6D precision for today’s nanometrology

WHY PRECISION AT THE NANOMETER LEVEL REQUIRES A MAJOR OVERHAUL OF LEGACY MEASUREMENT APPROACHES

Advancements in manufacturing approach and in metrology sensors have obsoleted legacy metrology motion platforms. Precision positioning systems that are based on six-dimensional motion error reductions are a must if measurements at the nanometer precision level are to be made with any confidence.

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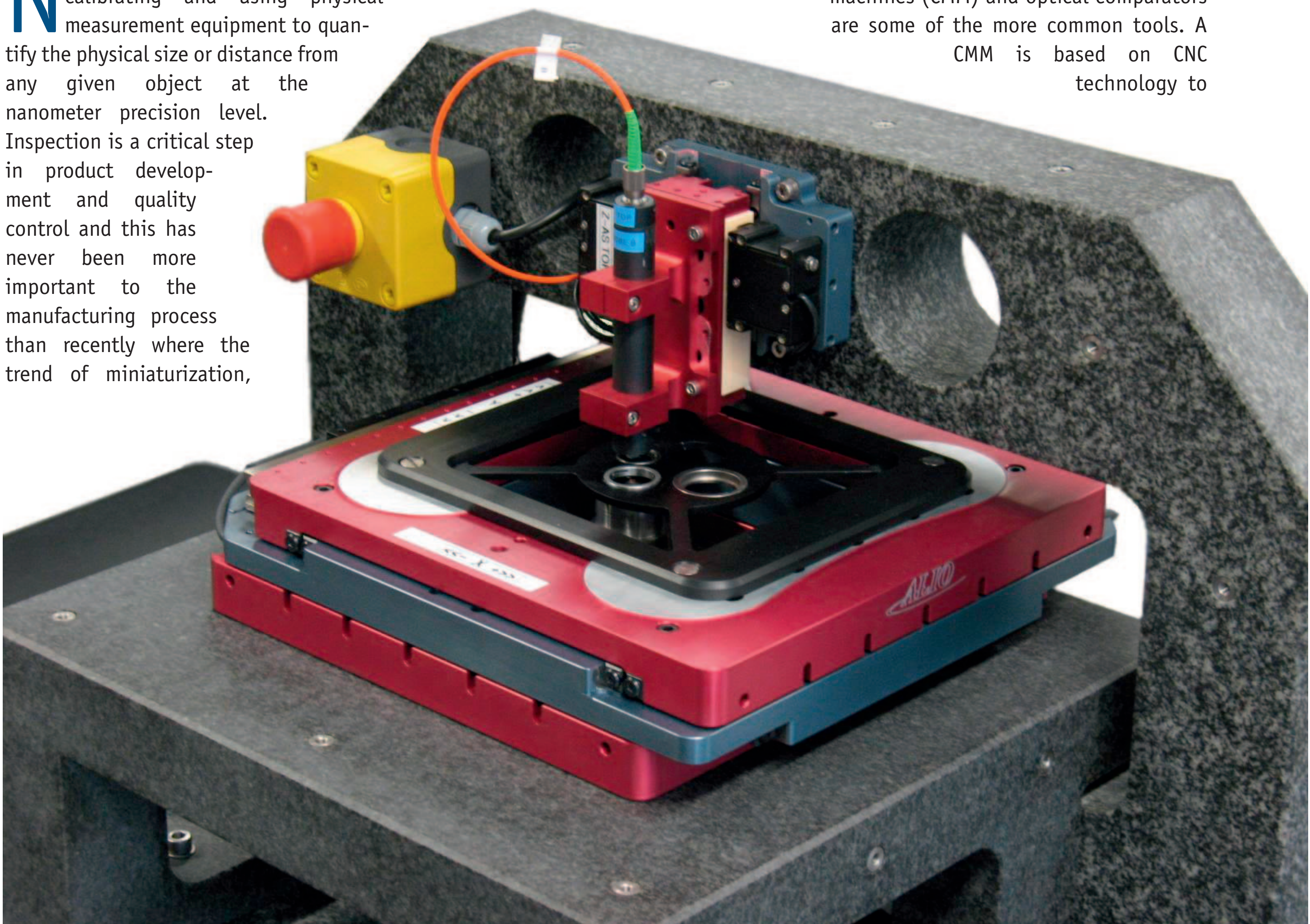
Nanometrology is the science of calibrating and using physical measurement equipment to quantify the physical size or distance from any given object at the nanometer precision level. Inspection is a critical step in product development and quality control and this has never been more important to the manufacturing process than recently where the trend of miniaturization, nanoprecision processes and precision manufacturing has challenged legacy metrology motion systems and sensors.

