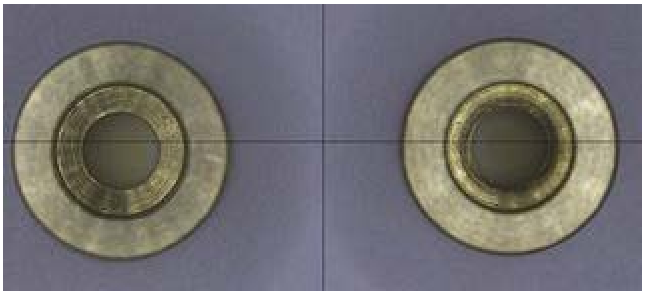
USING TELECENTRIC OPTICAL SYSTEMS TO OPTIMIZE INDUSTRIAL IMAGE ACCURACY AND REPRODUCIBILITY

How to eliminate hidden errors in manufacturing

Introduction

When the first multi-lens microscopes were invented in 1590, scientists marveled at their new ability to see small objects and features in the natural world that were previously invisible to the eye and therefore seemingly nonexistent. With the constant miniaturization of parts and products in automated manufacturing over the past five decades, the use of microscopes has spread increasingly from science to industry. Today microscopes are found in a multitude of assembly and inspection applications wherever visualization and measurement of miniscule features are required.



The images now available to us are large, sharp and brilliantly illuminated. With such impressive imaging it's easy to assume that the displays we see are dimensionally accurate, but this is not necessarily so.

When studying a point whose distance from the lens is not precisely known or that is not located directly on the optical axis of a microscope's lens system, fundamental principles of optics can introduce distortions that lead to observational and measurement errors.

Standard optics can be sufficient for inspection of very two-dimensional objects such as the traces on a printed circuit board, or for qualitative analysis of non-flat objects. However, for precise measurement or comparison of features on a three-dimensional object, such as the curved surface of an injection molded part, such errors are problematic.

Choosing a microscope with the right optics can reduce these hidden errors considerably to provide results that are both more accurate and more reproducible – two attributes that are both essential in modern inspection and optical measurement.

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Types of error

Magnification error

Magnification error is a phenomenon in which an object placed in front of the objective appears to be smaller or larger than the same object placed closer or farther away (Figure 2). This error is commonplace in microscopes using standard optics. It comes into play when attempting to repeatably measure a series of objects that are not at a consistent distance from the objective lens or when measuring multiple features that are at various heights on a very three-dimensional product.

Magnification error reduces the accuracy of measurement of features and can cause an inspector to fail good parts or pass bad ones, leading to increased rework and scrap costs at the assembly level. It also reduces reproducibility of results when the distance from the sample to the lens varies, such as with handheld inspection, re-inspection after rework or re-inspection after an assembly step that changes the height of the sample.

