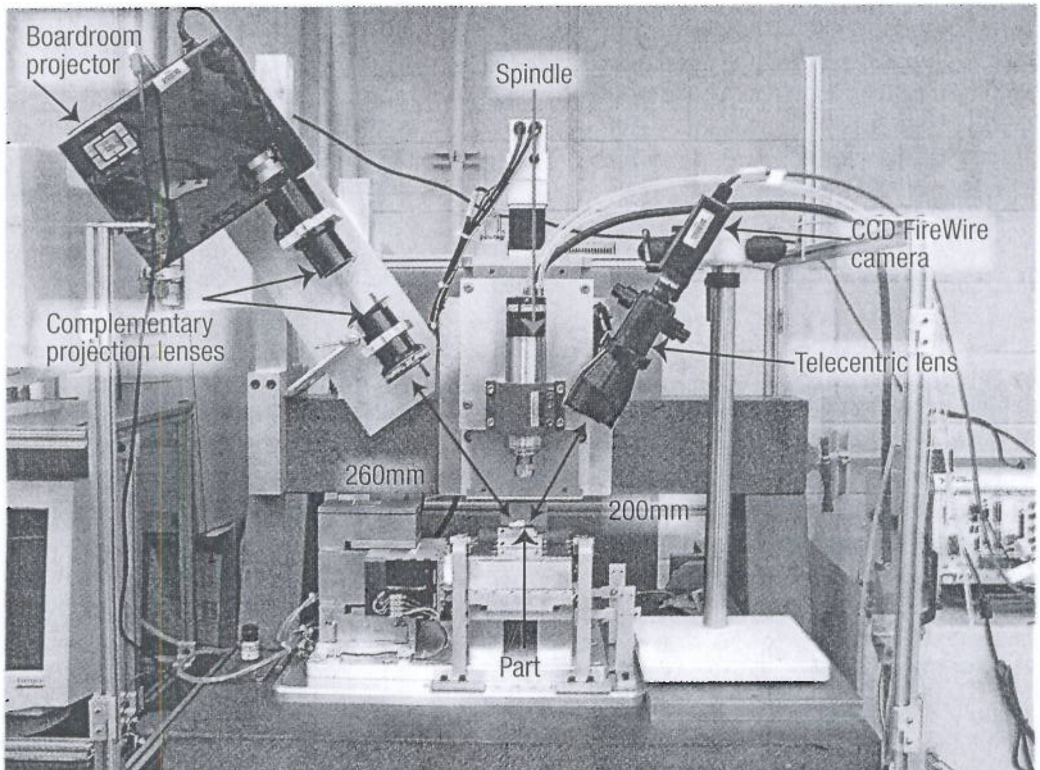
Complete Inspection

In-situ system enables 100 percent inspection of microparts

By Dr. Shawn Moylan, NIST*



All images: NIST

NIST's experimental measuring system is designed to allow parts to be measured on micro/meso machine tools.

In-situ, or on-machine, metrology can improve discrete part manufacturing markedly because it allows for 100 percent inspection without removing the part from the production line. In addition to saving space by eliminating the need for a separate metrology station and time by not having to reposition the part for measurement, on-machine metrology has many additional benefits, particularly in the realm of micro/meso (m/m) manufacturing.

The small sizes and fragility of m/m features and parts present unique metrology and handling challenges. Small errors in part registration not only increase measurement uncertainty, but also may make finding tiny part features time-consuming. Micro/meso parts can present difficult fixturing scenarios, often requiring expensive custom fixtures. All of these problems can be avoided if the part is registered once for machining and remains in place, in the same fixture, during machining and measurement.

Because the part is measured without removing it from its registration on the machine tool, measurement results are better correlated to machine tool errors. Some measured errors can be corrected immediately by the user or the controller. Further, measured-error magnitudes can be used for machine tool-condition monitoring. The measured and logged errors can be used to improve machining accuracy on subsequent parts. Trends in the data may indicate when machine maintenance is needed. These qualities make an m/m machine tool with on-machine metrology more of a "smart"

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machining system.

A major challenge for on-machine metrology is decoupling machine tool errors from measurement uncertainty. No machine tool is perfect and machine tool motion errors, which produce part imperfections, have largely been found to be systematic. If the same machine again moves to perform the measurements, the systematic error motions repeat, obscuring part imperfections from the measurement. This is a significant obstacle and, if not properly addressed, will defeat any advantages on-machine measurement can offer.

