Error Simulator Users Guide

Table of Contents

Introduction

The *Error Simulator* utility allows simulated CMM measurements of various artifacts 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 physically changing the shape of the machine in order to test different scenarios is not possible in many cases and measurement noise can bias data.

The *Error Simulator* utility can simulate a variety of machine errors on CMM's with various kinematic configurations including tower deflection for horizontal arm CMM's. In addition to providing test data for tool development the *Error Simulator* utility was also intended to perform automatic comparison testing of different measurement strategies for CMM performance testing.

The measurement positions can include variables for dynamic adjustment of size and location to suite the target machines measurement volume. If setup as intended no changes to any measurement should be required when switching between different measurement volumes.

Overview

The *Error Simulator* utility consists of a main window and two dockable widgets for various machine configurations and measurements. Illustration 1 shows the main window of the *Error Simulator* utility.

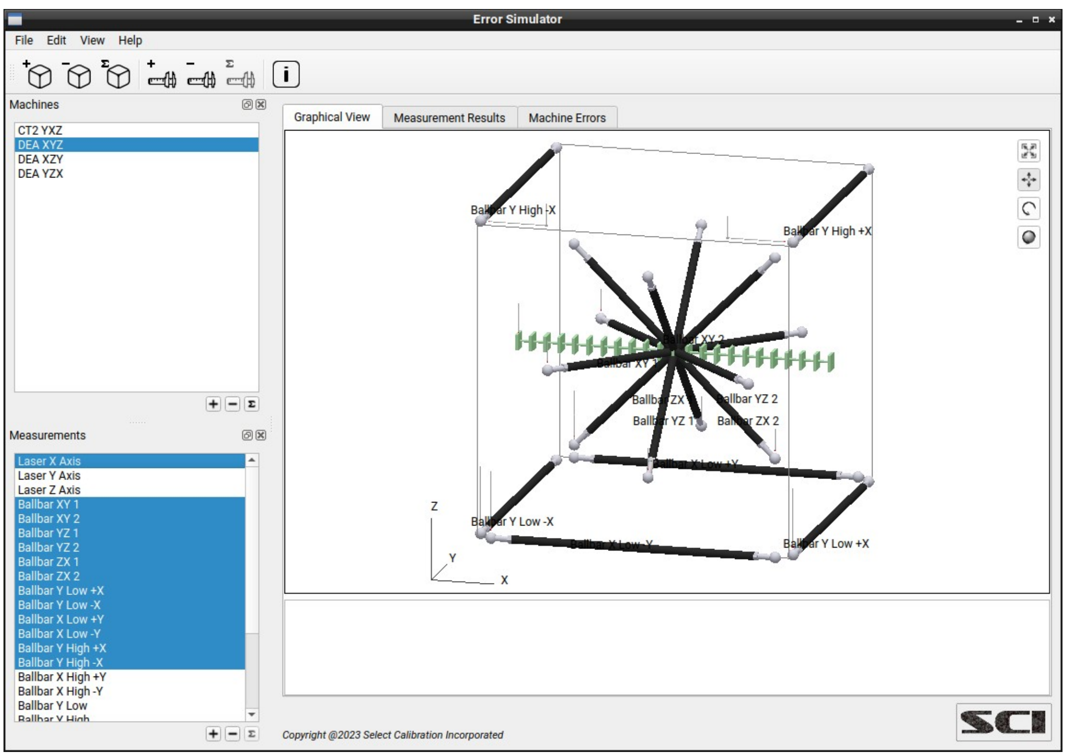


Illustration 1: Main view from the Error Simulator utility showing a graphical view of various measurements inside the volume of a selected machine.

Graphical View

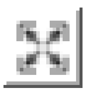
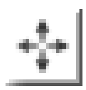
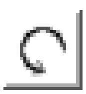
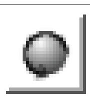
This view shows a 3D representation of the measurement volume for the active machine and all selected measurements. Measurement items displayed inside the graphical view will report individual results when clicked with the left mouse button. The selected measurement item will be highlighted and the text of the measurement will appear in the section below the graphical window.

A machine must be selected in order to display one or more measurements in the graphical view.

Graphical View 3D Controls

The 3D model display is not fixed and can be manipulated in a variety of ways. The volume of the selected machine is displayed as a wire cube.

Options:

Image	*Description*
	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. The computer must support OpenGL version 2.x or higher in order to run this utility program with a functional 3D view of the measurement data.

