Application Note

Motion Control

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On the Origin of Motion Control Specifications

An Investigation of Repeatability

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On the Origin of Motion Control Specifications:
An Investigation of Repeatability

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Introduction
High-precision motorized positioners are used for a wide variety of applications such as fiber alignment, semiconductor wafer positioning, micro-assembly, and device testing in a number of different industries. When selecting the appropriate positioner for an application, it is common to evaluate them with regard to the product specifications – such as repeatability, accuracy, pitch, roll, and yaw – as supplied by the manufacturer. In particular, users often compare different manufacturers' products in a "spec-to-spec" comparison. This can be a very risky way to choose a product – especially in the submicron performance range.

Consider an automobile with a "0 to 60 mph in 5 seconds" specification. Does this mean while carrying any number of passengers and any amount of cargo? Does this mean while driving off-road? Probably not. Rather, the automobile manufacturer's specification is for a given set of conditions. The same is true with high-precision motion control. So when a manufacturer claims 0.1 µm repeatability, for example, that repeatability is also for a given set of conditions.

By analyzing one important specification in high-precision motion control (repeatability), this paper will demonstrate that further investigation into the origin of motion control specifications and how they are actually obtained is ultimately more telling than the actual spec itself.

The Idea of Repeatability
The general idea of repeatability is the measure of the ability of a system to achieve a commanded position over many attempts when approached from either the same or different directions. This is crucial in high-precision motion applications because the user must have very high confidence in knowing the probability that a device will consistently move to a commanded position.

Repeatability should not be confused with accuracy. In fact, as Figure 1 illustrates, a system may be very repeatable yet lacking accuracy.

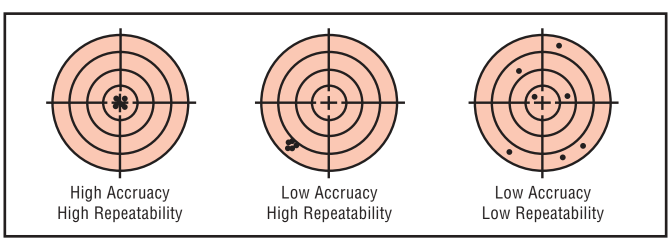

Figure 1. Accuracy vs Repeatability

Repeatability is essential to ensuring quality in many different areas. Without a proper repeatability in a manufacturing environment, there can be no reliable process to assure that products are manufactured the same way and meet the same specifications all the time. Repeatability is also crucial for research and process development efforts. For example, when modifying one parameter and repeating a process or experiment, the effect of the uncertainty or non-repeatability of the other parameters should be minimized for best results. Increasing demands for accurate metrology are being driven by the seemingly never-ending requirement for greater precision in many industries such as fiber communications and semiconductor manufacturing. This has meant an ongoing need for increasingly higher precision motion control systems and the resulting demand for accurate measurement of performance to ensure repeatability.

Comparing Test Methods
Catalog specifications are often gathered in near "perfect" conditions that rarely replicate the actual conditions that will be present in the customer's environment. This is particularly true for repeatability. As a result, a catalog's claim of repeatability may not always be an accurate indication of what the user expects or needs in anticipated performance. Moreover, a wide variety of repeatability values can be obtained with the same test setup but with different methodologies and mathematics employed.

So in order to properly determine the true value of repeatability, it is necessary to conduct a comparison of test methods, since a whole slew of factors such as the number of data points measured, the "randomness" of those points, different statistical and mathematical methods used, and the metrology standard used, can lead to a wide possibility of values representing "repeatability."

Collecting the Data
Quantifying repeatability begins with the collection of data. Quality of data has everything to do with the manner in which it is collected, as this determines both the probability of error and the margin or size of error. The illustrations in Figures 2-4 show the potential for error in this regard. This is a simplified example of the potential for error based on the direction of movement of the positioner. Quite different data result based upon measurements taken from either the forward or reverse direction of motion. (Note that measuring a perfectly repeatable positioner would always result in data plotted exactly at the same position.)

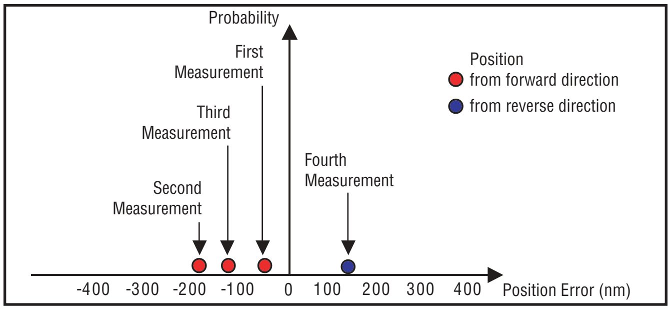

Figure 2. Measuring Position Error

In Figure 2:

- Upon taking the first measurement, the error is 55 nm
- The second measurement gives an error of 195 nm
- The third measurement has an error of 120 nm
- Taking a measurement from the other direction yields a 130-nm error

But what exactly is the "repeatability"? Is it 140 nm (the difference between the first and second measurements)? Is it 75 nm (the difference between the second and third measurements)? What about 65 nm (the difference between the first and third measurement)? Or is it something else? Depending on the direction of motion collection as shown in Figure 2, the next plot (Figure 3) shows a distribution of possible errors for a larger number of measurement points.

