Using Metrology to Measure and Enhance the Performance of a Positioning System

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Objective Statement

This white paper will explain what positioning system metrology is, why it is important, how to conduct metrology and how to make use of the results. Metrology is conducted to ensure that a designer's positioning system meets a set of required specifications once it is mechanically built. The following material will be geared toward precision motorized positioners under closed loop control.

What Is Motion Metrology?

Motion metrology is the practical science behind defining and measuring values for different performance metrics that a designer may care about. It allows someone to verify the differences between an as-designed and as-built electromechanical positioning system. This verification is done through measurement of the as-built system using various metrology techniques. Figure 1 depicts an early stage of the process.

Figure 1. *Metrology technician setting up laser interferometer testing.*

Understanding What Is Measured Using Metrology

As a simplification, motion metrology is used to measure the "goodness" of a positioning system's ability to move between Point A and Point B in physical space. No motorized positioning system will be able to move between the two points perfectly. The imperfections in the motion are due to error sources that are inherent or otherwise present in an as-built positioning system.

Since motion occurs in physical space, there are ways to relate the actual geometric performance of a positioning system to different mathematical coordinate frames. A common way to do this is by using a cartesian coordinate frame and relating the motion to a point in space. This point in space can move in as many degrees of freedom as the designer needs, but an additional mechanical positioning axis will be needed for each additional degree of freedom of motion required.

The coordinate frame illustrated in Figure 2 shows that a point in cartesian space can move in up to six different directions, or degrees of freedom.

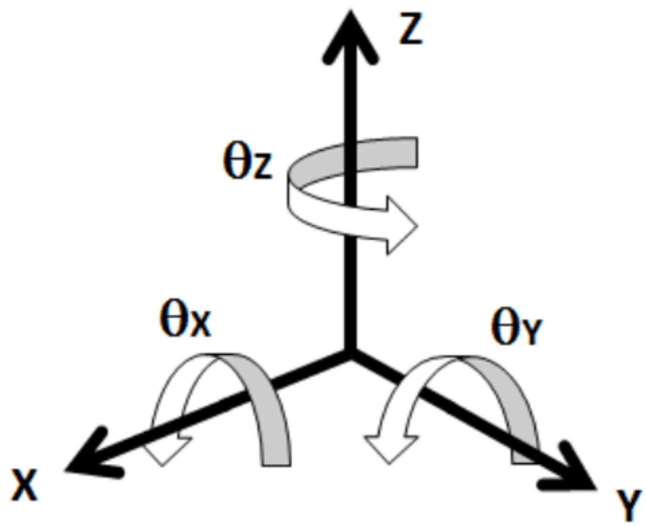

Figure 2. *Cartesian coordinate frame showing the three possible linear degrees of motion freedom and their corresponding rotational degrees of freedom.*

A mix of linearly translating axes and rotational axes, such as those shown in Figures 3 and 4, is used to achieve all six degrees of freedom.

Figure 3. *Showing translation point motion along the X direction.*

Figure 4. *Showing rotational point motion about the Z axis in the Θz.*

Using metrology techniques will allow the designer to measure the “goodness” of these axes, both as individuals as well as in combination at a specific point in space. The result will verify the positioning system’s ability to meet the geometric specifications for which it was designed.

How These Measurements Are Quantified

There are industry-accepted ways to quantify the performance of a motorized positioning system. These are typically referred to as positioning specifications, and they can be used to quantify both static and dynamic motion characteristics. The performance specifications are accepted in industry because they can be measured and verified using metrology techniques.

First, the most common specifications requested to quantify the performance of a positioning system are accuracy and repeatability of motion. Fundamentally, they are a measurement of how close the end position is to the commanded position and how close the end positions are over a series of the same commands, respectively. This is illustrated in Figure 5. The "commanded position" for each dot is to be in the center of the target. Any deviations from the center of the target are picked up in terms of accuracy and repeatability.