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.

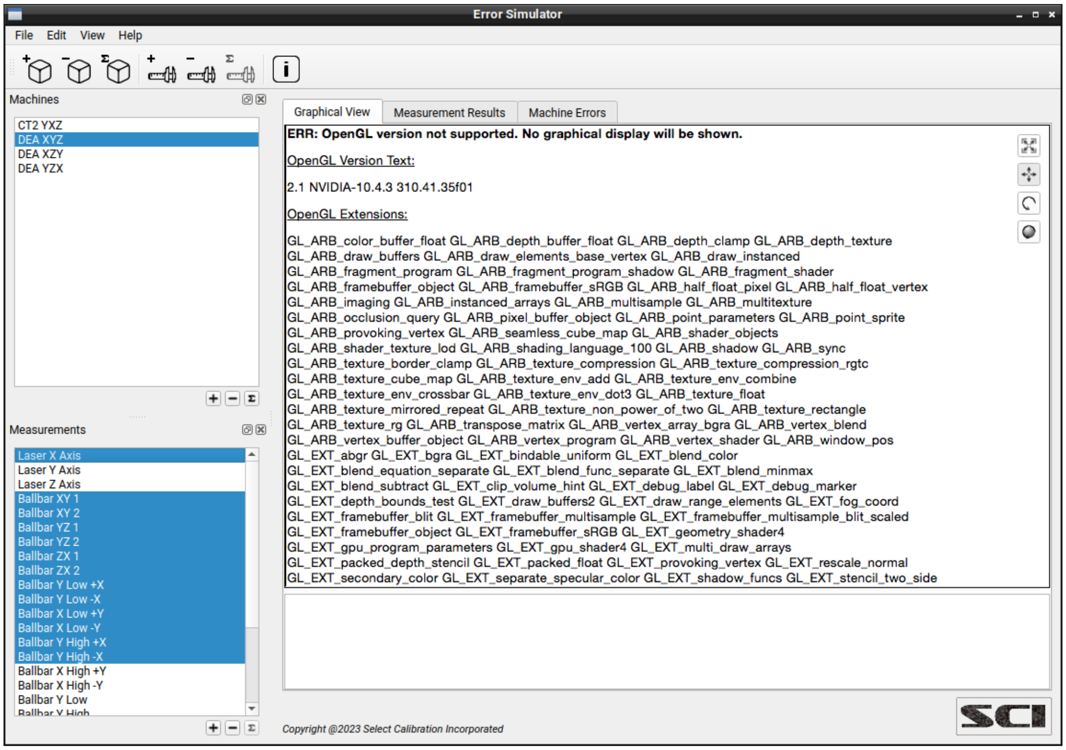


Illustration 2: Information screen that is displayed with unsupported OpenGL versions.

Machines

A machine is a configuration of the simulated CMM with unique dimensions, kinematic order, parameter errors, and other characteristics. Machines can be edited using the edit function below the machine list or from the main toolbar of the *Error Simulator* utility.