The growing demand for smaller parts has led to the development of new m/m machine tools significantly smaller than their macroscale cousins, and often with different designs. An on-machine measurement device would need to operate within the confined work volume of any m/m machine tool, often just 25mm × 25mm × 25mm. Just as m/m machine tools vary in design, m/m parts can vary greatly in both size and shape. Entire parts can be as large as 25 cu. mm and can contain many features smaller than 100µm.

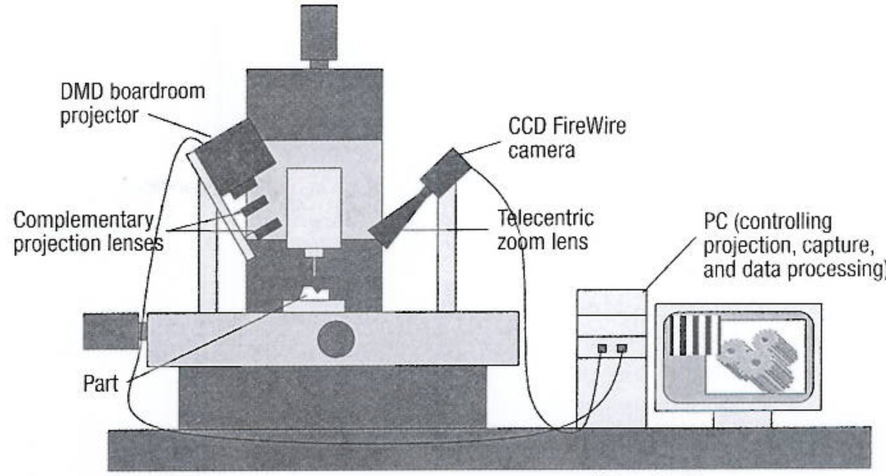


Figure 1: The experimental measuring system incorporates off-the-shelf components, none of which cost more than $2,500.

An on-machine measurement device should accommodate measurements that encompass this entire size scale and should meet the accuracy requirements.

Fringe projection

One approach to on-machine metrology under investigation in the Manufacturing Engineering Laboratories at the National Institute of Standards and Technology uses fringe projection, or structured light.

Fringe projection is based in photogrammetry—the art and science of obtaining reliable information about physical objects through processes of recording, measuring and interpreting photographic images and patterns [1-5]. Specifically, a branch of photogrammetry known as stereovision allows 3-D information to be extracted by analyzing 2-D images obtained from at least two views (more views can be added if desired to increase system robustness). Triangulation of a single, common distinguishable point between the two images allows the determination of X, Y and Z coordinates. These common points are termed correspondence points and the mathematics involved is known as the "stereo correspondence problem."

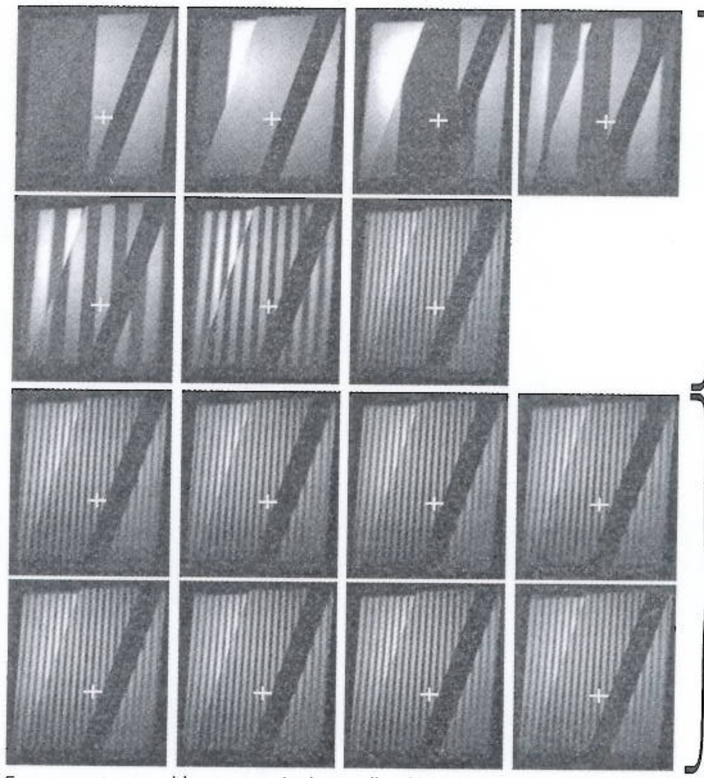
With fringe projection, unlike stereovision, a projector replaces one of the cameras in the typical stereovision setup. With stereovision, multiple images are analyzed and correspondence points are often determined manually (and can have large uncertainty). A projector is simply an inverted camera, both physically and mathematically. With fringe projection, the mathematics to determine the X, Y and Z coordinates is the same as with stereovision [1, 2, 4]. However, the projector projects patterns onto the scene captured by the cameras, allowing correspondence points to be determined automatically through simple image analysis techniques (see sidebar below).