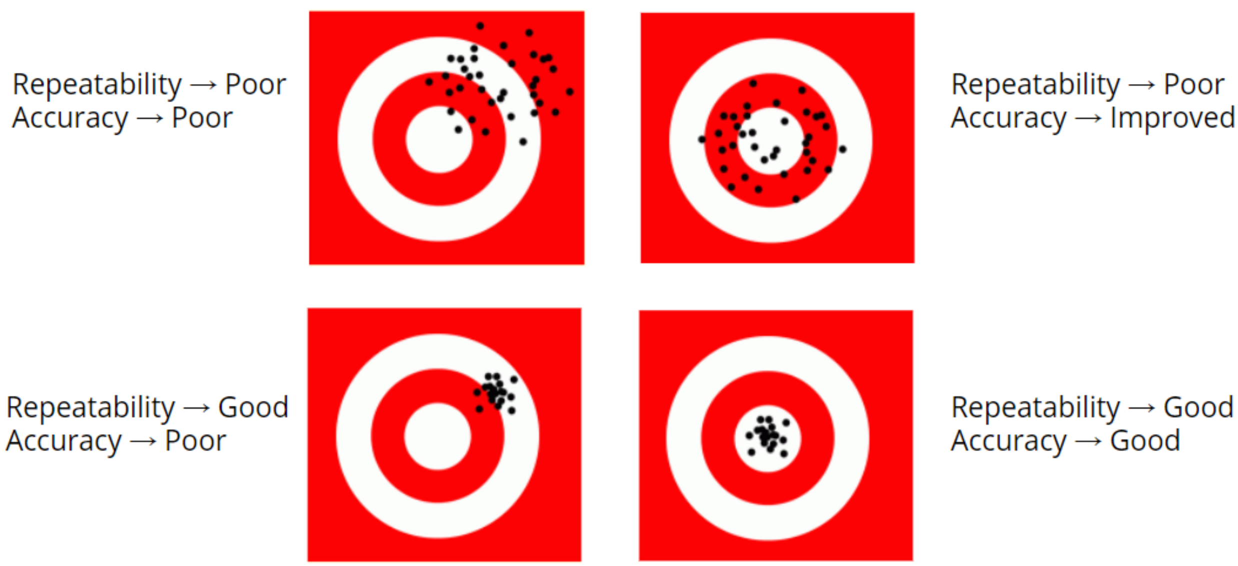

Figure 5. *An illustration showing what good and poor accuracy and repeatability look like.*

Accuracy and repeatability are typically specifications for the single direction of motion in which a mechanical positioner is designed to move. This is called the "on-axis" direction. For example, a designer could command a 50 millimeter move on a mechanical linear positioner. If the positioner actually moved 50.5 millimeters, it would have an on-axis accuracy of 0.5 millimeters. This on-axis accuracy is considered an error source in the mechanical system. Error sources are the reason that all positioning systems will never be able to move from Point A to Point B perfectly.

An important concept to understand is that a mechanical positioning axis has more than one error source. Although in theory it is constrained to move in only one degree of freedom, there are many other undesirable motions that occur as an axis moves throughout its range of travel. In fact, there are a total of six sources of motion related errors per mechanical positioning axis. One of these error sources is the on-axis error as discussed above. The other five are "off-axis" geometric errors. Figures 6 and 7 show linear and rotational "off-axis" errors.

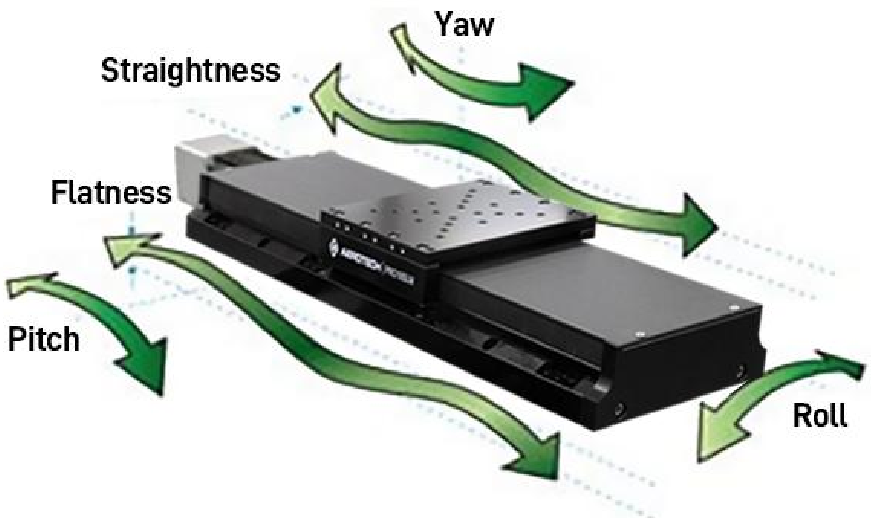

Figure 6. *For a linear axis, the off-axis errors are straightness, flatness, pitch, roll and yaw errors.*

Figure 7. *For a rotational axis, the off-axis errors consist of one-axial, two-radial and two-tilt error motions.*

Combining the on-axis and off-axis error sources of a multi-axis positioning system into a table shows how each axis relates to each other. Figure 8 shows an example of a six-axis positioning system, and Table 1 presents axes' error sources as they relate to the other axes. Since each axis has six potential error sources, a positioning system with six axes will include a total of thirty-six sources of error. Each one of these error sources could negatively affect the positioning system's ability to perform as the designer intended.