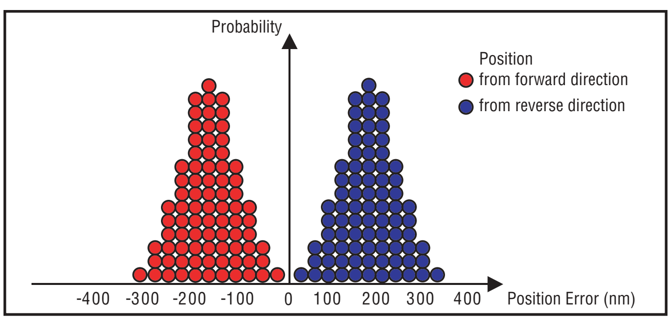

Figure 3. Distribution of Position Errors

As one may see, after taking "many" measurements, one will get a distribution of many errors. (Note: In Figure 3, we are assuming a normal distribution for illustration purposes only.) In these graphs, we have two different sets of data compiled based on the direction from which the measurements have been taken.

So back to the question of what exactly is "repeatability"? As shown in Figure 4, one may have a different range of "repeatabilities" depending on the definition of "repeatability" that one chooses. Only three different values for repeatability are shown here – mean uni-directional, maximum uni-directional, and maximum bi-directional – but there can be more.

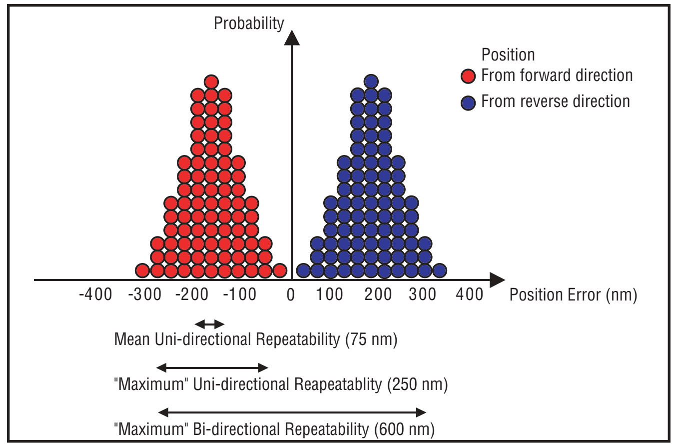

Figure 4. Definitions of "Repeatability"

Mathematics Applied

In quantifying repeatability, certain rules apply:

- The "mean" value is a statistical formula dependent on the number of samples (i.e., error measurements) one takes:

$$\overline{x} = \frac{1}{n}\sum_{j=1}^{n} x_j = \frac{1}{n}\left(x_1 + x_2 + \ldots\ldots + x_n\right)$$

where the mean value, $\overline{x}$ of the sample or simply the sample mean is defined as the sum of the samples divided by the size n of the sample.

- The "maximum" value is dependent on both the mean and the number of standard deviations ("sigma" or "σ") of the sample population. Sigma is calculated as follows:

$$S^2 = \frac{1}{n-1}\sum_{j=1}^{n}\left(x_j - \overline{x}\right)^2 = \frac{1}{n-1}\left[\left(x_1 - \overline{x}\right)^2 + \ldots\ldots + \left(x_n - \overline{x}\right)^2\right]$$

$$\sigma = \sqrt{S^2}$$

But in order to begin to properly determine the true value of repeatability, one must delve further into the analysis by also knowing:

- the sample size (note that the term "n-1" carries a different "weight" for small and large sample sizes)
- if the final value of the statistical errors is based on 2-sigma, 4-sigma, 6-sigma, or other (for example, ISO 230-2 assumes 4-sigma)

Thus, it is important for the equipment user to ask questions about stated specs based upon these criteria. One cannot stress this enough, and the reason, as illustrated in Figures 2-4, becomes self-evident. For example, one should ask:

How often does a spec sheet specifically state…

- **… uni- or bi-directional repeatability?**
- **… "mean," "maximum," or some other formula?**

- **… 2-sigma, 4-sigma, 6-sigma, or RMS?**
- **… the amount of measured data points?**
- **… the percentage of the total travel range used in the data collection?**

It is only after answering these types of questions that one can more honestly compare specifications for motorized positioners.

