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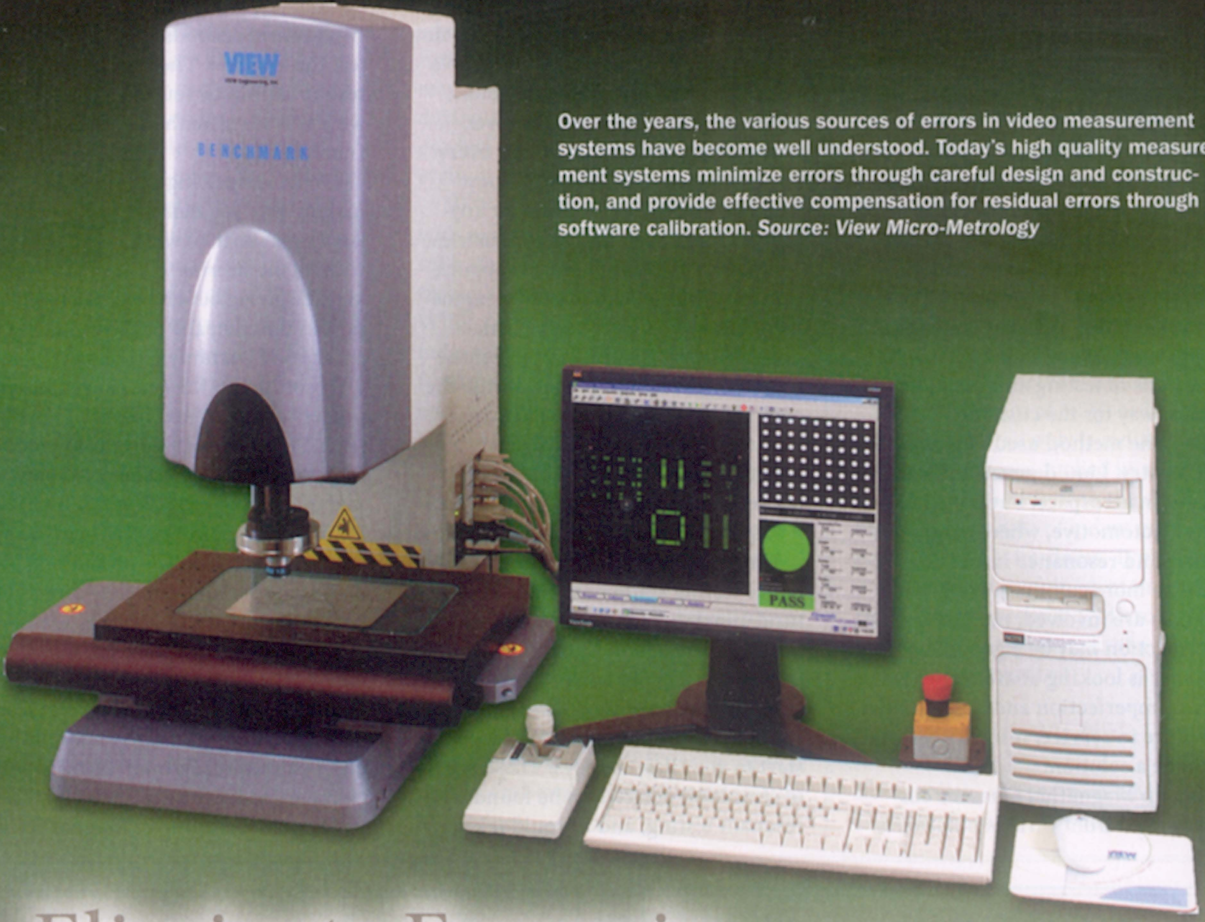


Over the years, the various sources of errors in video measurement systems have become well understood. Today's high quality measurement systems minimize errors through careful design and construction, and provide effective compensation for residual errors through software calibration. *Source: View Micro-Metrology*

Eliminate Errors in Video Measurement Systems

Take a closer look at sources of error in video measurement systems and their comprehensive analysis.

BY MUTHUKRISHNAN (KRIS) CHELLAPPA

Noncontact video measuring systems have been in widespread use for more than 30 years. Over the years, the various sources of errors in these systems have become well understood. Today's high quality measurement systems minimize errors through careful design and construction, and provide effective compensation for residual errors through software calibration.