Figure 8. *Example of a 6-axis positioning system. Each arrow denotes an axis of motion.*

Table 1. *All of the potential error sources included in a six-axis positioning system. Note that depending on how these axes are mechanically configured, some of these deviations may move locations within this table, but theywill always exist.*

Axis	Deviations about the 6 DOFs					
	δ(X) µm	δ(Y) µm	δ(Z) µm	δ(θX) sec	δ(θY) sec	δ(θZ) sec
X	Acc X	Str X	Flt X	Roll X	Pitch X	Yaw X
Y	Str Y	Acc Y	Flt Y	Pitch Y	Roll Y	Yaw Y
Z	Flt Z	Str Z	Acc Z	Yaw Z	Pitch Z	Roll Z
θX	Ax θX	Rad θX	Rad θX	Acc θX	Tilt θX	Tilt θX
θY	Rad θY	Ax θY	Rad θY	Tilt θY	Acc θY	Tilt θY
θZ	Rad θZ	Rad θZ	Ax θZ	Tilt θZ	Tilt θZ	Acc θZ
	Does not change with Axis Orientation					
	Can change with Axis Orientation					

Finally, Table 2 outlines the most commonly requested specifications that customers of Aerotech's positioning systems ask us to measure using metrology techniques. Certain specifications are more important than others depending on the use case for the motorized positioning system and the customer's application.

Table 2. *Additional sources of error in a motion system.*

SPECIFICATION	PURPOSE ***(Specification is used to determine...)***
On-Axis Accuracy	The difference between the commanded position and the measured position along the axis of translation or rotation.
On-Axis Repeatability	The amount of variation between the commanded position and the measured position along the axis of translation or rotation over multiple move cycles.
Off-Axis Flatness Error	How much vertical error is present while translating in a straight line.
Off-Axis Straightness Error	How much horizontal error is present while translating in a straight line.
Off-Axis Roll/Pitch/Yaw Error	How much angular error is present while translating in a straight line.
Off-Axis Axial Error	How much error exists along the axis of rotation as a rotary positioner rotates about its center of rotation.
Off-Axis Radial Error	How much error exists perpendicular to the axis of rotation as a rotary positioner rotates about its center of rotation.
Off-Axis Tilt Error	How much angular aberration or "wobble" exists with respect to the axis of rotation, as a rotary positioner rotates about its center of rotation.
Off-Axis Runout	How much displacement a surface exhibits as a rotary positioner rotates about its center of rotation. This is different from axial or radial error, since an actual surface is being measured instead of a theoretical axis of rotation. Examples of runout surfaces are pilot holes and rotating platforms.
On-Axis Minimum Incremental Motion	How small of a motion is discernibly possible. This is the physical resolution of how small of a move a positioning system can make.
On-Axis Velocity Error	The difference between the commanded and measured velocity as a positioning system conducts a particular move profile.
On-Axis Acceleration Error	The difference between the commanded and measured acceleration as a positioning system conducts a particular move profile.
Mechanical Alignments	The amount of misalignment between two or more mechanical axes in a multi-axis positioning system.

Why Motion Metrology Is Important

Motion metrology lets designers understand and characterize their as-built mechanical systems so that they can make improvements. These improvements could be anything from positioning with a higher degree of accuracy to being able to reduce the cost of a positioning system. Also, if the motion performance can be measured using metrology, there are ways to compensate for and remove undesirable motion errors proactively. See Figure 9 for an example of a common outcome when compensating for measurable and repeatable sources of errors.