Legacy metrology systems

Modern measurement equipment such as hand tools, coordinate measurement machines (CMM) and optical comparators are some of the more common tools. A CMM is based on CNC technology to



automate measurement of Cartesian coordinates typically from physical contact with the part, although they can have laser and vision-based sensors. Optical comparators are used when physically touching the part is undesirable. Optical 3D (laser) scanners are also becoming more common – by using a light sensitive detector (for example, a digital camera) and a light source (laser, line projector), the triangulation principle is employed to generate 3D data, which is evaluated in order to compare the measurements against nominal geometries.

These systems, especially CMMs, have used motion systems that provide only 2D precision for the most part. They do address repeatability, accuracy and resolution, although this is actually only part of the motion performance as repeatability and accuracy are dimension-relative to a plane in space. Modern metrology systems need to be referenced to a point in space.

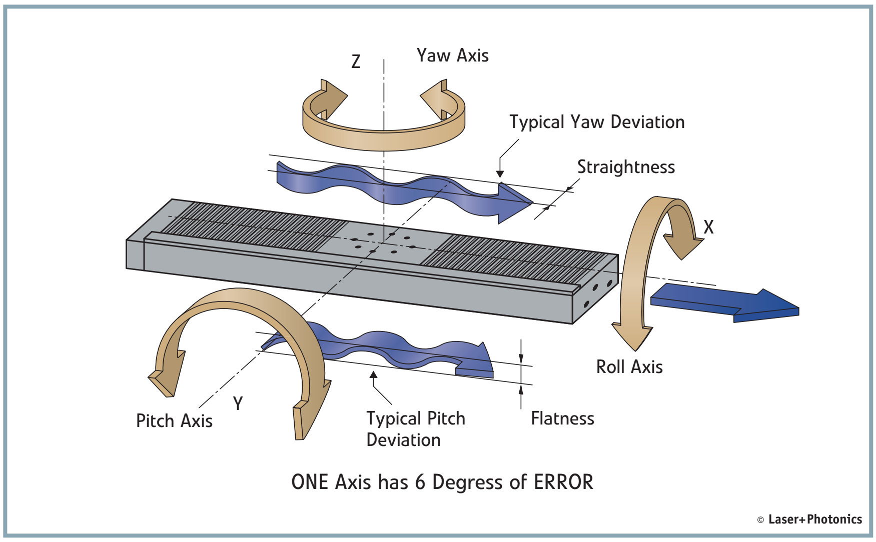
The net outcome for equipment that combines legacy metrology motion systems with the newest technology sensors, is that they often only measure the inadequacies of the motion system in trying to follow a nanometer-accurate path, not the actual object itself.

There is thus a strong need for motion systems and the kinematic models of modern measurement systems to evolve to a much higher level of precision. However, basing the approach on legacy 2D positioning technology often fails spectacularly, as the measurement tool dot size is much smaller than a traditional 2D motion systems' ability to follow a programmed path.

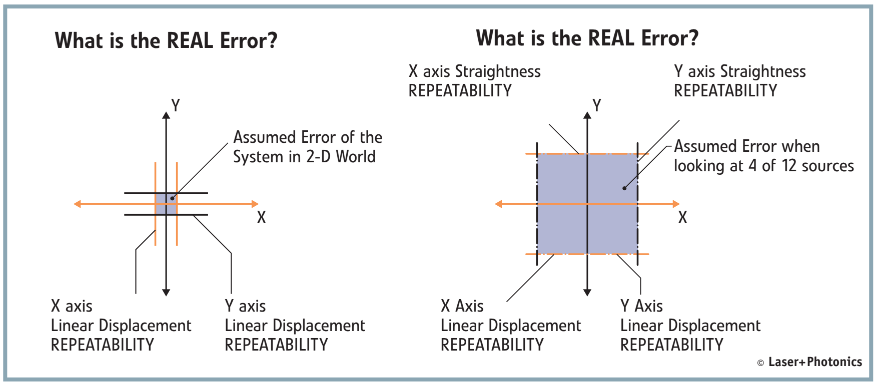
The 6D model

The correct approach to nanometrology entails visualising the point in space that you wish to measure in six dimensions (6D), as opposed to the conventional 2D thinking of a plane somewhere along the path of measurement. Critically, both motion system design and the system manufacturing approach need to be radically modified in order to meet the requisite precision demands in 6D and thus complement the capabilities of modern sensors.

