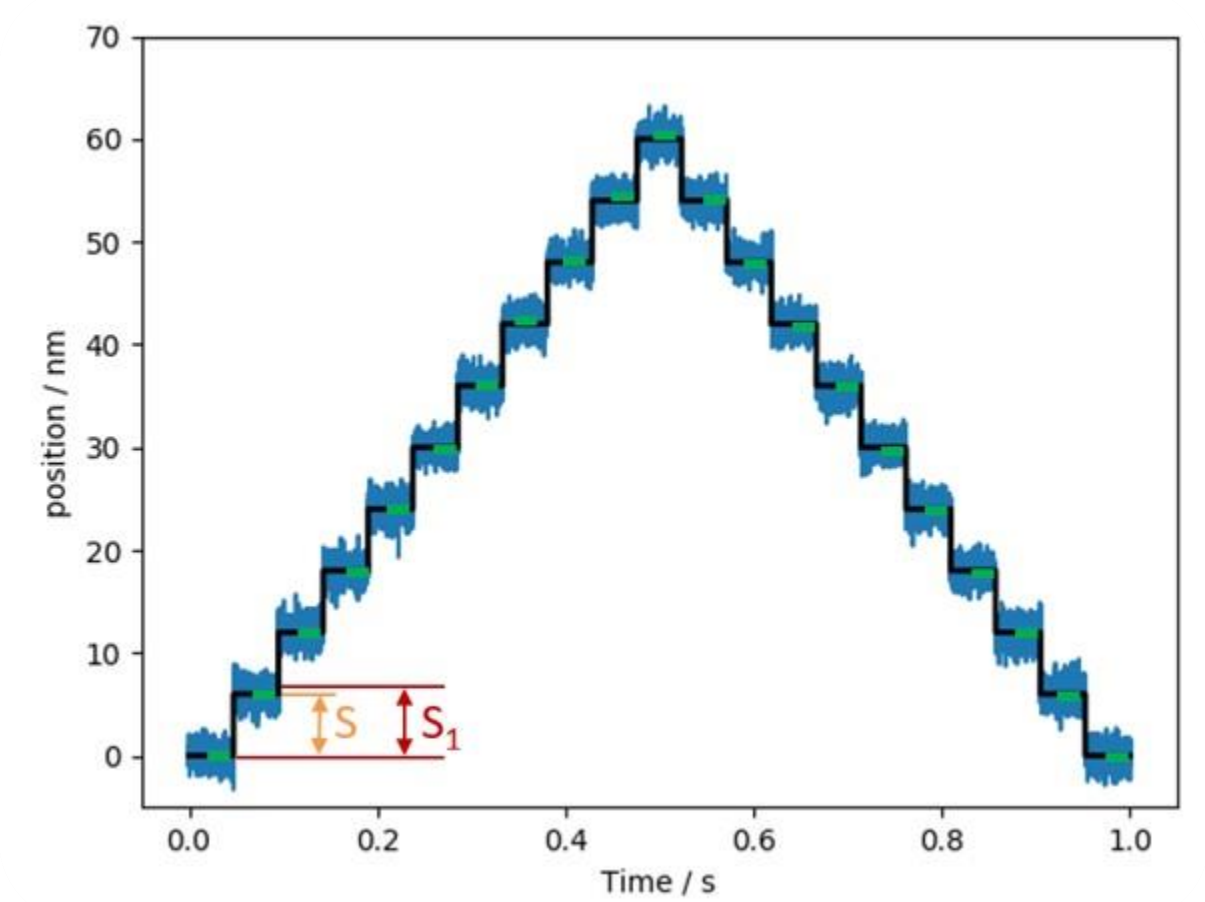
This Is How PI Does Measuring - Part 3

Resolution / Noise / Minimum Incremental Motion



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1 Motivation

Micro- and nanopositioning systems from PI are characterized by their ability to execute the smallest positioning steps as well as stand still with as little change in position as possible. This document presents three variables which PI uses as a reference to make these system properties both visible and comparable:

- Resolution
- Noise
- Minimum incremental motion

2 Performing the measurements

Before presenting the individual variables, we will briefly describe the measuring equipment used. For further information on measuring equipment, please refer to the white paper "This Is How PI Does Measuring - Part I".