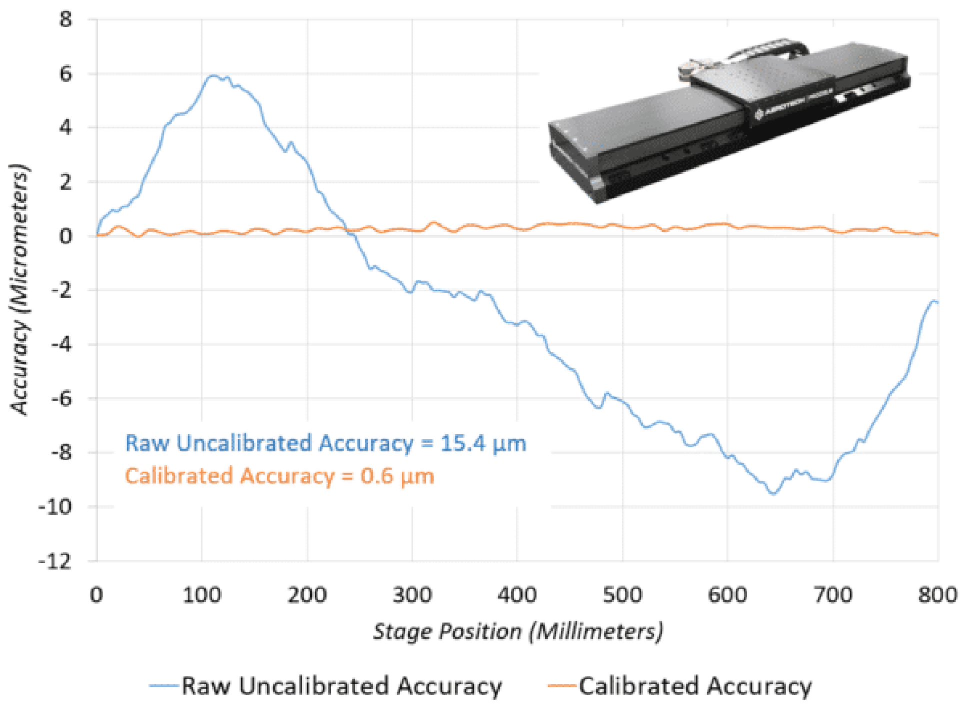

Figure 9. *Plot showing actual measured metrology data both pre- and post-calibration, using an Aerotech PRO225LM linear motor mechanical bearing positioner with 800 millimeters of travel.*

Measuring positioning performance is especially important in industrial applications, as it paints a clear picture of how reproducibly a motorized positioning system will act in the field. Improving and verifying reproducibility helps make sure that mass-manufactured goods all have the same tolerances and assures that automated processes can run continuously without expensive human intervention. Without measuring a positioning system's capabilities using metrology, there would be little reliable insight on what a manufacturer should expect when trying to replicate and scale their motorized automation processes. Also, motion metrology can be used as a trusted way to verify that a manufacturer of motorized positioning equipment is meeting the motion performance requirements of the application.

Aerotech uses metrology and guarantees performance specifications to reduce a customer's risk. This is done by measuring the actual positioning performance of the equipment after it is built to show that it meets the requirements specified by the customer.

How to Conduct Motion Measurements Using Metrology Techniques

These techniques will focus on conducting motion metrology on linear and rotational axes of positioning equipment as a single axis or for a combination of axes.

Incorporating the Correct Boundary Conditions

The results from conducting motion metrology are only useful if the motorized positioning system is tested under the same conditions as its final installed use case. Each of the items in Table 3 must represent the intended working conditions under which positioning system will be used. It is likely that the as-tested and as-used performance will vary greatly if the conditions below aren't matched in both cases.

Table 3. *Important considerations that must be incorporated into a metrology test setup.*

BOUNDARY CONDITIONS TO MATCH WHEN CONDUCTING METROLOGY
The payload being carried by the positioning equipment, including mass, CG, inertia and stiffness characteristics.
The environmental factors that the equipment will see, including temperature and humidity.
The dynamics (motion profile) that the equipment will be used to recreate.
The base structure to which the positioning equipment will be mounted.
The sensitive direction of the process. Understanding if it is the process tool or object being worked on that is moving. This changes the metrology artifact location.
The working location where the payload or tool will be used in space.

The last condition in the table above is especially important for recreating the situation for which the equipment will ultimately be used. This is because there is another source of error that comes into play when there is an offset between the positioning application's work point, or point of interest, and the measurement device being used to provide feedback to the closed loop control system.

This error, illustrated in Figure 10, is called the Abbe error and it proportionately increases as the offset to the working point in space increases. It is very important that a designer understands the point in space at which the process is occurring and conducts metrology at this location.