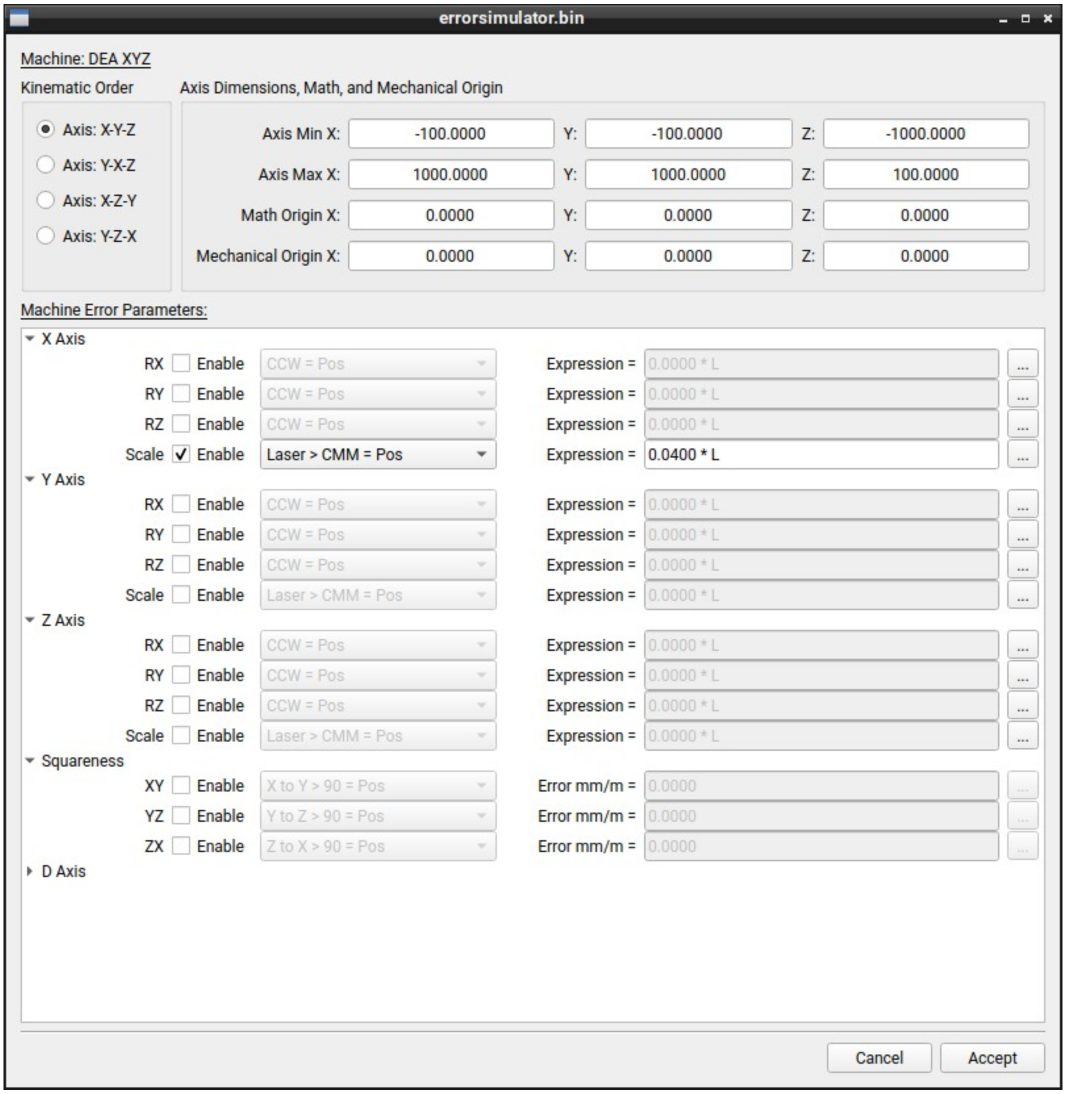


Illustration 3: View from the Machine editor of the Error Simulator utility.

Kinematic Order

The kinematic order defines how the axis of a machine is connected to each other. The four kinematic orders supported by the *Error Simulator* utility are described below:

Kinematic Order	*Description*
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. This configuration is typical for legacy DEA and LK machines.
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

Kinematic Order	*Description*
	vertical arm CMM. This configuration is the common configuration used for bridge or gantry CMM's.
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 machine axis. The math origin defines the position where calculations of errors from the machine angular compensation data is performed. The mechanical origin defines the position where the physical rotation occurs on a machine. The mechanical rotation is critical for proper calculation of deflection effects for a horizontal arm CMM.

Illustration 4 shows an example for the mechanical rotation point on the bridge axis of a CMM. When specifically testing for the effect of compensation calculated from different points of an axis this feature is invaluable.