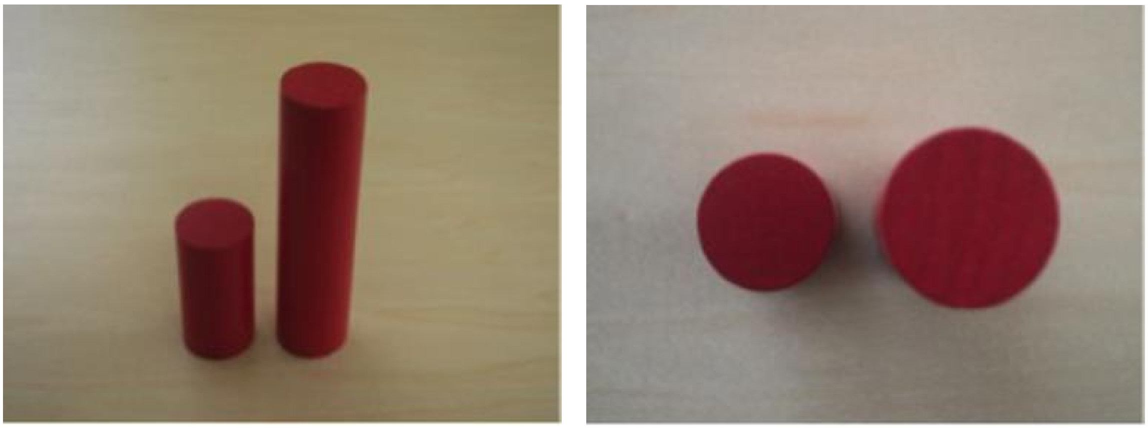

Fig. 2: An example of magnification error using two dowels of same diameter but different height. Perspective view shows relative size (left). In top view of the same items (right), the taller dowel appears to be larger because it is closer to the lens.

Zoom-related error

Magnification error also causes a secondary error when using a zoom function. Zooming and focusing in non-telecentric lenses can cause unintended and uncontrolled variations in magnification. This reduces the measurement accuracy of the inspection.

Manual "free zooming" has an additional negative impact on reproducibility. Reproducibility is defined as the ability to return to the same settings for repeated tests and to reliably repeat an examination at a later date with the same results. Since it is routine for inspection stations to switch back and forth between setups for many different parts and assemblies, high reproducibility is key. Reliably returning to the same test settings with manual free zoom is very difficult and the resulting human variation can lead to inconsistent measurements from one test to the next.

Parallax error

Parallax error (also known as perspective error) is caused by magnification error when viewing objects that are highly three-dimensional or when comparing objects that are at different heights in the optical path. Points in the field of view that are vertically aligned in reality appear to no longer line up.

This error is created when looking at the object from an inclination (non-perpendicular) angle (Figure 3). A common example in microscopy is the apparent movement of a reticule in an optical sight relative to the sample under test when the user moves his/her head from side to side. The same effect can be seen when measuring a feature on a sample by holding it in front of or behind the edge of a ruler or the jaws of a caliper, causing a height mismatch between the object and the measuring device.

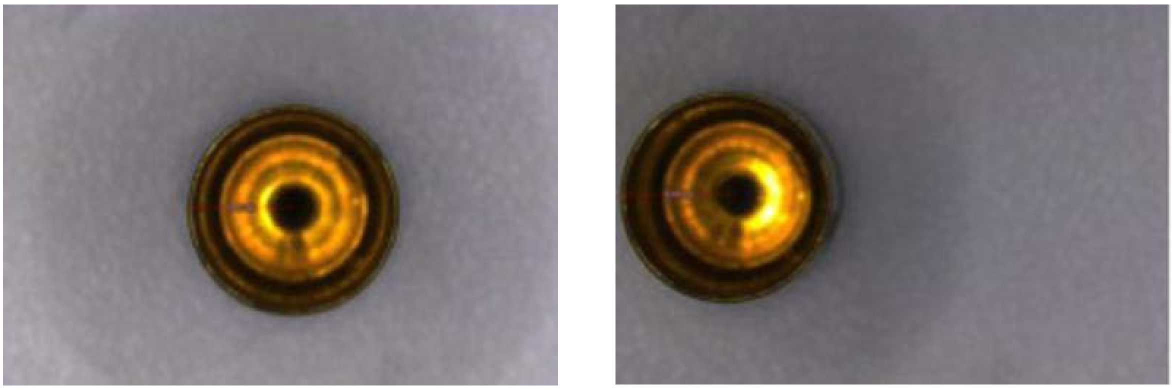

Fig. 3: Parallax error causing measurement inaccuracy. In left image, cartridge case is centered in field of view and on-screen measurement reads 4.62 mm from center of hole (far from objective) to edge of case (close to objective). In right image, same measurement is taken off-center and reading changes to 5.12 mm.

Parallax error also causes features that stand proud from the product's surface to appear to lean away from the optical axis (the center of the field of view). The direction and magnitude of the apparent lean varies with the position of the feature within the field of view (Figure 4). This distortion makes reproducible testing difficult to achieve unless the sample is fixtured to be placed in exactly the same position each time.