2.1 Measurements using external measuring equipment

The external acquisition of measurement data is typically done using interferometers to determine the linear deflection or – for rotatory systems – the angular deflection.

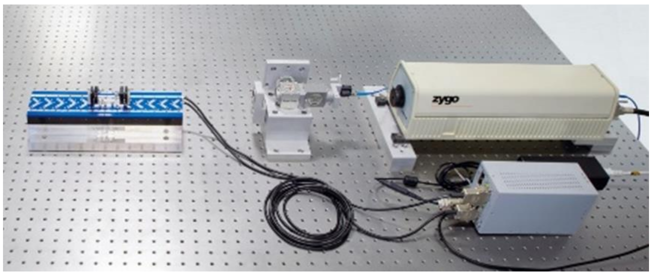

Figure 1 *Setup for measurements using external measuring equipment: positioning axis with mount for a reflector mirror, interferometer setup to measure the position*

One such measurement setup is shown in Figure 1,whereby the linear deflection of the positioning axis is determined using an interferometer. The positioning axis is equipped with reflector mirrors which are used by the interferometer for its measurements.

2.2 Internal measurements

For an internal measurement, no external measuring equipment is used. Instead, sensor systems that are present within the system itself are also used for position control. Data can be obtained from these sensor systems by recording the position data via the controller's data recorder in digital systems, for example, and reading it out from there. In analog controller systems, the signals are tapped at the monitor output and evaluated.

2.3 Measuring position and other influencing factors

The measurements described here are typically performed at a position within the positioning range of the axis. Measurements at other positions may result in deviating measured values.

Furthermore, the values may differ depending on the controller used and the chosen settings for the control and measuring equipment. For example, it makes a difference whether the position control for the system has been optimized for low noise or for high dynamics. Ideally, the external measuring equipment should not influence the measurement results, but in practice this is not feasible in all situations and systems.

The measurements described here are typically performed on a time scale of a few seconds.

3 Resolution

3.1 Definition and special features of positioning system

In general, the resolution is defined as the smallest perceptible difference, for example to characterize measuring equipment. Translating this widely used term into the world of micro- and nanopositioning requires further delineation.

With regard to the resolution of positioning systems, it matters whether the data in the system is processed in digital or analog form.

Furthermore, a positioning system consists of different components that must be considered separately. Parts of the positioning system to which a resolution can be assigned:

- Electronics to control the actuator technology
- Drive element to generate the movement
- Sensor and internal measuring system to read out the position data
- Overall system, which is typically stabilized via a servo loop

Finally, it must be distinguished whether the underlying data is recorded internally in the system or externally via an external measuring device such as an interferometer; see chapter 2.

3.2 Digital or analog?

If a digital data stream is available, the resolution corresponds to the smallest possible digital unit. This may be, for example, one bit from a digital sensor system or from the data stream at the digital interface of a controller, but also the smallest possible unit of control with a digital-to-analog converter.

If a digital data stream is not available (e.g., in completely analog systems), the resolution always corresponds to a standard deviation of a measured value. To allow this, of course, the resolution of the measuring equipment must be sufficiently high.

3.3 Components of a positioning system, design resolution

In some systems, the drive element itself has no limitation with regard to triggering. This applies to piezo actuators, for example. In other systems, however, the drive element has a specific resolution, such as a stepper motor that has a defined resolution per step. In all cases, the resolution of the overall system is ultimately determined by the interaction between the control electronics and the drive element. In a closed servo loop, the resolution of the position sensor also contributes to the position resolution. Therefore, the resolution of the overall system may differ depending on whether the system is operated in servo-loop or open-loop mode.

Based on these considerations, a theoretical resolution limit can be calculated for certain systems, the so-called “design resolution”. For a linear axis with a stepper motor, for example, the design resolution would be the resolution of one step converted to a linear movement. This calculated value indicates a theoretical lower limit which, however, is usually difficult to achieve in the overall system due to the interaction of the large number of individual components.

