Sub-angstrom roughness measurements for manufacturing environments

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Demonstrating the ability to measure in any orientation, a NanoCam on a robot arm can sample a large or complex part, or an array of parts with sub-Angstrom RMS precision.

Sub-Angstrom Roughness Measurement for Manufacturing Environments

By Stephen J. Martinek

How do you measure sub-nanometer roughness on precision optical components in a noisy, shop floor environment?

Metrology of supersmooth surfaces

Manufacturers of large and smaller optics require high resolution metrology to guide their processes and assess finished quality. The challenges grow for large diameter optics, and for optics with highly polished or super-smooth and ultrasmooth (sub-angstrom) surface finishes.

In all cases, roughness metrology systems must provide 3D surface measurement data in order to highlight surface imperfections and residual machining marks from the polishing process. The instruments must also be non-contact, to avoid damage to the precision surfaces.

Optical profiling offers a non-contact, interferometry-based method for 3D, areal measurement of optical surfaces, with sub-nanometer height variation. In this paper we discuss the challenges of using optical profiling for roughness metrology in a production environment. We will show how a vibration-immune, “dynamic” optical profiler can successfully measure roughness on small and large optics, on the shop floor, in a variety of mounting configurations and applications.

Why does this matter?

To produce high precision optical components, manufacturers need to measure surface roughness with sub-angstrom height resolution. Optical systems that can benefit from these measurements:

- Large terrestrial telescopes
- Space telescopes
- Defense-industry imaging applications
- Laser gyro optics
- X-ray optics for particle accelerators
- Laser amplifier slabs
- Low earth orbit satellite imaging
- High-end film industry optical systems

Measuring in a production environment

Coping with vibration, premium space, ease of use

To control the production of optics and other highly polished components, technicians and quality engineers require rapid, in-process surface finish measurements with minimal turnaround time. Because of the noise and vibration of most production environments, however, the required measurement systems have traditionally been relegated to a metrology lab in an isolated area of the facility. Moving components to and from the lab requires significant time and risks damage to the components. Queue times for lab instruments will significantly increase production cycle times. The risks and cycle times increase dramatically for large optics, such as telescope mirrors which may be many meters in diameter.

To provide sufficient stability, traditional measurement systems are also typically mounted to highly rigid frames, often mounted to heavy granite slabs floating on pneumatic, vibration isolation pistons. The superstructure of these systems constrains the size of test components to just inches, or tens of inches, and makes them infeasible for larger optics.

Cabinet profilers typically require a quiet lab environment. Their architecture limits the size of parts that can be placed in the field of view.

Intermediate methods have not proven production capable

For some process requirements the limitation of transporting parts to, or positioning large parts under, a microscope in the metrology lab have been mitigated by creating replica impressions of the test surface, using pliable molding material. The replica can then be measured instead of the actual test piece, making it possible to assess portions of a large optic using standard equipment, or to access sides, fillets and grooves that aren't possible to position in the profiler's field of view. The process is time-consuming, which typically limits the number of measurements that can be made per component. More importantly, available replication materials have proven to have insufficient fidelity to accurately reproduce the sub-nanometer roughness of supersmooth surfaces.

Similarly, small-scale "witness samples," which are finished using the same processes as a larger test piece, have been tried as measurement stand-ins. Unfortunately, finish uniformity over the small witness sample does not reliabily translate into uniformity across a large surface. Moreover, witness samples respond differently to orbital motions and pad pressure than do larger surfaces while being polished. More conclusive, direct measurements are required, particularly for mission-critical surfaces which may be destined for space-based telescopes or the largest terrestrial observatories.

Taking metrology out of the lab

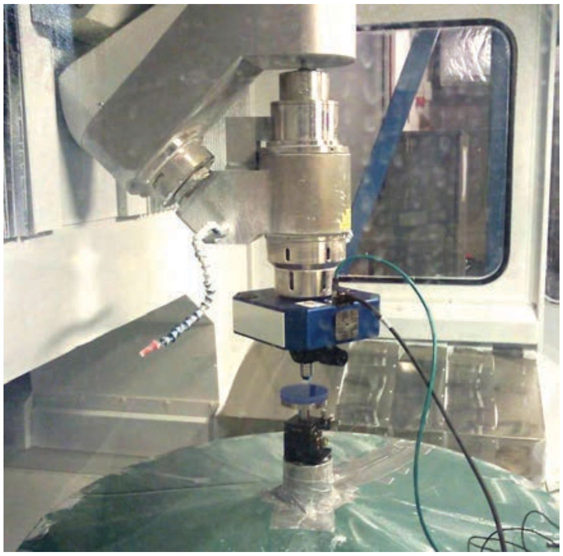
Measuring components near, or even within, production equipment potentially offers dramatic reductions in cycle time and handling risks. Only a few optical technologies can make the claim that they are stable enough to accurately measure despite the vibration prevalent on the shop floor. Moreover, production lines tend to be densely packed for optimal manufacturing capacity. Accommodating a table or cabinet for a metrology tool requires a tradeoff of premium space.