Fringe projection is intriguing for on-machine metrology at the micro/meso scales because some of the process strengths—setup flexibility, large field of view and long working distance—directly address obstacles to on-machine metrology. The setup for fringe projection is very

Best fringe projection option for on-machine metrology

A MAJOR SOURCE of uncertainty in stereovision is the determination of correspondence points. This determination requires points of reference captured by all images, and is often done manually. In fringe projection, a projector projects patterns onto the scene captured by the cameras. This allows the pattern to act as the reference and the determination of correspondence points can then be automated.

There are many different pattern types and schemes used in fringe projection applications, but the scheme most appropriate for on-machine metrology is the combination of grayscale patterns with pattern shifting [2, 3]. Correspondence cannot be determined with only one pattern because the part's contours may obscure areas of the pattern from the cameras. With grayscale patterns, a set of seven patterns with increasingly fine fringes are projected onto the part in sequence, one after another. When analyzing the captured patterned scene, the sequence of a specific point's intensity values reveals from which projector pixel that ray of light emanated.



Seven patterns with progressively smaller fringes. The finest fringe pattern is shifted eight times to improve resolution.

The figure here shows an example of how grayscale patterns work. The point highlighted with the cross in each image is 360 pixels from the left and 410 pixels from the top of each image. Thus, the coordinate of this point in the camera frame is (360, 410). In the first image, this point is in the brightly lit portion. This point is given a value of 1 for this image. In the next image, the point is again in the bright region, providing another value of 1. In the third image, the point is in the darkly lit region, and it is given a value of 0. This continues for the next four images, producing a sequence of 0s and 1s. In this example, the sequence is 1100101, and it is unique to one particular fringe in the finest fringe pattern. In this case, the center of that fringe emanated from a point 580 pixels from the left of the pattern. As such, projector point 580 corresponds to the camera point (360, 410). This, combined with calibration, provides sufficient information to solve the stereo correspondence problem.

With grayscale patterns, however, resolution is limited to the size of the smallest projected fringe. Because better resolution is required, pattern shifting is used in addition to the grayscale patterns [3, 5]. By digitally shifting the finest fringe pattern, the projector point can be determined within one fringe. With a shifting technique, the specific projector fringe cannot be determined unambiguously, but the distance to the right or left from the center of the fringe can be accurately determined.

For the current application, the finest fringe pattern is shifted one pixel to the right eight times, using the entire resolution of the projector. Here, the sequence of 11100000 means the point is two pixels to the left of center, or projector point 578.

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flexible, meaning measurement can be accomplished with system components in a variety of positions.

Flexibility within a single machine means the process can adapt to a variety of part and feature shapes and sizes (though measurement uncertainty will change with different fields of view). In general, flexibility means the process can fit a variety of machine tool shapes and sizes. Many other on-machine measurement setups utilize spindle-mounted measurement devices that limit the flexibility and adaptability of the processes.

Digital projection and imaging can easily scale fields of view to envelop the entire feature or part being measured. This means the entire part can be measured without any movement of the machine or the measuring device. Because the machine does not need to move, coupling between machine tool errors and measurement uncertainty is avoided. Other microscope-based optical measurements often do not have a large enough field of view to measure the entire part at once. These processes require many measurements to be stitched together, introducing an additional source of measurement uncertainty in the stitching algorithm.

The working distances of fringe projection components are long, isolating them from the harsh machining environment. This eliminates the risk of damaging the measurement system during machining. Spindle-mounted measurement setups require continual mounting and removal of the device, introducing yet another source of measurement uncertainty.

System setup

An illustration of the experimental NIST on-machine fringe projection setup is shown in Figure 1 on page 38. The projector is a standard boardroom model with a resolution of 1,024 pixels × 768 pixels. The projection technology is DMD (digital micromirror device). This projector was chosen over an LCD (liquid-crystal-display) device because DMDs project darker blacks than LCDs, an important aspect of the patterns used in this setup. The camera is a FireWire CCD (charge-coupled-device) array with a resolution of 1,392 pixels × 1040 pixels.