As the basic components of video coordinate measuring machine (CMM) systems—stages, optics and cameras—have become readily available as OEM assemblies, a host of new video CMM products have come on the market. An accurate measurement system depends on much more than a simple combination of catalog components. In this article we'll reflect on 35 years of lessons learned about the sources of errors in video CMM systems, and how to account for them.

SOURCES OF ERRORS

Errors in a video coordinate measuring system can be broadly classified into systematic errors and constant errors.

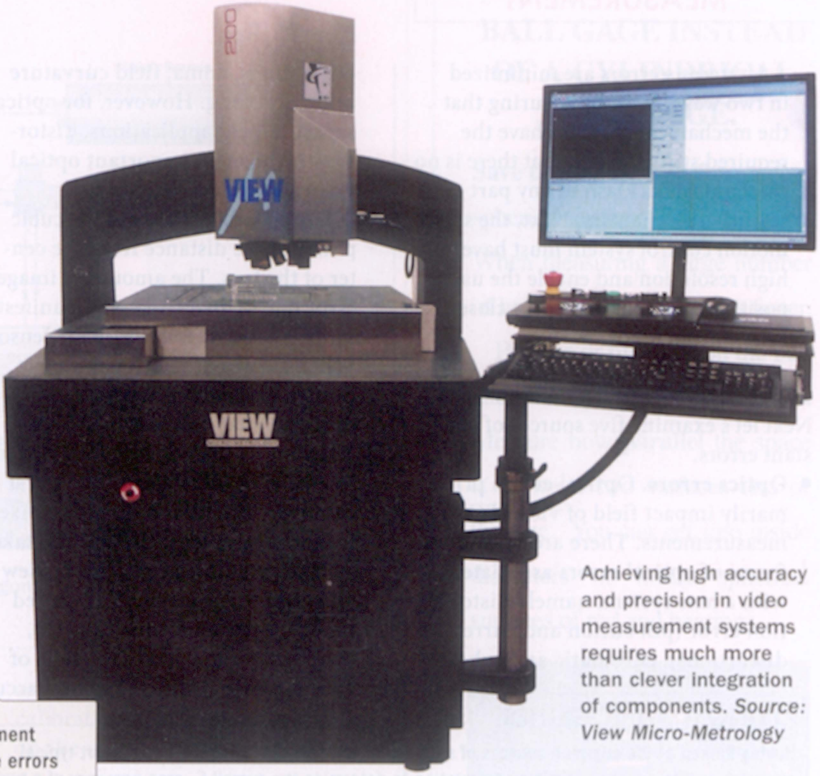
Let's look first at the systematic errors:

- **Straightness (or yaw) errors.** When the X or Y stage moves nonlinearly, there is a shift in the perpendicular direction of motion relative to the axis of travel. In other words, as a stage moves in the X direction, it also is moving in the Y direction. Straightness errors are a function of the quality of materials and manufacturing of the stage ways and bearings. The straightness error for a well-made, cross roller bearing type compound stage is typically less than 40 microinches per inch of travel.
- **Abbe (or pitch) errors.** Pitch error occurs when the axis of the measurement system is offset from the plane of the work piece and the motion of the work piece and measurement axis are not horizontal and parallel.

The most common cause of pitch error is the combined weight of the stage and work piece deflecting the stage downward at each end of travel. This makes the stage move in an arc rather than a straight line. A high quality compound stage will exhibit pitch error less than 5-arc seconds over its full range. An ultra-precise compound stage suited for micron or submicron accuracy will exhibit less than 0.1 arc seconds of pitch per millimeter of travel.

- **Orthogonality errors.** Orthogonality error is caused by an out-of-square condition between two or more axes. The extent of the error varies as a function of stage length and squareness.