Some options, described below, offer high-resolution metrology on the shop floor with a minimum of additional floor space.

Option 1: Integrate metrology into process equipment

One compelling idea for inline process feedback is to place the measurement optics directly within the processing equipment itself. Doing so enables near-immediate feedback to control the process, with no tradeoff for production floor space.

The challenges are significant. The measurement system must be robust enough for ongoing operation in a noisy, and potentially dirty or wet environment. The system must be able to capture reliable, repeatable data despite vibration. And, it must be small enough to be enclosed within the system, while not interfering with processing.

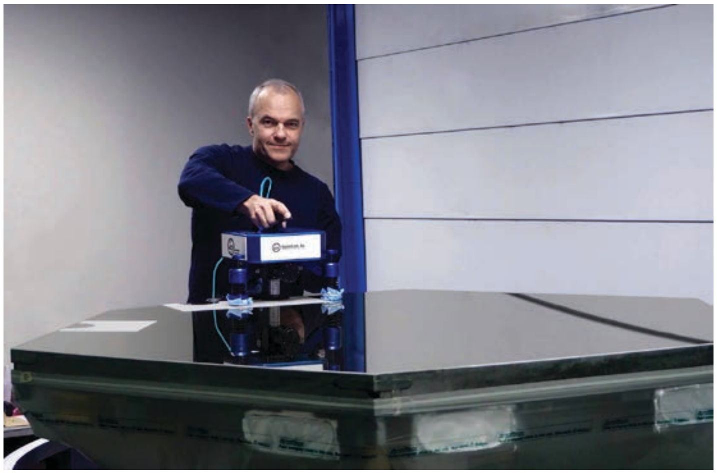


A metrology tool mounted inside a polishing station allows quick measurement between passes of the polishing process.

Option 2: Portable metrology

Another option for shop floor metrology is to reduce the size of the measurement system such that it can be placed directly on a large polished surface—such as a telescope mirror. A portable measurement device would allow measurement at any location on the part, including measuring edge-to-edge across very large optics.

To be viable, a portable profiler must be small and light enough to be safely handled and situated on the component without risk of damage to the surface. It must also be robust enough to measure *in situ* without vibration isolation. Power and data cable management must also be considered, as cables dragged across a large component can damage its surface.



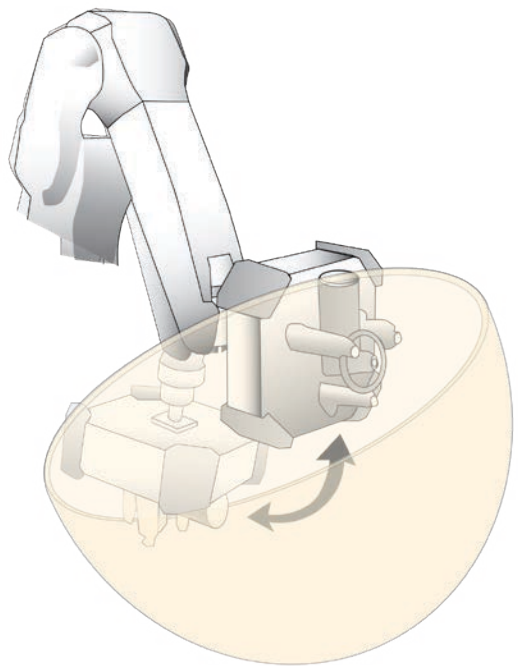
Portable, placeable metrology is convenient on a factory floor as well as on large optics. Even so, vibration immunity in the profiler, or an extremely quiet environment, is required for this to work.