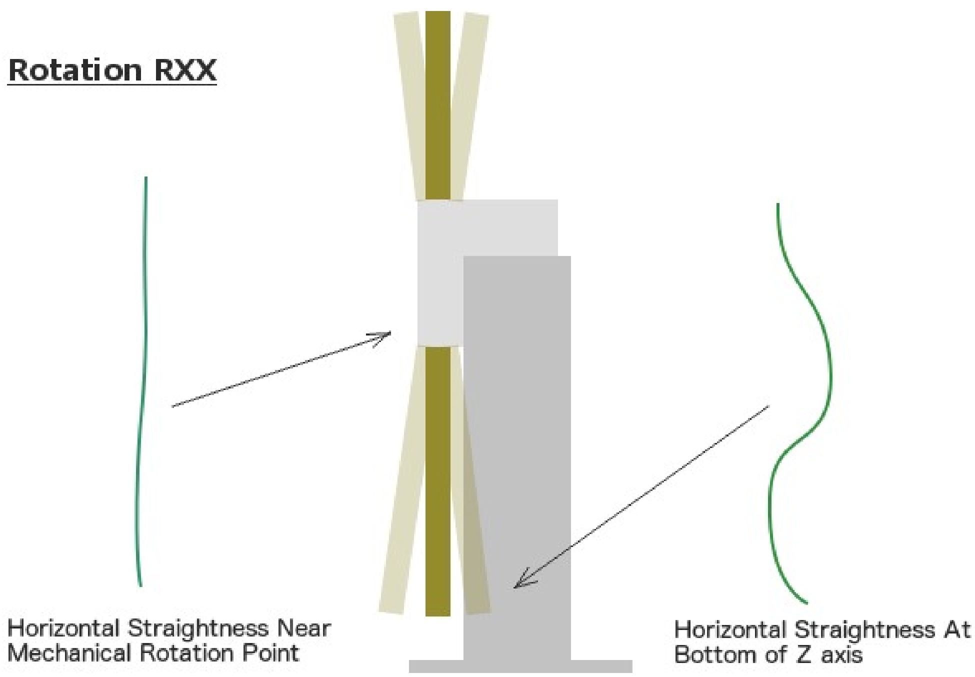


Illustration 4: Example of the effect of rotation error RXX at different points in the X axis affecting the Y axis straightness.

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 available allowing the entry of a value representing the tower deflection angle.

All parameters are entered as a constant or formula expression except for deflection and the three squareness parameters. The following are examples of different expressions that can be used to describe machine axis errors:

Expression	*Description*
0.005	This value will be applied evenly to all parameter data of the simulated CMM.
$0.005*L$	The parameter data is a gradient with variable *L* substituted for the actual position of the axis.
$0.005+0.002*L+0.003*L^2-0.004*L^3$	The parameter data is in the form of a polynomial with coefficients with variable *L* substituted for the actual position of the axis. The resulting shape from this expression is complex.

Expression Variables

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

Variable	*Description*
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.

Expression Editor

The expression editor allows the user to input measurement errors along the length of an axis and convert this into an equivalent expression. It is very useful for errors that have an odd shape. The expression editor dialog can be accessed by clicking on the ellipse button to the right of the expression field.

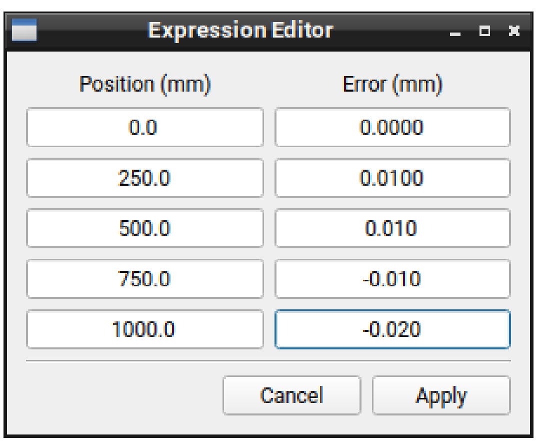


Illustration 5: Expression editor showing five data points along the axis of the machine and the amount of desired error at each point.

Using the inputs from the example shown in illustration 5 the resulting expression is:

$$0.0067*L+0.2933*L^2-0.7467*L^3+0.4267*L^4$$

The expression editor is not available for squareness or deflection parameters. The entry for these fields is a constant representing the angle in mm/m.

Deflection Expressions

The tower deflection of a horizontal arm is entered as a constant value representing the rotation angle of the tower when measured with the Z at the top of the axis on a physical CMM. The angle units are mm/m.

When viewing the error map data for the machine the tower deflection will be shown as a table containing the result of the expression at different points along the two input axis.

Deflection errors is based on the expected change in the tower angle as the arm axis moves from one extreme to the other. Most software apply compensation assuming that there is no deflection when the arm is at the home position (near the tower) but the reality is that the weight of the arm rotates the tower outward at the home position and does the opposite when the arm is fully extended with only the arm at mid position resulting in zero deflection. The simulation of the deflection matches the expected deflection as shown in illustration 6 and not that of the typical software compensation. The intention was to match reality as much as possible.