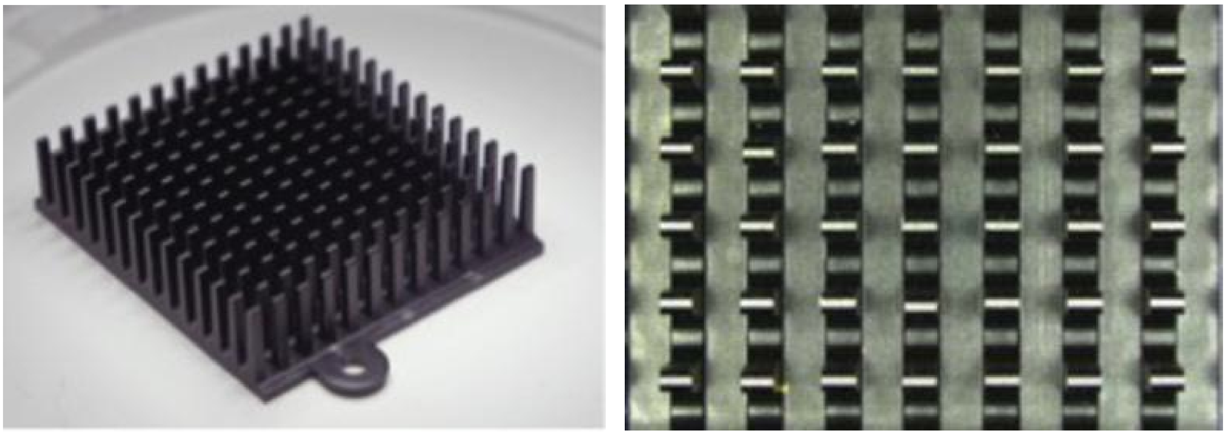

Fig. 4: Parallax error causes tall features (left) to appear to lean away from the center of the field in top view (right).

Telecentricity in modern microscope design

With so many errors hidden in the optics of standard microscopes, it may seem impossible to reliably inspect anything requiring quantitative reporting. However, careful consideration of a microscope’s optical design can avoid this problem. For example, some microscopes are available with telecentric optics that eliminate or dramatically reduce inaccuracies and loss of reproducibility caused by magnification error, zoom and parallax.

Telecentric lenses have existed for decades, but through the 20th century were labeled as "exotic" and sidelined to fringe applications. The technology first gained widespread use in the last ten years with the expansion of machine imaging and vision-based quality control measurements in industrial manufacturing.

Telecentricity is a feature of an optical system in which all chief rays (the center ray of each ray bundle) passing through the system are very nearly collimated and parallel to the optical axis. An optical system can be telecentric in the image space (the eyepiece/camera side), the object space (the objective side) or in both. Telecentricity is achieved by placing an optical stop (an opaque screen with a small hole in the center) at the back focal point within the compound lens (Figure 5).

In simpler terms, when viewing an object through a telecentric lens, the viewer is looking "straight down" on all points in the field of view. In contrast, with non-telecentric optics the viewer looks straight down only at the very center of the field of view and at an angle at all off-center points.