3.4 Internal or external measurement

In the case of an external measurement, for example the measurement of a complete system in front of an interferometer (see Figure 1), the resolution corresponds to a standard deviation of the measured values determined with the external measuring system. The resolution of the external measuring system is typically higher than the resolution of the system to be measured and can be regarded as quasi continuous.

4 Noise

4.1 Definition

At PI, the noise is defined as the standard deviation determined from the measured values of a positioning system by means of statistical evaluation. If it is not possible to calculate such a standard deviation in a meaningful way, 0 is specified as the value. This may be the case, for example, if the incremental sensor of a system provides a noise-free signal, or if a stepper motor is only controlled in single steps, thus making the drivetrain noise-free.

4.2 Noise vs. resolution

There are a number of cases where noise and resolution can be equated. These include, for example, all fully analog positioning systems, since no discretization is available in this case.

4.3 Noise measurement

In the standard case, the noise measurement is performed by determining the noise power density in the relevant frequency range. In the simplified case, only a cumulative single value is determined over a specific frequency range.

In terms of the overall system, PI distinguishes between internal and external noise. The internal noise is measured using a signal generated by the system itself (e.g., analog output of an analog controller, internal data recorder in a digital system), while the external noise is measured using an external measuring device (e.g., an interferometer) on one axis of the positioning system. These relationships are shown in Figure 2.

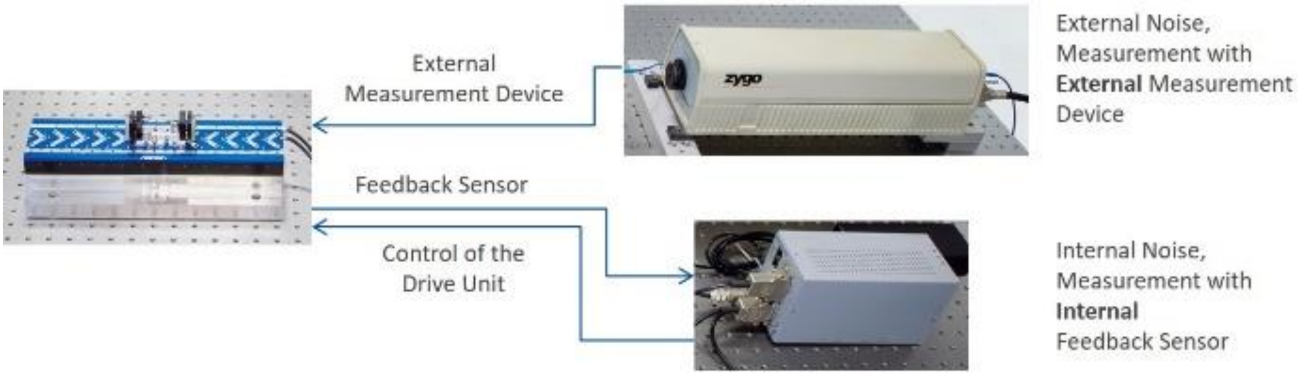

Figure 2 *Illustration of the difference between the internal and external noise. The internal noise is measured via the feedback sensor installed inside the positioning system; the external noise is measured using external measuring equipment, e.g., an interferometer*

4.4 Internal noise

For purely analog systems, the internal noise is measured with a digital multimeter in AC-coupled mode at the monitor output.

An example of internal noise measurement with a digital controller in the complete system case is shown in Figure 3. Here, position data was recorded using the controller's internal data recorder. The resolution of the complete system is small compared to its noise, so the position noise is normally distributed and a standard deviation can be determined (Figure 3, bottom right). The data was recorded at the maximum sampling rate for a defined period (typically 1 second).

Figure 3 illustrates the difference between the internal resolution and the internal noise when the data was recorded with a digital system. According to the definition in chapter 3, the resolution corresponds to the smallest incremental movement of the system that can be detected in the digital data. Accordingly, it is evident that a meaningful histogram as shown in Figure 3 (bottom right) can only be created if the internal resolution is correspondingly small. If the internal resolution is larger than the signal noise, then the noise can take the value 0. The value of the noise is therefore limited by the value of the resolution.