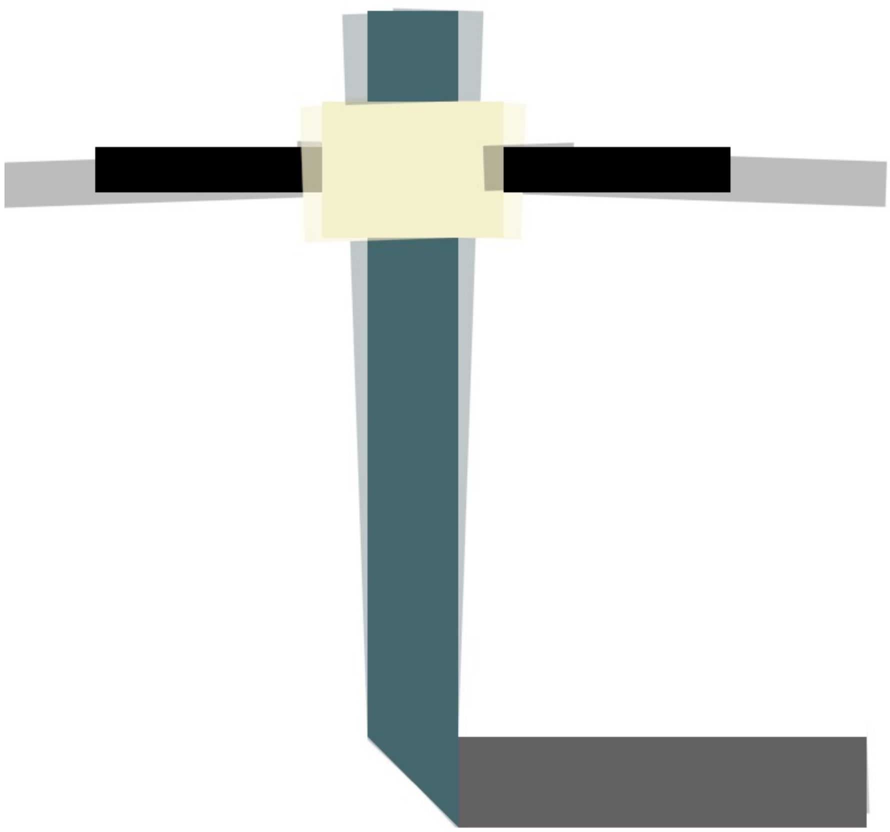


Illustration 6: Deflection estimation.

For horizontal arm CMM's it is important the mechanical rotation point is set appropriately.

Expression Signs

For angular data the interpretation of the machine error expression is determined by the sign selection of *CCW=Pos* or *CW=Pos* when viewing from the positive end of the axis rotated around. This selection does not change the sign of the expression but how the data is to be interpreted when converting the angular value into a position error.

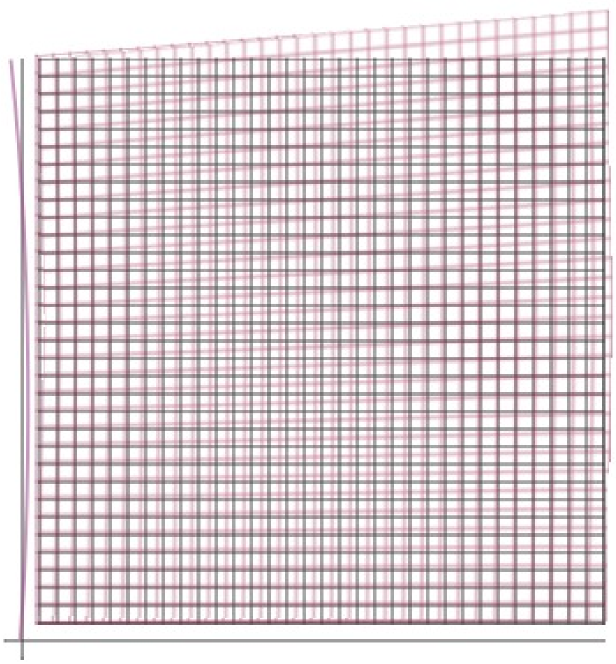


Illustration 7: Interpretation of machine error for rotation around Z axis (viewer).

The interpretation of the machine error is a description of the physical machine characteristics. A machine error with a *CCW=Pos* sign and an expression that produces a positive value will result in a simulated machine as shown in illustration 7. 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 prior to compensation.

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

For scale data the sign represents the deviation when comparing to a laser. For machines using DEA compensation error maps the laser deviation relative to the machines real position would be entered as measured (laser > CMM = pos) where BnS would have the sign reversed (laser < CMM = pos).