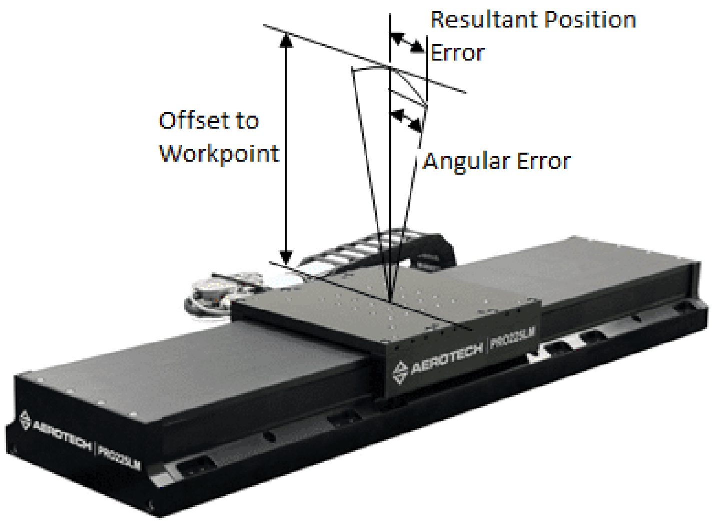

Figure 10. *Showing the resultant positioning errors created by the offset to the workpoint and the inherent angular error of the positioner itself. The positioning errors caused by Abbe errors will affect both on-axis and off-axis specifications.*

Linear Motion Metrology

The most popular way to conduct metrology on a linear positioning axis is to use a laser interferometer. As shown in Figure 11, a moving optic is mounted to the translating portion of the positioner, and a fixed optic is mounted between the positioner and the laser itself as a reference.

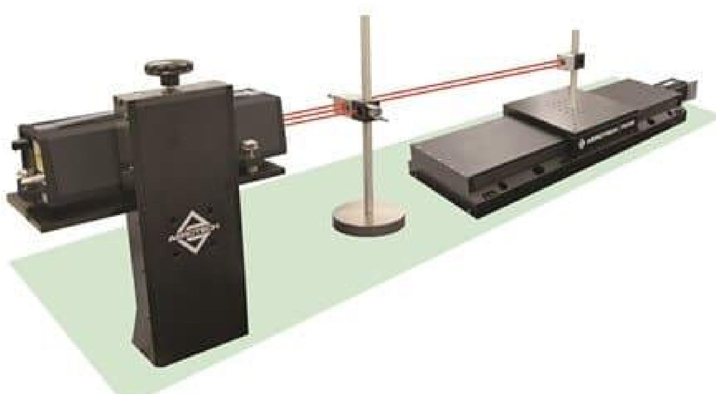

Figure 11. *A visual showing the laser interferometry setup to measure a linear positioner.*

As the laser reaches the fixed optic, it is split using a beam splitter. One half of the beam is returned using a retroreflector mounted to the fixed optic stand. The other half travels through the fixed optic and is reflected by the optic that is mounted to the moving positioner. When both lasers are returned to the laser unit, the phase shift between the two optical paths generates an interference pattern. Changes in this interference pattern are then used to determine the absolute position of the translating positioner. This method can be used with different optical setups to determine the various specifications in which a designer may be interested. For example, different optics and prisms can be added to the translating portion of the positioner to measure other error sources, like straightness or flatness error. In some cases, an autocollimator angular measurement device will be used to measure errors such as pitch and yaw.

The result of a linear measurement test is data displaying the error a positioner exhibits throughout its entire travel. The error source being measured depends on the measurement artifact and setup being used. Figure 12 depicts a resultant accuracy and repeatability plot that shows the interferometer data as the positioner moves through full travel in both the forward and reverse directions. Aerotech takes the worst-case error from both the forward and reverse runs and sums them absolutely to report the total accuracy error. Aerotech's repeatability is calculated as the largest difference between the forward and reverse direction's position at any one measurement point along the total travel of the positioner.

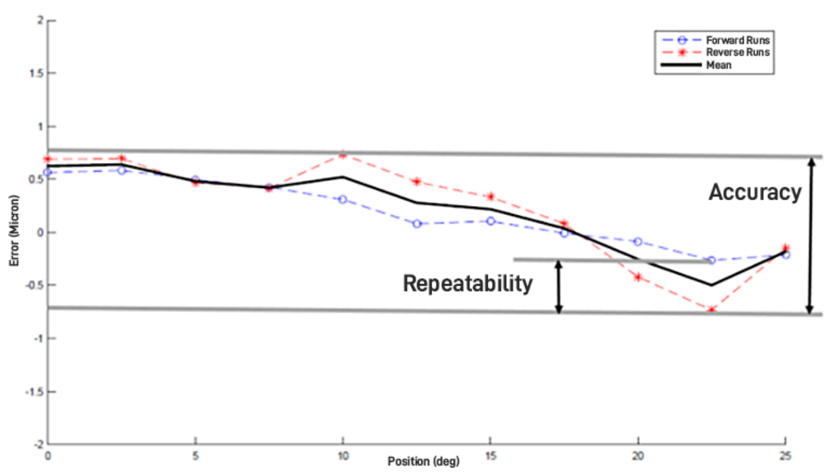

Figure 12. *The resultant metrology plot from measuring a linear positioner along its axis of motion.*