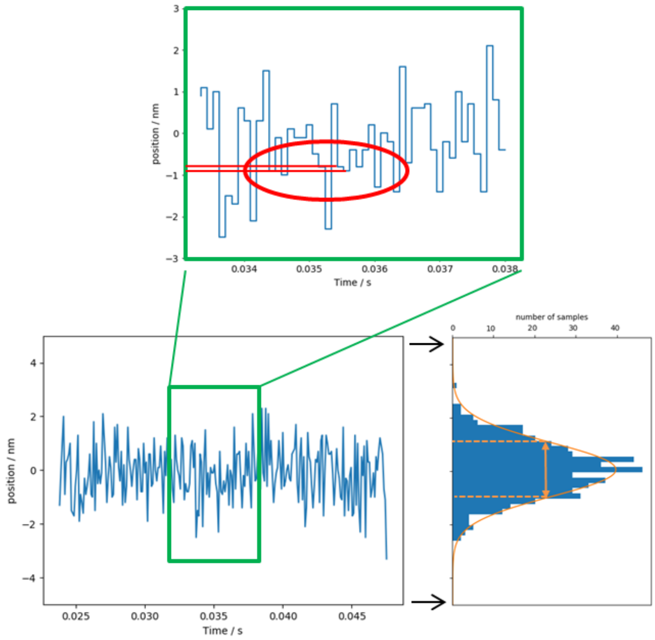

Figure 3 *Example of an internal position measurement of a positioning system. The obtained measurement data is normally distributed (bottom right). The value of one standard deviation of this position data corresponds to the value of the noise (bottom right, orange). One digital increment corresponds to the resolution (top).*

4.5 External noise

A measurement of the external noise is generally performed with external measuring equipment, e.g., an interferometer. For this purpose, the system is held at a specific position while simultaneously recording position data over a defined period (typically one second). To compensate for environment-dependent drifts during the measurement time, the data may be filtered with a high-pass filter (default: 1 Hz) or smoothed with a polynomial up to a maximum of the 5th order. If the noise is to be measured over longer periods, this high-pass filter must be adjusted accordingly. The standard deviation, which corresponds to the external noise of the overall system, is then determined from this position data.

The external noise defined here is also called "standstill jitter".

5 Minimum incremental motion

5.1 Definition

PI defines the minimum incremental motion as the size of the smallest reliably detectable steps that the positioning system is capable of executing. To determine the smallest step size for the system, PI measures a predefined number of steps in forward and backward motion. For this purpose, measurement profiles with staircase functions for different step sizes are created and commanded. The obtained measurement data is then evaluated using predefined criteria.

5.2 Measurement methods and evaluation criteria

The procedure for measuring the incremental motion and the criteria for the reliable detectability of a step are explained below.

Each staircase function is defined with a fixed step width and number of forward and backward steps. The profile ends again at the defined starting position after the corresponding steps have been completed. Ten steps are selected by default. Additional steps can be inserted which take into account any backlash and ensure that this backlash does not influence the subsequent measurement results (the backlash can be determined via a separate measurement, which will not be discussed in detail here). If backlash steps have been inserted during a measurement, this can be seen from the log. Figure 4 shows an example measurement profile with 3 backlash steps and 6 measurement steps per direction of motion.

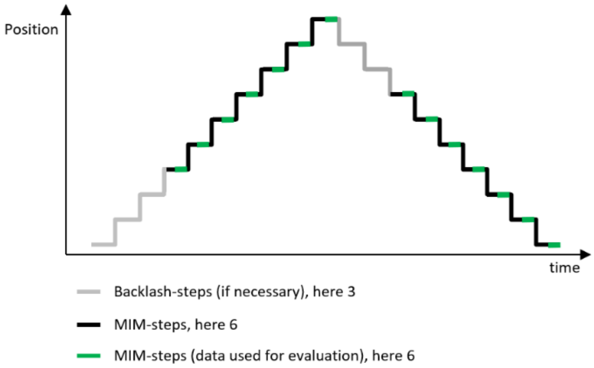

Figure 4 *Typical measurement profile for determination of the minimum incremental motion*

As standard, only the measured position information obtained during the second half of the individual steps is taken into account in the evaluation (marked in green in Figure 4). This is to ensure that the step-and-settle of the positioning axis in relation to the target position is not included in the measured value. An attempt is also made to separate factors that are already determined by other measurements, such as noise.