Squareness interpretation is based on angle measurements between the primary and secondary axis for each of the three planes. The nominal angle is 90 degrees between the primary and secondary axis while the error entry increases or decreases the angle between the two axis. For example, if the XY squareness sign is set to *X to Y > 90 = Pos* and the input error is positive then the angle between the X and Y axis will be greater than 90 degrees.

Measurements

The measurement view allows creation, selection, editing, or deletion of measurements that are to be evaluated by the selected machine. Four different kinds of measurements are currently supported by the *Error Simulator* utility:

Measurement Type	*Description*
Laser	Measurement using a six parameter laser. If the measurement axis is close to one of the three machine axis the results will show all linear and angular data otherwise only linear data is shown.
ISO/IEC 10360-2	Measurement of five unique lengths performed along any measurement line of the CMM.
Renishaw Machine Checking Gauge	Results from the Renishaw MCG.
ASME B89.4.1 ball bar	Results from ball bar positions placed anywhere in the machine volume.

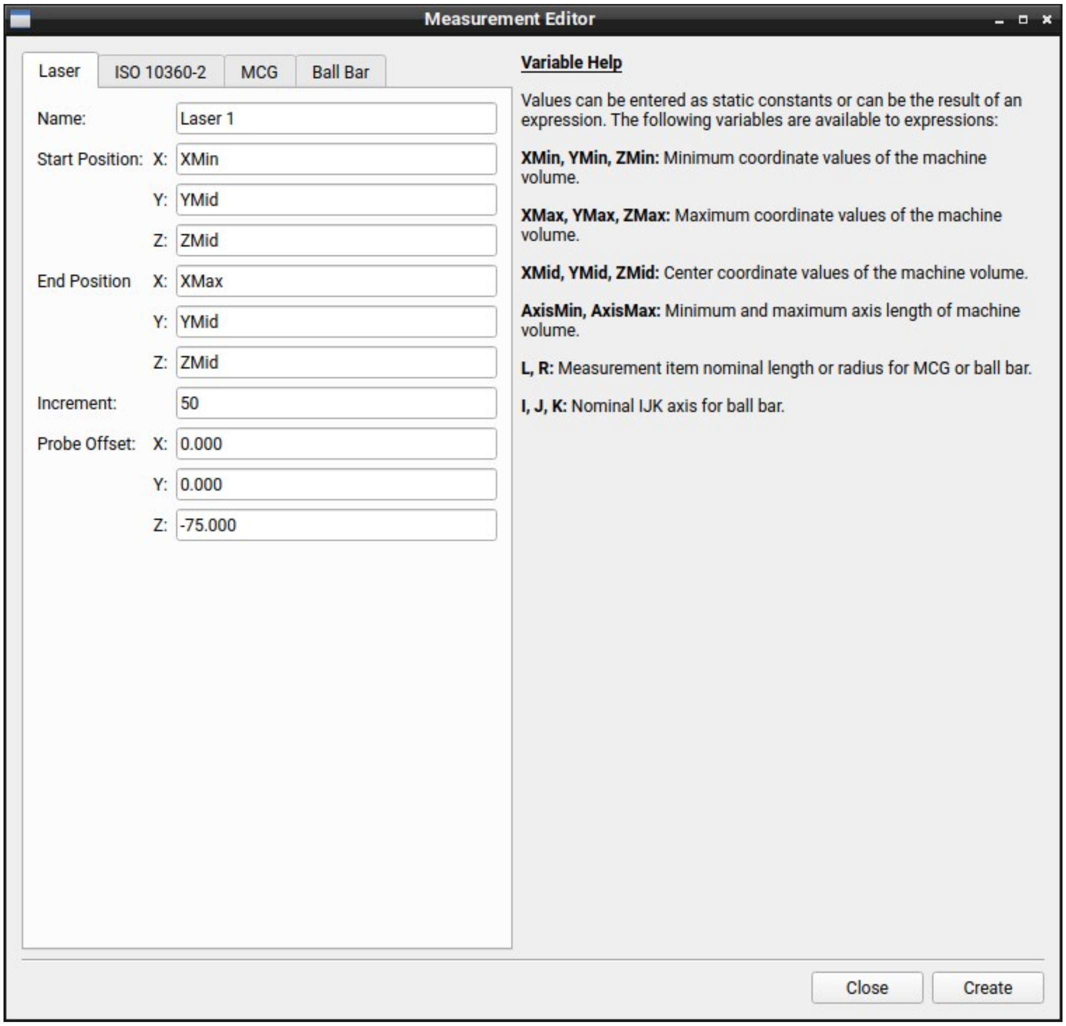


Illustration 8: View of the measurements tab with the laser active.