Laser interferometers have a measurement resolution of sub-nanometer when appropriately used. There are many best practices that must be implemented to achieve this level of resolution. First, the environmental stability is critical, as temperature, humidity and air turbulence can interfere with the measured phase offset generated by a laser interferometer setup. Many times the environmental stability necessitates collecting fewer points so that the entire metrology process can be accomplished in a matter of minutes instead of hours. The tradeoff of running a test faster is the lower number of measured data points. However, it is sometimes required to achieve results that have not been compromised due to changes in the environment.

Second, the distance between the fixed and moving optic where there is no relative motion is called the dead path. The laser unit can only compensate for environmental effects in ranges where there is relative motion, so it is important to minimize the dead path distance as much as possible.

Finally, the laser must be aligned to the optical path with minimal cosine error. As shown in Figure 13, this error will increase as the measured travel of the linear positioning system is increased.

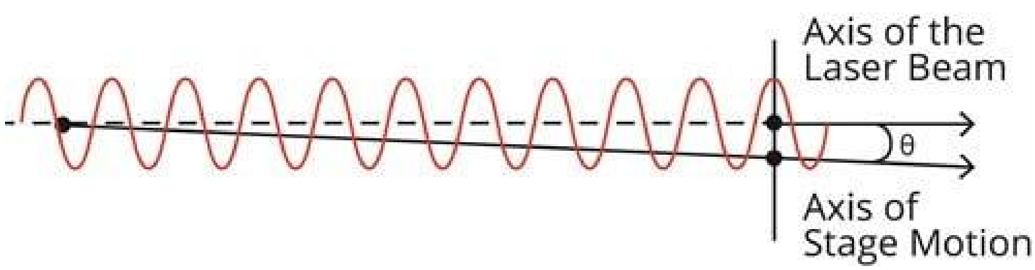

Figure 13. *Showing cosine error of a laser interferometer setup.*

Rotary Motion Metrology

Rotary positioning devices are measured using different techniques than linear positioning devices. They typically do not use laser interferometers as measurement tools. Autocollimators and capacitive sensors are the most common metrology devices used.

For on-axis accuracy and repeatability of a rotary positioner, a common measurement technique is the master-axis method. Here, a reflective flat mirror is attached to the surface of the rotary positioner being measured. An autocollimator is positioned so that it can see the slightest of angular changes in the flat mirror. The rotary positioner under test is bolted to another very accurate rotary positioner called the master-axis.

As the rotary positioner under test rotates a certain number of degrees, the master-axis is rotated the same number of degrees in the opposite direction. An example of a rotary calibrator master-axis system and an autocollimator device is shown in Figure 14.

Figure 14. *A rotary calibrator master-axis system and an autocollimator device being used to test a rotary positioner carrying a flat mirror optic.*

We assume the master-axis has perfect accuracy and that any deviation measured by the autocollimator is caused by inaccuracies of the rotary positioner under test. This makes it extremely important to use a high-precision master-axis. Aerotech has built and tested its own master-axis for this type of metrology that is accurate to 0.6 microradian (<0.12 arcsecond) and stable over long time periods.

Similar to the linear metrology results, a rotary positioner test will report the positional errors throughout the positioner's travel. Figure 15 shows an example of a rotary positioner test's metrology plot. For an Aerotech rotary positioner, the total accuracy would be reported as the absolute difference between the lowest and highest error values throughout the entire travel of the test. The repeatability is reported as the largest error difference between forward and reverse runs at any given location throughout travel.

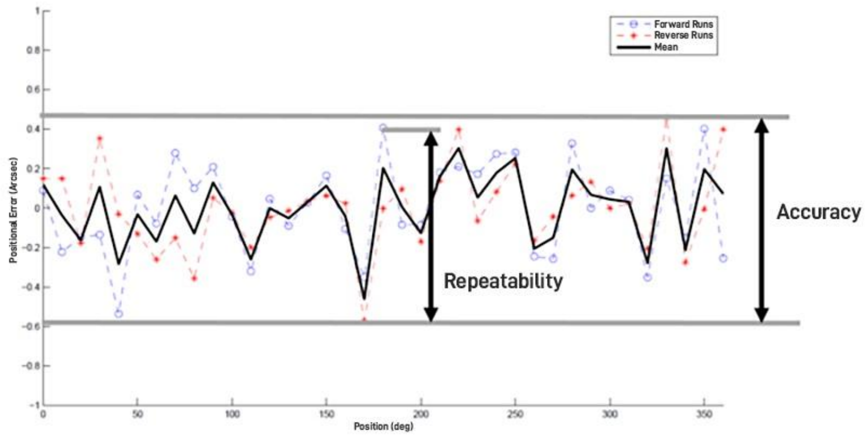

Figure 15. *The resultant metrology plot of a rotary positioner measured throughout its travel range.*

For measuring the off-axis errors produced by a rotary positioner, the most common method is to use a precision ground ball as the test artifact and capacitive probe(s) as the measurement device, as shown in Figure 16.