Option 3: Gantry or robotic handling

A measurement head can be positioned automatically using a pick and place manipulator, an overhead gantry, or a robotic arm. All of these structures remove the risk of damaging the precision surface through contact with the instrument. It may also enable repeatable, programmable positioning over large areas, making it possible to acquire an array of measurements across the optic.

As with the previous options, vibration insensitivity, size, and weight, are all critical for this type of deployment. Additionally, a long stand-off distance (the distance from the measurement optics to the test surface) is imperative to keep the moving instrument as far as possible from fragile, costly optics.

The pick and place and gantry options are limited in the component size and surface complexity they can support. The most significant challenge is in being able to tilt the measurement head to accommodate a non-flat surface, such as a convex telescope mirror. An articulated robot arm can move a measurement system more freely; however, a long robot arm makes for an inherently unstable, vibration-prone platform, requiring the most robust metrology system for repeatable measurement.



Robotic control allows non-contact measurement of complex objects.

A portable, vibration-immune solution

Patented Dynamic Interferometry—a technique in which 3D measurements are acquired in a few microseconds—permit 4D Technology's NanoCam Sq surface profiler to measure smooth and sub-nanometer ultra-smooth finishes in production environments.

The NanoCam Sq is small, lightweight, repeatable and extremely flexible in use. It's useable on-optic, on a workstation, or attached to automatic positioning equipment such as a gantry or robot.

Compact: no bridge structure or vibration reduction required

NanoCam is small and light. Its tiny footprint fits into many different situations:

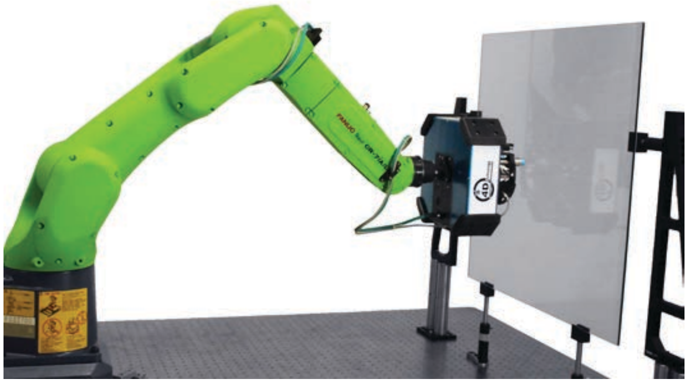
- Inside a glass polishing machine, mounted to the multi-axis polishing arm for metrology between polishing passes
- Inside semiconductor wafer processing equipment
- Directly on large telescope optics, including edge measurements and the corners of hexagonal mirror segments
- On a robot arm, measuring domes, cylinders and spherical optics
- On a lateral positioning gantry for measuring arrays of objects in production.

Fast: measure instantly, so it works anywhere

Near-instantaneous acquisition speed enables measurement despite the vibration of nearby machinery, so cleanroom air handling equipment, vacuum pumps and other equipment don't interfere with measurement. You can also successfully measure large optics for which the required vibration isolation would be so large or costly as to be impractical. Because dynamic systems are so tolerant of poor environments, components can be measured in situ at the point of processing, which limits the time, and potential damage, of additional handling.

A precision metrology benefit of fast acquisition is that multiple measurements are taken quickly, and then averaged together to remove random noise in the measurement. Averaged measurements are used to acquire the highest possible resolution data.

Nullifying the necessity for a metrology lab environment, and its related stability controls, significantly reduces the initial investment and ongoing cost of ownership of the optical profiler.



Robot-mounting a profiler, such as NanoCam, can enable measurements in virtually any orientation, and can measure complex objects.

Versatile: measure small optics through meter-class mirrors

The NanoCam is a mature and robust metrology product line with extensive mounting options, accessories and configurations for numerous applications.

A selection of Linnik objectives allows you to balance field-of-view size with lateral resolution—vertical resolution is not affected by magnification, unlike with confocal solutions. Linnik objectives provide long working distances, ensuring the profiler is kept safely from fragile surfaces. Glass-compensated objectives permit measurement through glass cover slips for use in biological research applications.