Creating Measurement

New measurements can be created by pressing the add button at the bottom of the list of measurements or by clicking the add measurement toolbar button. Existing measurements can be removed by selecting one or more measurements then pressing the subtract button. Renaming an existing measurement is done by double-clicking the measurement item.

When an existing measurement is selected prior to creating a new measurement the exiting item parameters are copied to the new measurement of the selected type. New measurements can be one of the four supported types and must be the active view when pressing create. The dialog will remain open until Close is clicked allowing more than one measurement, of any type, to be created.

Expression Variables.

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

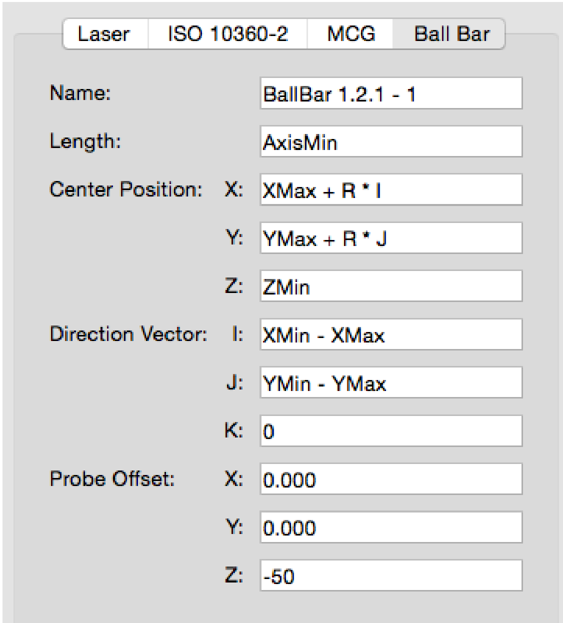
Variable	*Description*
XMin	The minimum X axis machine coordinate.
YMin	The minimum Y axis machine coordinate.
ZMin	The minimum Z axis machine coordinate.
XMax	The maximum X axis machine coordinate.
YMax	The maximum Y axis machine coordinate.
ZMax	The maximum Z axis machine coordinate.
XMid	The center 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.



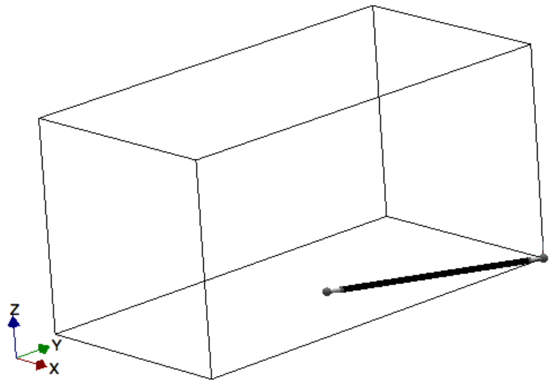


Illustration 9: Image showing position of the ball bar based on expression parameters shown to the left.

Expression	*Description*
Name	The name of the measurement as it will appear in the measurement list.
Length	The variable *AxisMin* 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 Y*Max + 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 Y*Min - 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.

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 measurement data is 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.