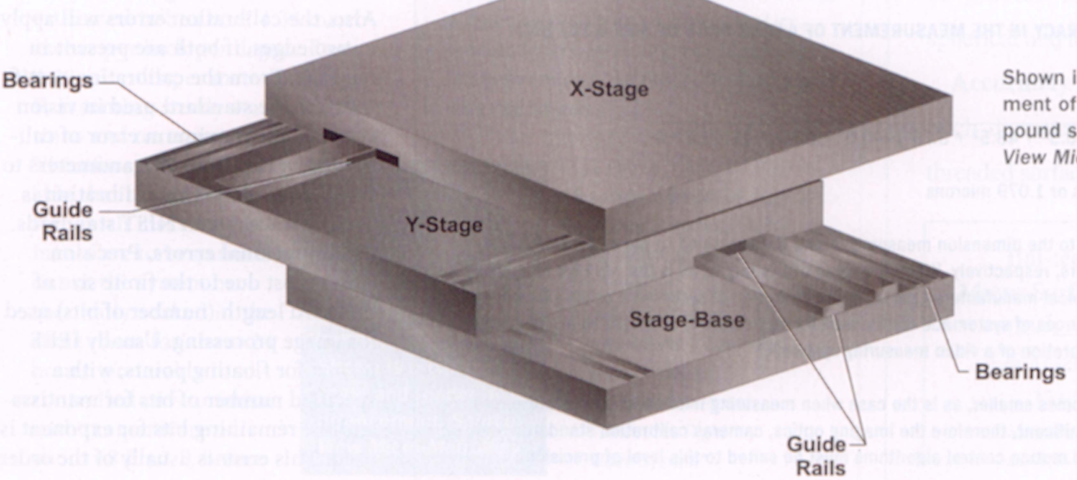
  In order to measure and correct for stage orthogonality errors, an orthogonal external reference must be established. This is most often done using a theodolite mounted in a fixed location near the stage, and an L-shaped mirror made out of low expansion quartz mounted on the stage. The stage is then moved within this frame of reference and both straightness and orthogonality errors can be measured.
- **Scale errors.** Scale errors are caused by variation in the scale reader head and associated electronics when determining the position on the scale. This is referred to as quantization error. Because the scale reader outputs an analog signal corresponding to the location of ticks on the glass scale, the uncertainty in the scale location error can be taken as ±1 scale tick, as the worst case scenario.
- **Lead screw and coupling errors.** Two types of errors are observed in the mechanical drive and servo control systems of stages. In the first case, when we use a rotary encoder on the drive motor, we see a cyclical error in the rotary mechanisms (encoder, bearing and coupling combination) that constitute a type 1 error on the order of 1 arc minute per revolution. Using a linear type encoder instead of a rotary encoder can eliminate this type of error, however, there will still be a lead screw accumulative error of (typically of 50 microinches per inch) due to hysteresis.



Achieving high accuracy and precision in video measurement systems requires much more than clever integration of components. *Source: View Micro-Metrology*

TECH TIPS

- » Today's measurement systems minimize errors through careful design and construction.
- » Errors in a video coordinate measuring system can be broadly classified into systematic errors and constant errors.
- » High accuracy begins with comprehensive understanding of the sources of error in measurement systems, and their effect on the overall accuracy and uncertainty of the resulting measurements.



Shown is a typical arrangement of a precision compound stage. *Source: View Micro-Metrology*

Hysteresis errors are minimized in two ways. First, by ensuring that the mechanical bearings have the required stiffness, and that there is no mechanical backlash in any part of the drive mechanism. Next, the servo motion control system must have very high resolution and enable the use of position maintenance in the closed loop control mode.

CONSTANT ERRORS

Next let's examine five sources of constant errors.

- **Optics errors.** Optical errors primarily impact field of view (FOV) measurements. There are several forms of optical errors associated with a lens system, namely distortion error (pin cusion and barrel distortions), chromatic and spherical aberrations, coma, field curvature and vignetting. However, for optical measurement applications, distortion is the most important optical error to be considered.

  Distortion increases as the cubic power of the distance from the center of the lens. The amount of image error due to distortion will manifest in the active area of the image sensor. When a conventional VGA format camera is used, typically optical distortion has no more than a 10% effect on the individual pixel element intensity. In other words, the worst case error can be about ¹⁄₁₀ of a pixel for the biggest lens. However, to take advantage of the larger field of view and greater resolution of advanced multi-megapixel format cameras, image distortion across the field of view must be minimal. Highest accuracy video measurement systems use optics that exhibit minimal distortion, typically fixed lens type systems with microscope objectives used as the front receiving lens.

- **Video errors.** Video errors are contributed by the charge-coupled device (CCD) detectors or complementary metal-oxide semiconductor (CMOS) digital camera imaging sensors and by the edge-finding algorithms in the image processing software.