Figure 16. *A precision test artífict (the ball) and the capacitive probe.*

These setups allow for the testing of error motions such as axial and radial error. If runout is desired, a capacitive probe or electronic indicator can be used to measure the surface that is under test. Refer to Table 2 for more information on the difference between error motions and runout.

The results of this measurement data can be used to determine the repeatable and non-repeatable components of the error motion being tested. The repeatable component is called synchronous error and the non-repeatable component is called asynchronous error. As you can see by the resultant error motion plot shown in Figure 17, the synchronous error follows the same path every time a full rotation is completed, whereas the asynchronous error is random and looks like a noise band around the complete rotation's path. Aerotech represents the total error motion as the peak error of both the synchronous and asynchronous components throughout the full travel of the rotary positioner.

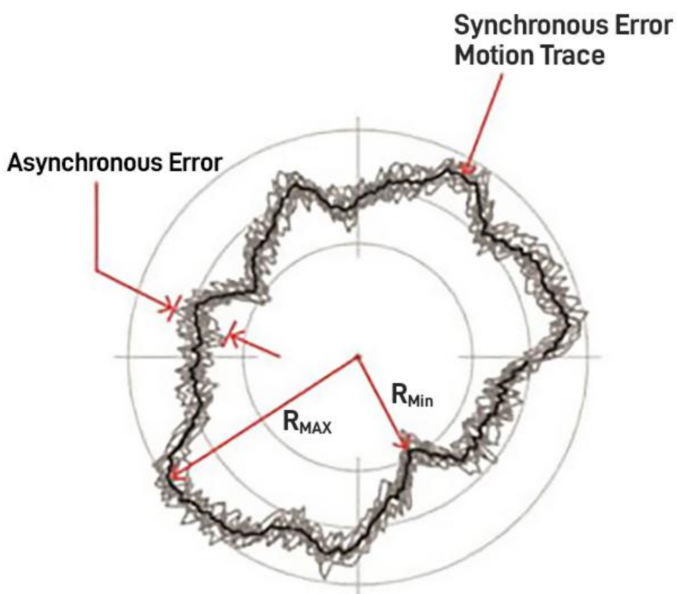

Figure 17. *Showing the synchronous and asynchronous error components.*

How to Use Motion Metrology to Meet Your Specifications

There are ways to compensate for undesirable motion errors after they are measured. Of course, once a positioning system's performance is measured and exhibits too much error, one way to meet the desired specifications would be to carefully rebuild the mechanics. Or, the system could be redesigned to incorporate higher precision guide surfaces or more accurate and better placed feedback systems for closed loop control.

Another way that doesn't require a redesign is to use a correction technique to subtract the measured motion error value from the motion controller's commanded position value, as depicted in Figure 18. Using correction is a reliable and inexpensive technique to quickly compensate for many errors that a positioning system may exhibit.

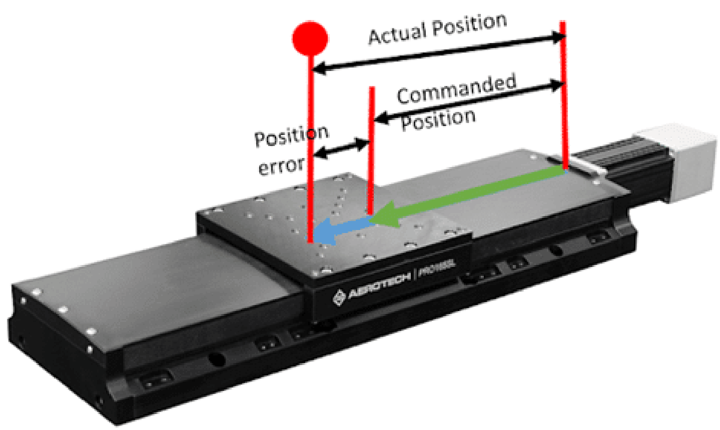

Figure 18. *Depiction of positioning error as a function of commanded position and actual position.*

The most common correction method is to measure the on-axis error of a linear system at the work point and to build a table, as shown in Figure 19, that is used by the motion controller to subtract the measured error component out of the commanded position signal. This correction value should be applied actively and with low latency via the motion controller.