Measurement Results

The measurement results 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 shows examples of measurement data displayed in this view:

```
ISO 10360-2 Measurement
-----------------------------------------------------------------------------------------
Name:           Position 1
Probe Offset:   0.0000, 0.0000, -151.0000
Start Position: 5000.0000, 2500.0000, -1800.0000
Test Axis:      -0.851379928, -0.425689964, 0.306496774

   Nominal     Actual      Dev
-----------------------------------------------------------------------------------------
 1175.0000  1175.0029     0.0029
 2350.0000  2349.9930    -0.0070
 3525.0000  3524.9753    -0.0247
 4700.0000  4699.9550    -0.0450
 5875.0000  5874.9372    -0.0628

Max Error:  0.0029
Min Error: -0.0628

MCG Measurement
-----------------------------------------------------------------------------------------
Name:            MCG 1
Probe Offset:    0.0000, 0.0000, -75.0000
Center Position: 2500.0000, 1250.0000, -1500.0000

  Elevation   Azimuth     Length     Error
-----------------------------------------------------------------------------------------
  -45.0009   359.9993   499.9921    -0.0079
  -45.0011    45.0011   499.9900    -0.0100
  -45.0006    90.0026   499.9950    -0.0050
  -44.9998   135.0025   500.0021     0.0021
 …
```

```
    45.0010   179.9993   499.9914    -0.0086
    45.0012   225.0011   499.9898    -0.0102
    45.0006   270.0026   499.9950    -0.0050
    44.9997   315.0026   500.0024     0.0024

 Max Length Error:  0.0077
 Min Length Error: -0.0102

 Laser Measurement
 ------------------------------------------------------------------------------------------
 Name:           Laser X Left
 Probe Offset:   0.0000, 0.0000, -125.0000
 Start Position: 0.0000, 10.0000, -900.0000
 Test Axis:      1.000000000, 0.000000000, 0.000000000

   Scale Nom  Scale Act  Scale Dev      XX         YY         Ra         Rb         Rc
 ------------------------------------------------------------------------------------------
     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
    50.0000    50.0000    -0.0000    -0.0008     0.0000     0.0009     0.0000     0.0000
   100.0000   100.0000    -0.0000    -0.0015     0.0000     0.0017     0.0000     0.0000
   150.0000   150.0000    -0.0000    -0.0022     0.0000     0.0026     0.0000     0.0000
   200.0000   200.0000    -0.0000    -0.0029     0.0000     0.0034     0.0000     0.0000
   ...
  4800.0000  4799.9999    -0.0001     0.0098     0.0000     0.0149     0.0000     0.0000
  4850.0000  4849.9999    -0.0001     0.0096     0.0000     0.0143     0.0000     0.0000
  4900.0000  4899.9999    -0.0001     0.0094     0.0000     0.0137     0.0000     0.0000
  4950.0000  4949.9999    -0.0001     0.0092     0.0000     0.0131     0.0000     0.0000
  5000.0000  4999.9999    -0.0001     0.0090     0.0000     0.0125     0.0000     0.0000

 Max Scale Error:  0.0000
 Min Scale Error: -0.0003
```

Options

Option	*Description*
Evaluation Report	Create a file containing an extensive comparative set of results from the selected measurements using all combinations of active machine errors.
Export Measurements	Create one or more measurement files containing data suitable for external testing from the selected measurements.
Save Text	Create an output text file of all the currently displayed results.

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 YXZ

Squareness
------------------------------------------------------------------------------
YZ: 0.0000
XY: 0.0000
ZX: 0.0000
```

X Axis Data

Pos	Lx	Ly	Lz	Rx	Ry	Rz
-100.0	0.0000	0.0000	-0.0008	0.0000	-0.0020	0.0000
0.0	0.0000	0.0000	0.0000	0.0000	-0.0000	0.0000
100.0	0.0000	0.0000	0.0006	0.0000	0.0020	0.0000
200.0	0.0000	0.0000	0.0009	0.0000	0.0040	0.0000
300.0	0.0000	0.0000	0.0011	0.0000	0.0060	0.0000
400.0	0.0000	0.0000	0.0011	0.0000	0.0080	0.0000
500.0	0.0000	0.0000	0.0008	0.0000	0.0100	0.0000
600.0	0.0000	0.0000	0.0004	0.0000	0.0120	0.0000
700.0	0.0000	0.0000	-0.0002	0.0000	0.0140	0.0000
800.0	0.0000	0.0000	-0.0011	0.0000	0.0160	0.0000
900.0	0.0000	0.0000	-0.0021	0.0000	0.0180	0.0000
1000.0	0.0000	0.0000	-0.0034	0.0000	0.0200	0.0000

Y Axis Data

Pos	Lx	Ly	Lz	Rx	Ry	Rz
-100.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
100.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
200.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
300.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
400.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
500.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
600.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
700.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
800.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
900.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1000.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Z Axis Data

Pos	Lx	Ly	Lz	Rx	Ry	Rz
100.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-100.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-200.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-300.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-400.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-500.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-600.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-700.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-800.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-900.0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
-1000.0	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 data view. The map can be interpolated to any desired increment by editing the increment fields at the top of the display 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.

Revision History

Date	*Version*	*Changes*
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.
Nov 28, 2018	2.2	Bugfix: Probe offset offsetting map axis positions. Added expression builder
Aug 30, 2023	3.0	Rewrite to make utility more intuitive.