Repeatability Values Applied to Motion Control (Linear Stages)

To illustrate how a single, unchanged test setup can still produce a variety of "repeatability" values, a Newport 150-mm aluminum linear translation stage with a ball screw drive, recirculating ball bearings, DC brush servo motor, and a rotary encoder located on the screw were set up in the configuration shown in Figure 5. A laser interferometer was used to measure actual position, with a retro-reflector mounted on the moving plate of the linear stage.

Figure 5. Metrology Test Setup for Linear Positioner

The positioner was mounted on a granite surface flat to 1 µm, and the following environment was maintained:

- Room temperature: 20° ±0.1° Celsius
- "Mini-Environment" of test station temperature: 20° ±0.03° Celsius
- Relative humidity: 45% ±5%
- Compensations for atmospheric pressure

Data was gathered using two different methods: "linear scan" and "pendulum."

In the linear scan method shown in Figure 6, positional data is acquired by first moving to position 1 (position 1 is the left-most position) and to each subsequent position, left to right. The direction of motion is then reversed to acquire values at each position from right to left. The method is repeated until five values have been acquired for each position and from each direction. (Note: one may acquire any number of values, but five was chosen in this specific example.)

For the pendulum method (Figure 6), values were obtained by moving back and forth at the first position until five values were acquired from each direction. The latter is repeated for all subsequent positions.

With both methods, sufficient time was allowed for a stage to settle to its final position before values were obtained. In all cases, a position is approached from a distance that is far greater than the combined backlash and hysteresis. Analysis is done by comparing the commanded position with that of the interferometer.

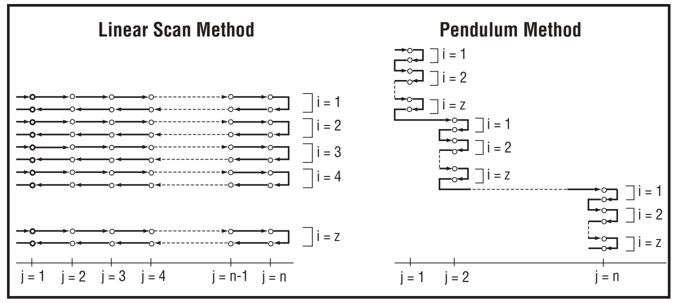

Figure 6. Different Data Collection Methods

Once the data was gathered, both the ASME (American Society of Mechanical Engineers) B5.57 procedure (Note: ISO 230-2 is essentially the same) and an independent, industry-utilized procedure were used to calculate "repeatability." For this specific example, the important differences between ASME B5.57 and the independent procedure are the mathematics used to interpret the exact same set of data.

Table 1 shows how dramatically different "repeatability" values – ranging from 0.14 µm to 0.86 µm – can be attained with the same test setup, but under different data collection methods and using different analyses (i.e., mathematics). This 720-nm difference can sometimes be minimal, but it can also be enormous, depending on the sensitivity of one's application.

Parameter	Procedure	Data Collection Method	Value (µm)
Forward Repeatability	ASME B5.57	Linear Scan	0.86
Forward Repeatability	ASME B5.57	Pendulum	0.39
Reverse Repeatability	ASME B5.57	Linear Scan	0.78
Reverse Repeatability	ASME B5.57	Pendulum	0.43
Bi-Directional Repeatability	ASME B5.57	Linear Scan	0.86
Bi-Directional Repeatability	ASME B5.57	Pendulum	0.45
Repeatability*	Independent	Linear Scan	0.34
Repeatability*	Independent	Pendulum	0.14

*A *combination of forward and reverse repeatability, but not truly bi-directional repeatability.*

Table 1. Different Measured "Repeatability" for the Same Test Setup

One reason for the different values obtained with the linear scan and pendulum methods is the effect of temperature. In the linear scan method, a longer section of the positioner's screw is subject to heating as the positioner moves over its full travel during data acquisition. On the other hand, heating from pendulum type motion is localized, and the time to acquire data for any one position is much shorter. Thus, although the two methods may produce significantly different results for repeatability, specification sheets alone generally do not divulge more information than the final value.

Conclusion

Many high-precision motorized positioners claim a "repeatability" in the sub-micron range (and some in the nanometer range), but repeatability means different things to different applications and environmental conditions. Specs for motion control product performance and repeatability can be literally meaningless unless grounded in the same foundation as that of the intended application and obtained under the same operating conditions.

This paper specifically focuses only on the numerous types of data collection and analytic methods that can be used to determine repeatability; but in addition to that, environmental factors – such as changes in temperature, relative humidity, airborne contamination, background noise, and vibration – may also affect performance of motion control products. Furthermore, the same breakdown of methods applied and referenced above can also be used for accuracy, pitch, yaw, roll, and other specs claimed in high-precision motion control products. Therefore, the equipment user should avoid making "spec-to-spec" comparisons and should always make it a point to ask about the true origin of a manufacturer's motion control specifications.

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