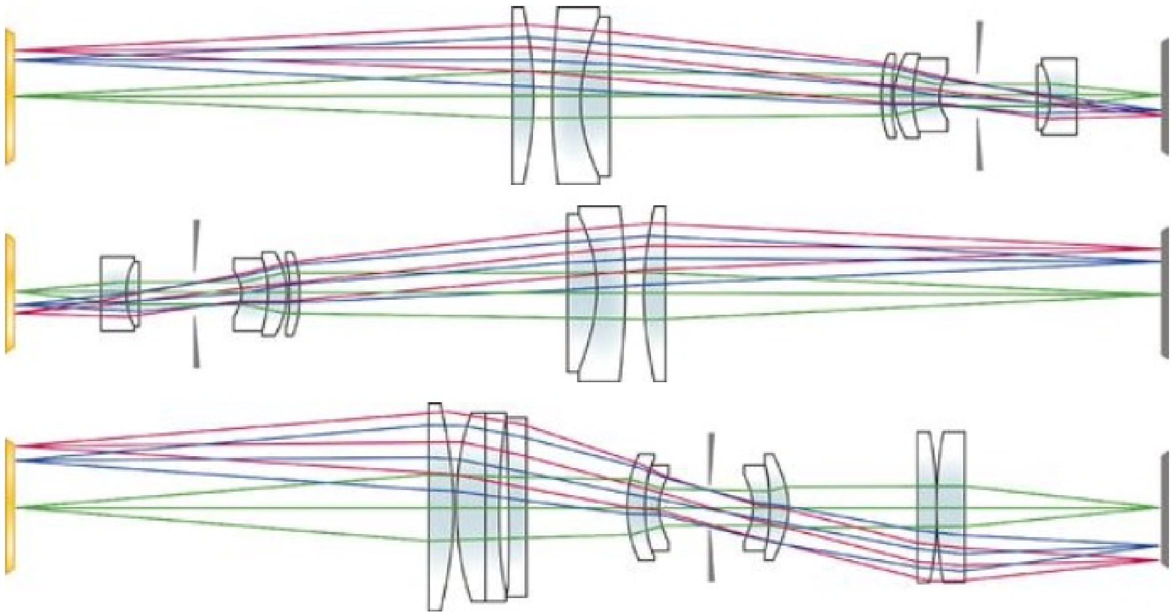

Fig. 5: Ray trace diagrams of telecentric optical systems. Chief rays are parallel to the optical axis in the object space (top), the image space (middle) or both (bottom).

Advantages of telecentricity in the object space (objective side)

Designing a microscope for telecentricity gives the system several optical properties that are highly beneficial for measurement accuracy, reduction of distortion and reproducibility of results.

Constant magnification

The most important property of the telecentric optical system is constant magnification with varying distance between the sample and the microscope objective. This concept can be difficult to grasp because we don't see telecentrically. To the human eye, closer objects appear to be larger than ones further away. This works well for normal viewing, but when creating images of products which must be precisely measured and reliably repeated, constant magnification is crucial.

Constant magnification provides better repeatability when inspecting samples of different heights because the apparent size of the object does not change with its distance from the objective lens (Figure 6). It also enables more accurate measurement of complex 3-D shapes, such as a large part whose surfaces are also at varying heights.

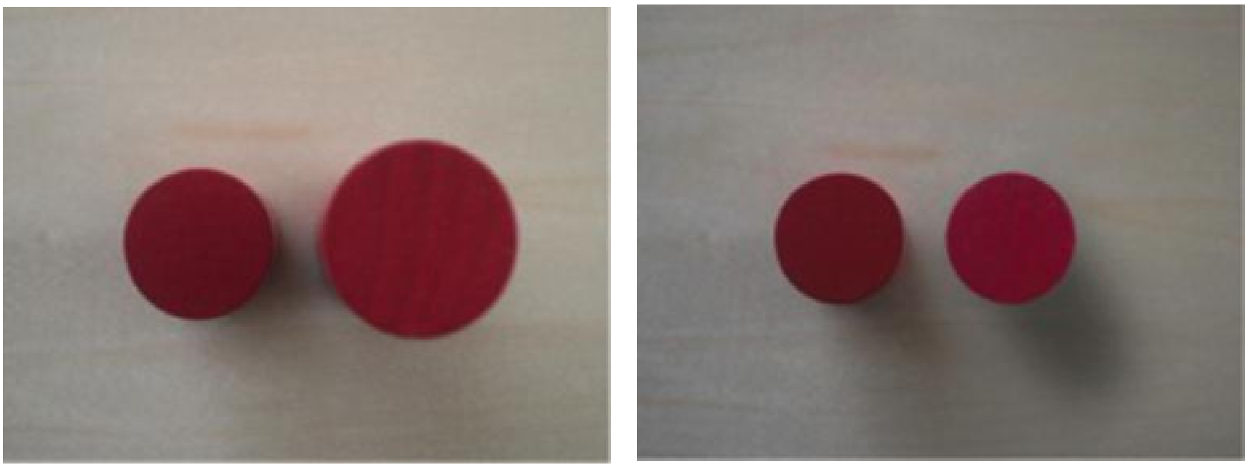

Fig. 6: Objects of same diameter at different distances from the lens (from Figure 2), as seen through standard camera optics (left) and telecentric camera optics (right).

