a positive error expression will create a simulated machine as shown in illustration 5. The input error expressions represent the physical machine errors and the measurement results are what would be expected on a machine with these physical errors and a zero error map.

Expression Variables.

The following are variables that can be used for the machine error expressions:

<i>Variable</i>	<i>Description</i>
L	Position in the map coordinates specific for each axis. The value is from the XYZ zero point regardless if this position is inside the machine volume or not.
PUp	Position from the XYZ zero point specifically for the vertical axis (Z). This variable is only used for the deflection axis parameter.
POut	Position from the XYZ zero point specifically for the horizontal axis (Y or X). This variable is only used for the deflection axis parameter.
LUp	Length from the minimum position of the vertical axis (Z). This variable is only used for the deflection axis parameter.
LOut	Length from the minimum position of the horizontal axis (Y or X). This variable is only used for the deflection axis parameter.

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Deflection Expressions

The tower deflection of a horizontal arm are not a constant expression. The value that is used for all evaluations is based on the result of the expression and is usually unique depending on the vertical and horizontal position. Most horizontal arm CMM's can be described with the following expression:

$$R_t = E * LUp * LOut$$

When viewing the machine error data in the Visualizer Tab the tower deflection data is presented in a table showing the product of the expression at different points in the axis related to the data.

Expression Signs

For angular data the interpretation of the machine error expression is determined by the selection of CCW=Pos or CW=Pos. This selection does not change the sign of the expression but simply how the data is to be interpreted.

For scale data a normal sign is based on the principal of comparing to a laser. If the machine scale error correction is more positive when the laser reading is more positive then the reported machine position then the sign is considered *Normal*. *Inverted* is the opposite where a more positive laser reading would be entered as a negative correction.

Squareness interpretation is based on true angle measurements between the primary and secondary axis for each of the three parameters. The sign settings show options based on how measurements would be interpreted at 45 degree angles between the two affected machine axis.

Straightness Signs

The straightness parameters are calculated automatically from the input angular data. These parameters cannot be directly accessed.

Measurements Tab

This view allows the editing of one or more measurements that are to be evaluated on the different simulated machines. Four different kinds of measurements are currently supported by the CMM Error Simulator program:

- Laser (six parameter).
- ISO/IEC 10360-2
- Renishaw Machine Checking Gauge
- ASME B89.4.1 ball bar

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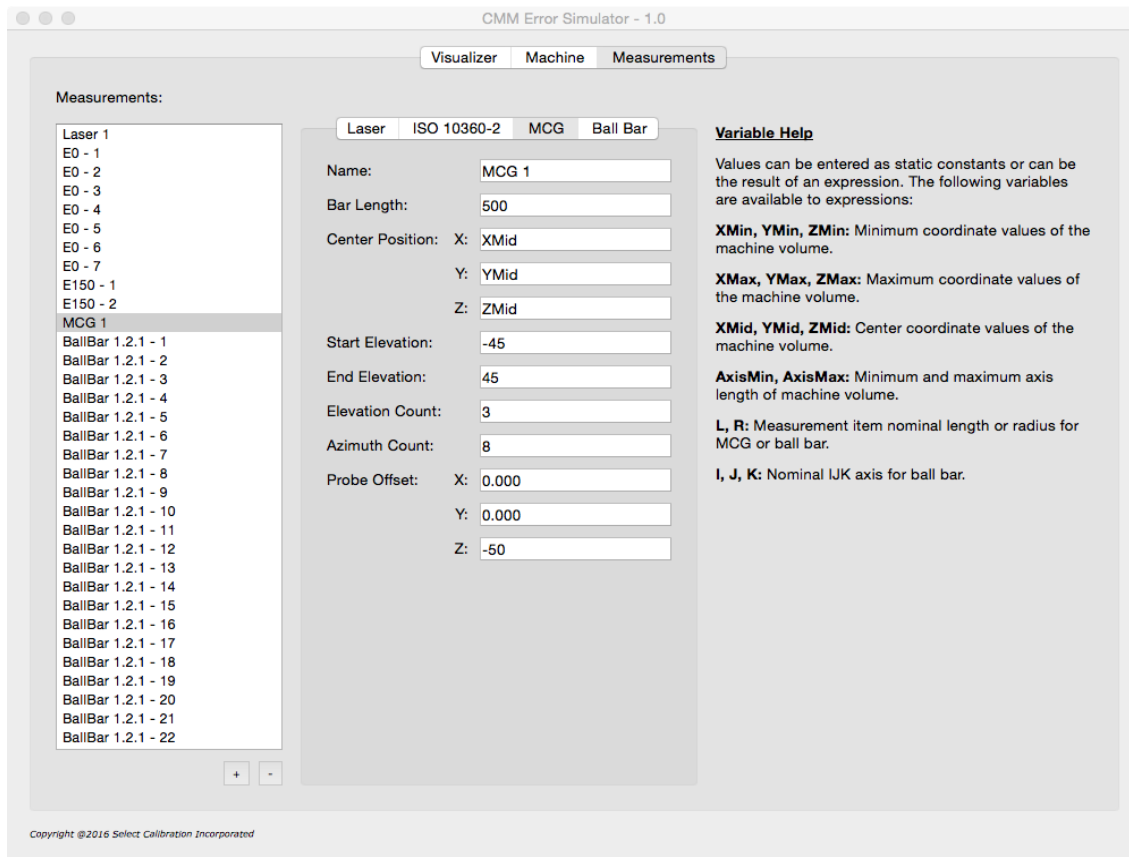


Illustration 6: View of the measurements tab with the MCG gauge active.

Measurement Management

New measurements can be created by pressing the '+' button at the bottom of the list of measurements. Existing measurements can be removed by selecting one or more measurements then pressing the '-' button.