One type of sensor for nanometrology is white light laser interferometer technology. These sensors (and others based on lasers) are driving metrology motion systems requirements with better than 100 nm accuracies and a 5 µm dot size (or smaller) data measurement range. The much more data will need to be collected and then manipulated with sophisticated algorithms in order to make any sense of the object measured.



1 The correct approach for nanometrology systems starts by considering the potential errors on all six degrees of freedom in any one axis



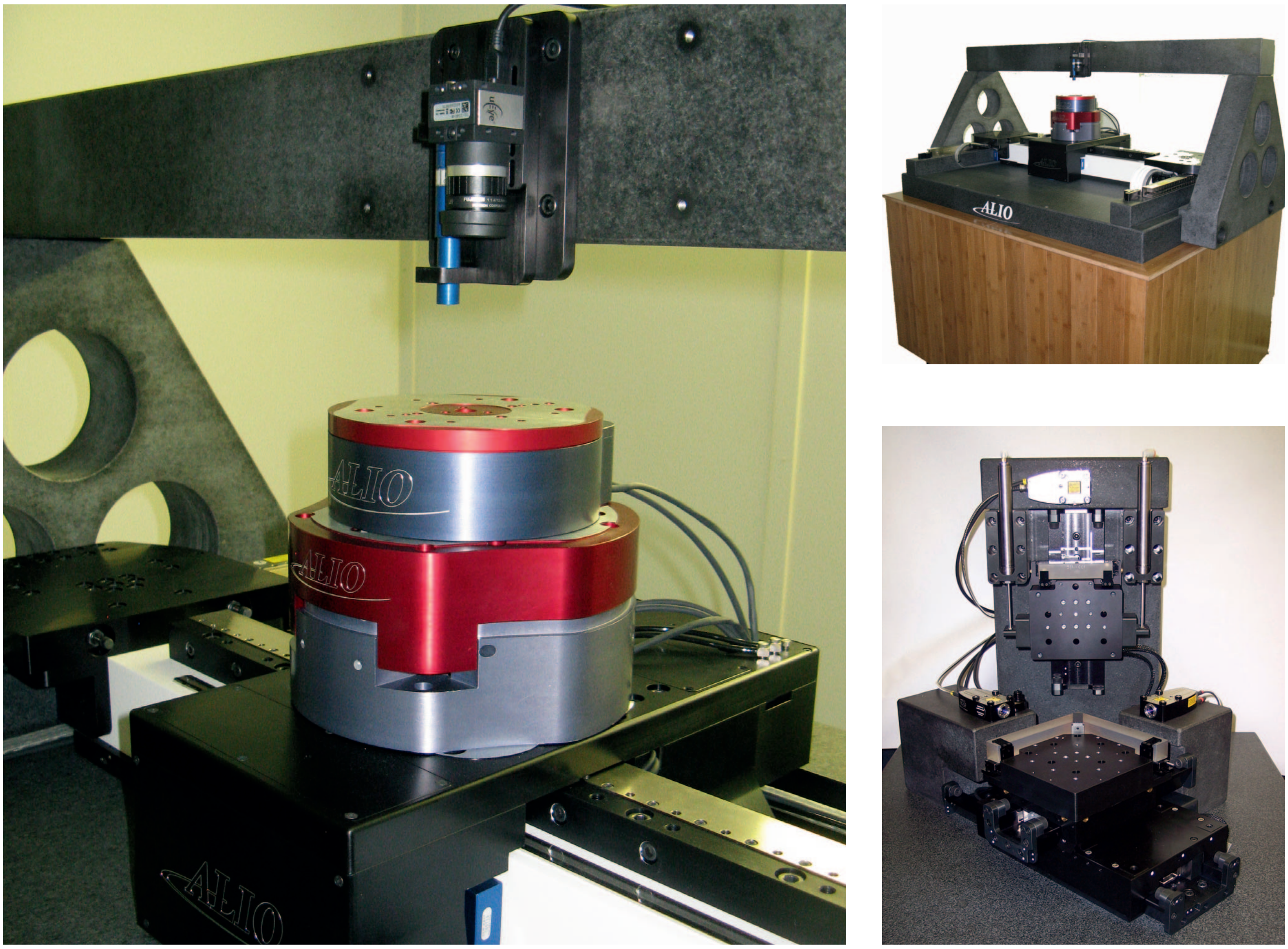
2 Comparison between the assumed and real error when considering legacy measurement systems. In nanometrology, ignoring requisite precision for the remaining degrees of freedom would result in large, underestimated systematic errors