POSITION COMMAND	ACTUAL POSITION	CORRECTION VALUE
100	101	-1
200	199	1
300	298	2
400	401	-1
500	499	1

Figure 19. *Example of a calibration table that can be used by a motion controller to compensate for errors seen in a positioning system.*

Many times, the individual on-axis errors are only a subset of the underlying errors hindering the performance of a motion system. This is common in multi-axis positioning systems since there are tolerance stackups of motion errors as the number of degrees of freedom increase. Think back to each axis having its own six error sources that compound when more axes of motion are added. The good news is that once the errors are measured using metrology techniques, a designer can often use the other axes in a positioning system to correct for each other's error sources. This is called cross-axis correction.

For example, as the lower axis in the XY positioner stack in Figure 20 moves, it will exhibit a straightness error that can be measured using a laser interferometer metrology setup. Then the results could be added to a correction table that commands motion in the upper Y axis to correct for errors in the X axis as it moves through travel. Using the cross-axis correction method makes it possible to significantly reduce the straightness error.

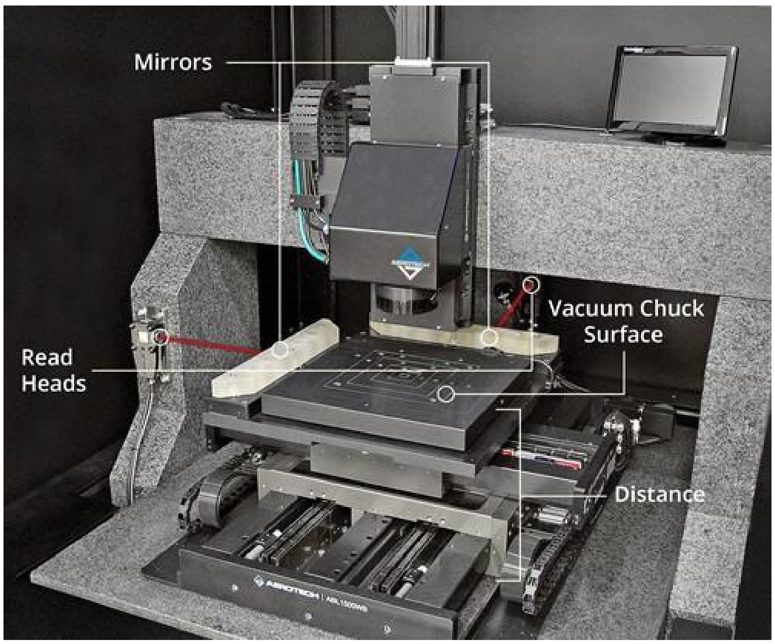

Figure 20. *Showing cross-axis correction.*

Another way to use metrology to compensate for positioning induced errors is to add in-situ feedback to be used by the closed loop motion controller. For example, we can incorporate the same laser interferometer measurement system we use to conduct offline metrology into the design of the positioning system itself to be used for continuous measurement. A common use case for this is reducing the amount of error in an XY plane at the elevated working height at which the process is occurring.

As shown in Figure 21, the working height is at the top of a flat vacuum chuck surface.

Figure 21. *A 2D laser interferometer system that is being used to compensate for Abbe error offsets and on-axis accuracy in real time.*

Because this working height is elevated from the bearing surface and encoder feedback locations, there will be Abbe error influences at the vacuum chuck surface. A two-dimensional (2D) laser interferometer can be used to measure the elevated position in XY space in real time. This position feedback can be used for close-loop control and the positioning system will no longer have to worry about the Abbe error effects (or some tertiary effects that get removed, such as Yaw errors).

Conclusion

It is clear that conducting motion metrology is a critical step in understanding the performance of a motorized positioning system. Making sure to apply the appropriate boundary conditions to the metrology test setup and using the right techniques for conducting metrology will produce valuable measurement data. This measurement data can then be used to compensate for positional errors that are inherent or otherwise present in a positioning system. If applied properly, metrology will increase a positioning system's performance and reduce the risk of such a system failing to meet an application's requirements. At Aerotech, we are experts at understanding and conducting metrology for our customers.

About the Author

RJ Hardt is the President of Peak Metrology, an Aerotech company focused on surface metrology equipment. He has over a decade of experience working directly with customers implementing motion control and automation technologies.