The name of the new measurement will be automatically generated from a default name or will be based on the name of the currently selected measurement item if a selected item exists. The name can be altered by editing the *Name* field at the top of the measurement parameters.

When a measurement is selected the editor will automatically highlight the settings specific for the type of selected measurement with all other measurement types disabled. To have all measurement types active unselect any active measurement first.

The type of measurement that is added is based on what is currently active. For example, to add a new ball bar measurement ensure the ball bar editor is the active view.

Expression Variables.

The following are variables that can be used for measurement expressions:

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<i>Variable</i>	<i>Description</i>
XMin	The minimum X axis machine coordinate.
YMin	The minimum Y axis machine coordinate.
ZMin	The minimum Z axis machine coordinate.
XMax	The maximum X axis machine coordinate.
YMax	The maximum Y axis machine coordinate.
ZMax	The maximum Z axis machine coordinate.
XMid	The center position of the X axis.
YMid	The center position of the Y axis.
ZMid	The center position of the Z axis.
AxisMin	The shortest length of the X, Y, or Z axis.
AxisMax	The longest length of the X, Y, or Z axis.
L	The nominal measurement length.
R	The nominal measurement length divided by two ($L/2$).
I	The normalized I value of the IJK direction.
J	The normalized J value of the IJK direction.
K	The normalized K value of the IJK direction.

Some variables cannot be used in fields that result in the creation of the variable (recursive variable). For example, the variable 'L' cannot be used inside any length field as the value of this variable must be determined by solving the expression of this field first.

Measurement Variable Example

The following shows an example of a measurement expression for a ball bar. The table following the image describes the different variables used.

In this example the goal was to have a ball bar placed at the bottom of the machines Z axis in a direction between the back/left and front/right corners. Since the dimensions of the machine are not (or may not) be cubical the I and J values would not be 0.707 and 0.707. Also, the position of one of the two spheres must be located at the back/left corner of the machines measurement volume. The length of the ball bar must be set to be the same as the shortest machine axis.

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Laser
 ISO 10360-2
 MCG
 Ball Bar

Name:

Length:

Center Position: X:

Y:

Z:

Direction Vector: I:

J:

K:

Probe Offset: X:

Y:

Z:

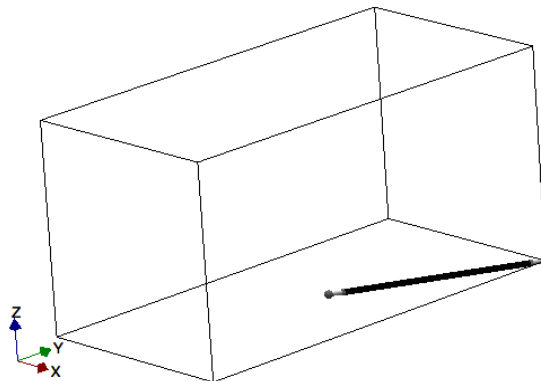


Illustration 7: Image showing position of the ball bar based on expression parameters shown to the left.

Expression	Description
Name	The name of the measurement as it will appear in the measurement list.
Length	The variable <i>AxisMin</i> is used for the expression. The length of the ball bar will be the shortest axis of the machine.
Center Position X	The expression $XMax + R * I$ will place the center of the ball bar measurement one half the length of the ball bar starting at the maximum X axis position and traveling in the normalized I value of the IJK direction.
Center Position Y	The expression $YMax + R * J$ will place the center of the ball bar measurement one half the length of the ball bar starting at the maximum Y axis position and traveling in the normalized J value of the IJK direction.
Center Position Z	The expression $ZMin$ will place the center of the ball bar measurement at the lowest position in the Z axis.
Direction Vector I	The expression $XMin - XMax$ defines the I value of the IJK direction. The direction is normalized automatically when processed.
Direction Vector J	The expression $YMin - YMax$ defines the J value of the IJK direction. The direction is normalized automatically when processed.
Direction Vector K	The expression 0 sets K value of the IJK direction to zero.
Probe Offset X	The probe offset in the X axis direction used for the measurement. The value is entered as a constant.
Probe Offset Y	The probe offset in the Y axis direction used for the measurement. The value is entered as a constant.
Probe Offset Z	The probe offset in the Z axis direction used for the measurement. The value is entered as a constant.

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Probe Offset Sign

The sign for the probe offset is always interpreted as the relative position of the stylus ruby from the probe connection point at the end of the last axis of the machine. The signs for all axis is using the standard convention and is reversed as compared to some inspection software (PC-DMIS for example).

All measurements will draw the relative position of the stylus provided the probe offset is not zero.

Laser Measurements

All simulated measurement results when using the laser report the scale, straightness, and all angular values typical for a six parameter laser. All simulated measurements are bidirectional.

Measurement lines that are not parallel to an axis will only show scale errors. The straightness and angular fields will still exist but all values will be reported as zero.

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Revision History

<i>Date</i>	<i>Version</i>	<i>Changes</i>
July 27, 2016	1.0	New Program
July 28, 2016	1.0.1	Revision of documentation regarding expression constants.
Aug 6, 2016	1.1	Added option to specify a mechanical rotation point independent of the mathematical rotation point.
Nov 6, 2016	1.2	Bugfix: Wrong IJK surface normal values sent to OpenGL Added minimum offset before drawing knuckle probes.
Dec 14, 2016	2.0	Bugfix: Software crash for horizontal arm when measurements exceed axis length. Improvements to selection. Added selection highlight. Switched to newer OpenGL base class. Added option to detect minimum usable OpenGL version and disable sections of the program that are not compatible.
Apr 25, 2018	2.1	Bugfix: Ball bar measurement data was created without the probe offset included in the position of each sphere. Bugfix: Ballbar data had an incorrect title label.