When measuring features using a reticule or on-screen graticule, constant magnification ensures that the distance between points on a tall feature doesn't appear artificially greater than the same distance on a low feature. It also provides better reproducibility when re-viewing a sample previously viewed at a different height.

Improved zoom

A critical benefit of constant magnification is that it enables repeatable and accurate zoom function. By virtually eliminating magnification error, telecentric lenses minimize the unintended and uncontrolled variations in magnification caused by movement of the objective when zooming and focusing. This greatly improves optical measurement accuracy. When coupled with a click-stop mechanical positioning feature or encoded zoom, telecentric lenses can provide zoom functionality which is both accurate and highly repeatable.

Symmetric blurring

With telecentric optics, features on a sample can be accurately measured even if they are out of focus because objects that are not at the point of best focus blur symmetrically. This holds the centroid position constant and allows for accurate location of features and edges without distortion. This removes the requirement on the user to keep all points on the sample in simultaneous focus.

No parallax error (perspective error)

The elimination of parallax error is critical to achieving results that are both accurate and reproducible when examining objects that are highly three-dimensional, such as when measuring small features at various points on a large part (Figure 7). Using telecentric optics ensures that the apparent shape and location of features on the object do not vary if the piece is moved to a different location in the field of view (or if the piece is removed and inspected again later at a different location).

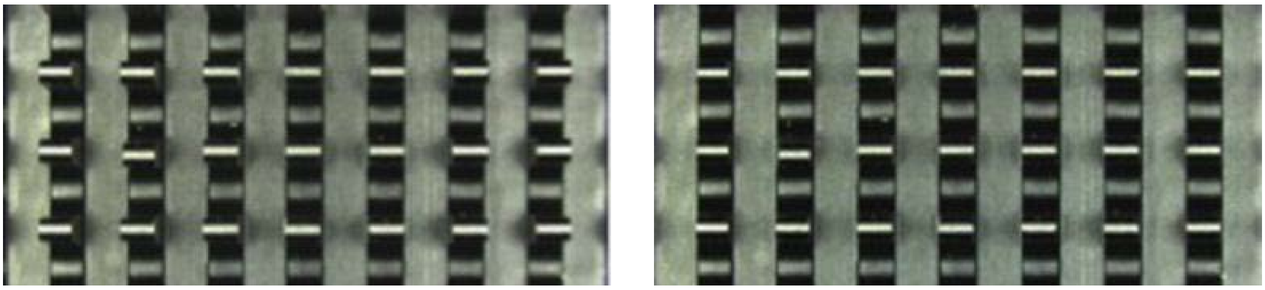

Fig. 7: A comparison of tall features (from Figure 4) as viewed through standard optics (left) and telecentric optics (right).

Equal sightlines to all points in the field of view

With standard optics, the line of sight is perpendicular to the inspection plane only in the center of the field of view, with all other points viewed at an angle. This means that low-lying features that are not centered in the field of view can be hidden by neighboring tall features. Since telecentric optics are designed to look straight down at all points in the field of view, these problems are eliminated. This enables visualization of challenging points such as the inner diameters of two parallel tubes that are spaced far apart, or the bottoms of deep holes that are off the optical centerline (Figure 8).