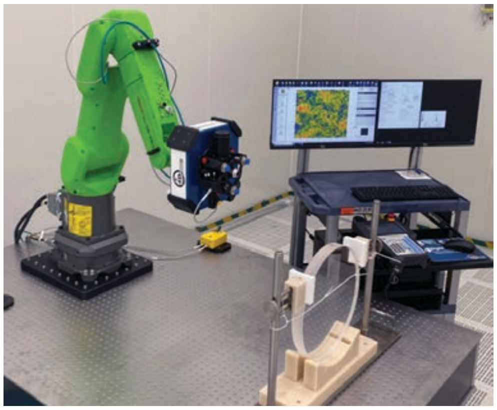
Configurations for mounting on gantries, on-machine interfaces, robot arms, or microscope columns are all options, with an established installed base for each. A tripod, with motorized or manual leveling, can be used for hand placing the profiler wherever you need to measure.

Ease of use features minimize the effort to obtain a highly precise measurement. Autofocus minimizes the need to make adjustments on the device, permitting remote operation with high-quality, operator independent results.

Assured precision

The 4Sight software that runs the NanoCam includes an array of analysis tools specifically geared toward roughness measurement in a production environment::

- 3D roughness and polish analysis with sub-angstrom (<0.1nm) precision
- ISO 10110, ISO 25187 and ASME B46.1 compatible parameters
- Intensity adjustments, to accommodate a wide range of surface reflectivity
- Instrument Transfer Function (ITF) verification to confirm system performance
- Robot interface API, integrated into the 4Sight software
- A 5Mpx data sensor ensures highest lateral resolution can be obtained from the instrument



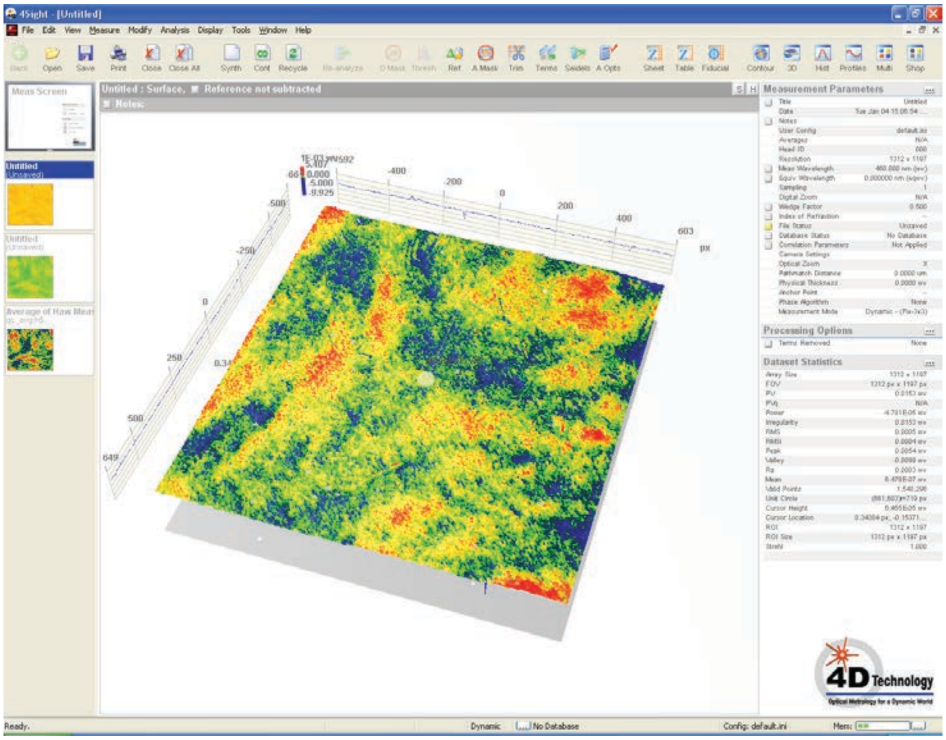
Measuring optics of a variety of sizes, at numerous points across their surface becomes faster and more automated with robotics.

Measuring and analyzing

4Sight Focus analysis software provides key analysis reporting and data visualization.

The software calculates standard roughness parameters, builds 3D plots and 2D profiles, and offers dozens of tools for visualizing, filtering, and exporting surface data. Built-in reference generation, with reference subtraction, ensures the highest precision in measurements, regardless of the objective. Automatic measurement averaging functions ensure high quality data without a lot of setup work. Export data in many standard file formats, including .4d, .opd, .dat, text and tabular.

NanoCam measures roughness (smoothness) with sub-angstrom RMS precision.



3D data modeling, alongside reported surface results.