motion systems and kinematic structure of the modern measurement systems need to have better precision than the sensors, thus the six degrees of error for each axis of motion need to be reduced from microns to nanometers. **Figure 1** illustrates the potential sources for error for a single linear axis.

To better appreciate the need for 6D precision we must understand where the point is in space that we are trying to measure. Flatness, straightness, pitch, yaw and roll of the motion system are now critical factors that require proper attention. If not, and as illustrated in **Figure 2**, the true precision at the nanoscale is much worse than that assumed in a macro 2D world, meaning that

Real world applications

Applications that benefit from this point precision are many, including, for example, the manufacture and quality control of optics for the photonics industry. In trying to measure the surface of a concave or convex surface with a 5 µm dot measurement size sensor moving in a serpentine motion multiple times back and forth across the surface, it is assumed that the motion system straightness and flatness are perfectly parallel and with no bidirectional motion errors. The reality is, however, that motion systems can have 20 to 50 µm of errors. 6D nanoprecision motion systems reduce these errors to below the 5 µm dot ▶



3 High-precision *xyzr* gantry system with air bearing positioning elements and an ultrastabile *xyz* interferometry system for measuring optics

measurement size of the sensor, thus allowing the optics to be measured and not the motion system.

6D motion systems

Now that we understand the challenges of measurement with new nanoprecision sensor technology, we need focus on the motion system and how to reduce all the errors of each axis. Nanoprecision motion systems begin with the design of a new product, from concept to component selection and especially assembly.

Figure 3 depicts, amongst others, an air bearing *xy* and *z*-axis gantry system in combination with a rotational axis on conventional roller bearings. A solid and flat granite table as well as the right choice of bearing types is critical in ensuring the requisite degree of precision and repeatability. Below right in Figure 3 is an *xyz* interferometry measurement system for optics.

In order to provide the necessary accuracy, mechanical stability is provided by massive, inflexible granite assemblies supported on appropriate high-end vibration-isolation systems. In constructing this type of system, potential compounding of systematic errors has to be minimized at every stage – during design, manufacture and assembly – in order to guarantee successful operation for the intended task.

The following is a list of critical areas that need to be considered:

- The design of the motion system structure is the critical foundation for 6D precision. Legacy designs and past design practices need to be replaced by an ›outside the box‹ look at the design, with environment, stiffness, thermal growth, assembly and quality as critical factors.
- Bearing selection should be determined on an application basis, where ultraprecise crossed roller or air bearings are the current precision standards.
- Drive systems, including amplifiers and controllers. Fundamental aspects are the speed of the position feedback system and its ability to not only move precisely to a point, but hold position without dither and minimise velocity deviation during continuous data capture.
- Position feedback systems, as based on optical encoders, laser interferometer

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and laser scales, and are application and environment dependent.
- Material selection is also application dependant, although 6061 aluminum is still the most cost-effective material if it can be machined to high tolerance without deforming the structure. Proper machining technique is a critical foundation of nanomotion systems.
- Regarding assembly, even the most precise structure can be deformed through the use of poor methods.
- Adequate characterization and testing, via laser interferometers and other NIST traceable metrology solutions, is the only way to verify all the previous steps have been completed successfully.

All of these items are very important to success in today's nanometrology world and to understand the true meaning and results of repeatability and accuracy of a system in the 6D nanoworld.

Fazit

The path to 6D precision for motion systems starts with the correct approach to the problem. ALIO design and manufacturing objectives have been focused on the nanoprecision of straightness, flatness and elimination of roll, pitch and yaw in an axis. Only by reducing these sources of error can measurements be made with any confidence.

AUTHORS

BILL HENNESSEY is Founder and CEO of ALIO Industries. ALIO Industries has been focused on 6D nanopositioning systems for over ten years and currently holds several patents, intellectual property and pending patents all based on ›6D Nano Positioning‹.

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