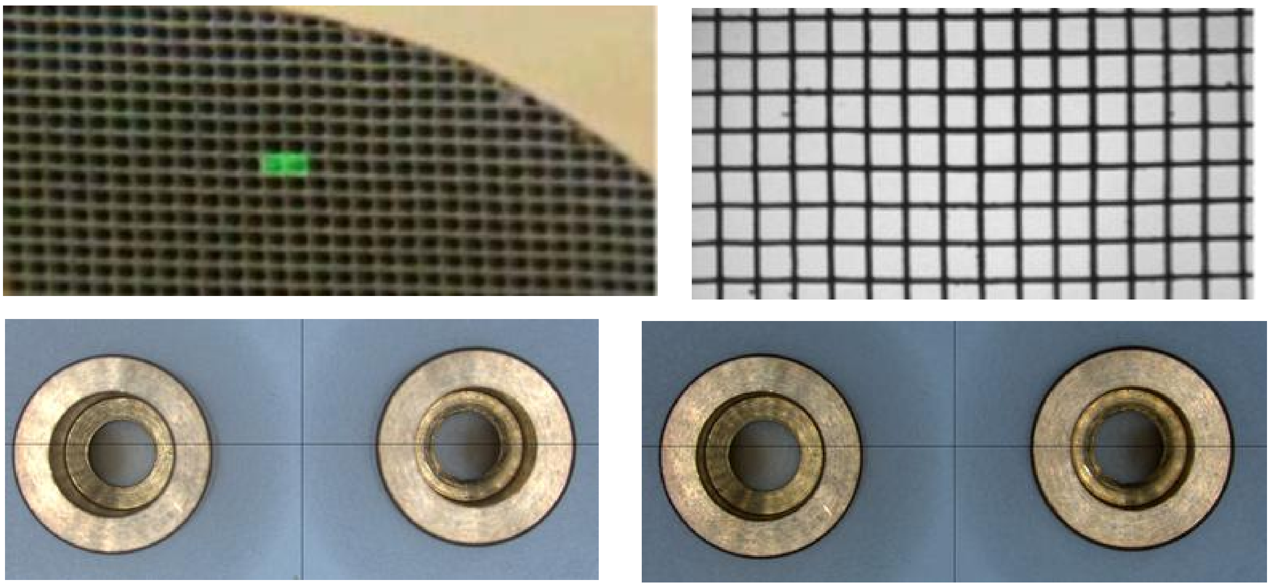

Fig. 8: A comparison of views of challenging shapes as seen through standard optics vs. telecentric optics. Sightlines to the bottoms of the deep holes are partially obstructed by the top edges of the holes when viewed off-center with standard optics (left). When viewed with telecentric optics (right), the entire surface of the bottom of the hole is visible.

Alternatives to telecentric lenses

Software

It is a common misunderstanding among users of equipment with telecentric optics that there is a software mechanism adjusting the image to achieve constant magnification and other error reductions. Although it is possible to do some of this, many of the advantages of telecentric lenses cannot be accurately reproduced by software.

Certification and calibration of optics

Another common misunderstanding in the microscopy community is that third-party certification of each microscope's optics ensures inspection accuracy and reproducibility. In reality, governmental standards organizations typically certify calibration equipment but do not certify individual instruments.

Microscope manufacturers can perform internal calibrations on individual instruments, but here another disadvantage of free zoom capability comes into play. After the initial calibration by the manufacturer, the variation introduced by the zoom setting makes it difficult to reproduce the calibration conditions in the field.

Calibrations performed at the time of manufacture can help reproducibility by improving consistency of performance between microscopes made by the same supplier. However, no calibration can eliminate errors which are caused by fundamental optical principals of non-telecentric lenses such as parallax and non-constant magnification.

Conclusion

Optical systems in modern microscopy equipment can be subject to a variety of hidden errors. Careful consideration of the optical design used in the equipment is critical. Using microscopes with telecentric optical systems reduces or eliminates many of these errors to optimize image quality, measurement accuracy and reproducibility.

References / Additional Reading

Klein C., Buttermore W., Doppler M.: Using Telecentric Optical Systems to Optimize Forensic Image Accuracy and Reproducibility - How to eliminate hidden errors in forensics, Leica Science Lab, July 2015

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