At the outset of the project, it was decided that the on-machine measurement system should be able to measure typical parts produced on NIST's m/m machine tool platforms. This meant that feature and part sizes ranging from tens of microns up to 25mm would be measured. This choice dictated the choice of lenses for the system. The large image emanating from the boardroom projector is scaled down to the appropriate size by a complementary lens system. The lenses are from a lens system that is split to achieve the level of demagnification needed. When separated by 75mm, a 25mm-wide image is obtained 260mm from the front lens. Because the camera images the part from a relatively large angle, a telecentric lens was chosen. A telecentric lens provides a greater depth of focus and, more importantly, the image is not distorted if points on the imaged surface are different distances from the lens. A telecentric lens with 0.16× magnification and a working distance of 200mm provides the appropriate field of view.

A commercially available software package was chosen to coordinate the pattern projection and image-capture process, as well as the image analysis and mathematical computations. Fifteen images (see sidebar on page 39) can be projected and captured within 4 seconds, allowing a 0.25-second settling time for the projector and camera between projected images.

The setup was made from relatively inexpensive, off-the-shelf components. Software was the most expensive system component. Otherwise, no component in the system used by NIST cost more than $2,500.

Early results from the on-machine fringe projection system show promise—and room for improvement. The fringe projection system successfully measured a step height of about 102μm (0.004"). Figures 2 a and b illustrate the results, showing a measured step height of 106μm. The standard uncertainty in the determination of an individual point's coordinates is approximately 10μm laterally (in the X and Y directions) and 16μm vertically (Z direction) [6].

Overcoming limitations

A troublesome limitation of fringe projection is its inability to measure reflective surfaces. For the measurement to function properly, the projected pattern must be in view of the camera. With diffuse or matte surfaces, the projected light is scattered by the surface, sending the light in all directions, including toward the camera. However, with a reflective surface, the light is reflected in only one direction. If that direction is not toward the camera, the pattern will not be seen and the measurement cannot take place. The current solution to this problem is to thoroughly clean the surface and apply a temporary, nonreflective coating (often white).

Ongoing research is aimed at improving the speed and uncertainty of the measurements. It is advantageous to use multiple views of the part for one measurement; this requires multiple cameras and potentially more than one

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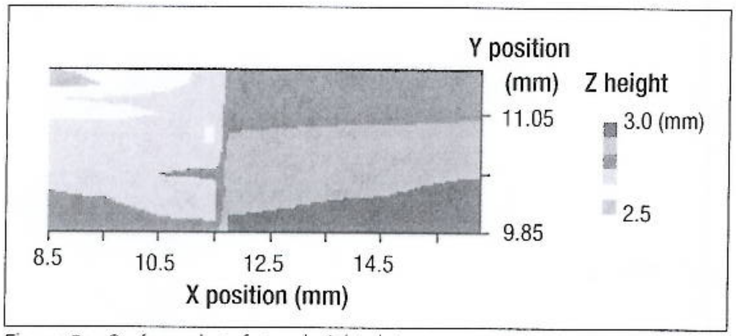

Figure 2a: Surface plot of step height data.

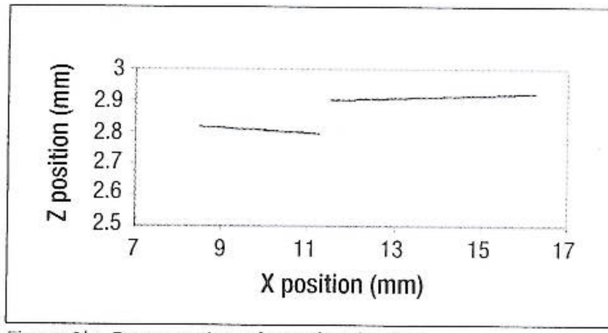

Figure 2b: Cross section of step height data.

projector. However, additional data will require higher data processing speed and efficiency.

The measurement uncertainty is larger than desired for a m/m measurement process. One of the limiting factors for uncertainty comes from the projector's resolution. Recent improvements in projector technology indicate that smaller projectors with better resolution will soon be available. Also, different pattern-shifting techniques may also reduce the uncertainty in determining the projector correspondence points.

The primary contributor to measurement uncertainty comes from the camera and projector calibration process. A calibration target with a greater number of more precisely known features will quickly reduce measurement uncertainty. Alternatively, self-calibration of the setup with every measurement may be an option. Using horizontal fringes in addition to the vertical fringe grayscale patterns allows determination of the X and Y projector correspondence points. This additional coordinate makes the system overdetermined, allowing the system's calibration to be done at the same time as the measurement. In photogrammetry, this practice is called "free network bundle adjustment" [7].

There are trade-offs in any measurement process, including fringe projection for on-machine measurement. However, the on-machine fringe projection process at NIST demonstrates the concept's potential with m/m machine tools. µ

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