To determine the minimum incremental motion, the mean incremental motion and its standard deviation are first determined using the obtained measurement data. This is shown as an example in Figure 5 with 10 measuring steps and without backlash steps.

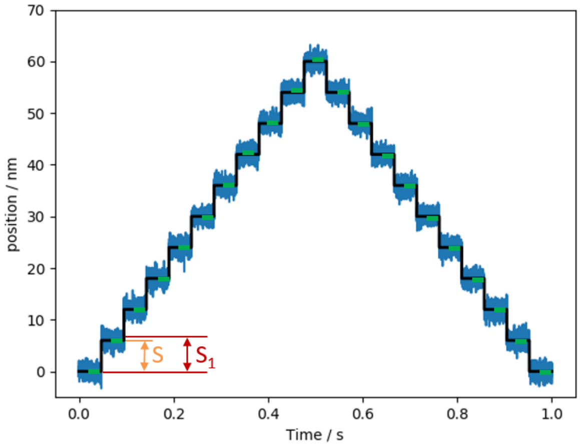

Figure 5 *Evaluation of a measurement to determine the minimum incremental motion. The target course is shown in black, the measured data in blue, and green indicates the range of the measured data that is used for the evaluation. The average size per step is shown in orange as an example. Red shows that the measured size of the first step differs slightly from the commanded step size.*

First, the incremental motion for each individual step is determined for both the forward and reverse directions, with only the area marked in green being included in the calculation. In Figure 5, the measured incremental motion for the first step is shown in red as an example. With n measured steps, this results in a data set of 2n step sizes, since the steps in the forward and reverse directions are included equally in the evaluation. The mean value of the measured step sizes SM and the standard deviation of the measured step sizes SSTD are calculated from these 2n step sizes.

The mean deviation in the incremental motion is then determined from the mean value of these step sizes:

$$\delta = (S_M - S)/S$$

Furthermore, the noise of the signal is determined. For this purpose, the raw measured values can be filtered with a low-pass filter (4th-order Butterworth filter). On the basis of this filtered data, the noise is determined separately for each individual step for the area shown in green by calculating the standard deviation. This results in the values NSTD,i for each single step i of the 2n steps.

Finally, it must be verified whether the measurement meets the requirements for the minimum incremental motion. A commanded step size is then accepted as the minimum incremental motion if all of the following criteria are met after a measurement run:

1. $|\delta| < 20\ \%$
2. 4 · SSTD < S and
3. $4 \cdot \mathrm{N}_{STD,i} < S$, for each single step i

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PI at a glance

For many years, PI (Physik Instrumente), founded in 1970, has been a market and technology leader for high-precision positioning technology and piezo applications in the semiconductor industry, life sciences; photonics, and in industrial automation. In close cooperation with customers from all over the world and for 50 years now, PI's specialists (approx. 1,300) have been pushing, again and again, the boundaries of what is technically possible and developing customized solutions from scratch. Technologies from PI achieve reproducible accuracies in the millionth of a millimeter range. More than 350 granted and registered patents underline the company's claim to innovation.

PI develops, manufactures, and qualifies all core technologies in-house, thereby constantly setting new standards for precision positioning: Piezoceramic patch transducers and actuators, electromagnetic drives, and sensors working in the nanometer range. As the majority owner of ACS Motion Control, PI is also a leading global manufacturer of modular motion control systems for multi-axis drive systems and develops customized complete systems for industrial applications with the highest precision and dynamics.

With six manufacturing sites and 15 sales and service offices in Europe, North America, and Asia, PI is represented wherever high-tech solutions are developed and manufactured.