  The pixel arrays are arranged in rows and columns with a fixed spacing between each row and column, so there are active areas, as well as dead spaces on the detector surface. Hence, some information is lost due to chip geometry and spatial variation.

  In the case of analog cameras with frame grabbers, there is a pixel jitter, measured in nanoseconds, which may cause as much as 0.4 pixel error. The quality and stability of the frame grabber and camera must be carefully evaluated to minimize video errors. In digital cameras, there is no concern of pixel jitter.

  However, the light sensitivity of a CMOS chip tends to be lower and hence, subject to noise. Thus, the extent of potential error due to this sensitivity varies considerably depending on the make and model of the camera. While there are many multi mega-pixel digital cameras available, few have the S/N performance, pixel symmetry and thermal stability required for precision measurement. Therefore, digital cameras must be selected with great care.

- **Calibration errors.** Calibration errors increase linearly from the center of FOV to the edges of interest. Also, the calibration errors will apply to two edges, if both are present in the FOV. From the calibration certificate for the standard used in vision systems, the maximum error of calibration varies from 70 nanometers to 100 nanometers. This calibration is usually traceable to NIST standards.

- **Computational errors.** Precision may be lost due to the finite size of the word length (number of bits) used for image processing. Usually IEEE format for floating points, with a specified number of bits for mantissa and the remaining bits for exponent is used. This error is usually of the order

TYING IT ALL TOGETHER

Having looked at the common sources of systematic and constant errors, we can insert typical error values into our area accuracy calculation to determine the overall E_2 area accuracy of a typical video measuring system:

ASSUMPTIONS:

- Pixel calibration value of 25.79 microinches for a system with a 10X objective lens
- 20 microinch linear scales
- Some of the errors are stated per unit length

SYSTEMATIC ERRORS: (LENGTH DEPENDENT) "A"

Straightness error: 40 microinch/inch
Abbe error: 48.5 microinch/inch (based on 5 arc sec of angle and Abbe offset of 2 inches)
Orthogonality error: 48.5 microinch/inch (based on 5 arc sec)
Thermal error: 8.76 micro inch/inch/2 F
(the temperature assumed to be maintained within ±2 F)

CONSTANT ERRORS: "B"

Scale error: 20 microinch X 2 locations
Optical error: ¹⁄₁₀ of pixel X pixel value (2.58 microinches)
Video error: ½ of pixel X pixel value (12.895 microinches)
Calibration error: 4 micro inch

OVERALL RMS ACCURACY IN THE MEASUREMENT OF A RING GAGE OF SIZE 0.107 INCH

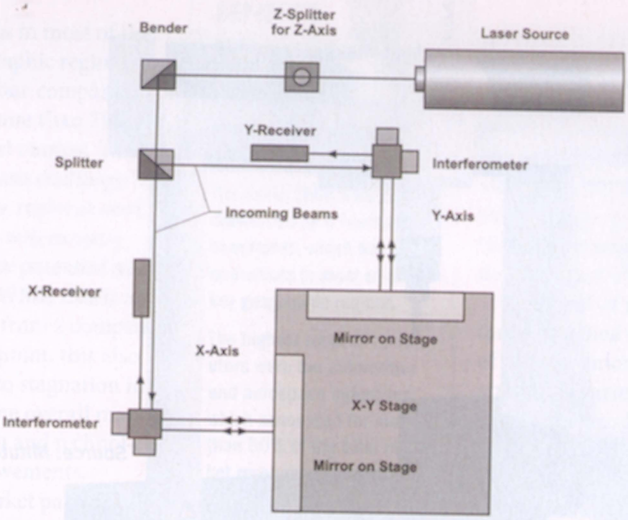
$$= \sqrt{L^2\,[A] + [B]}$$

$$= \sqrt{0.107^2[40^2 + 48.5^2 + 48.5^2 + 8.76^2] + 40.0^2 + 2.58^2 + 12.895^2 + 4^2}$$

= 43.151 microinches or 1.079 microns

Where L corresponds to the dimension measured. A and B correspond to the systematic errors and the constant errors, respectively. When the value of L is larger, as is the case for measurements of length in typical manufactured parts, the contribution of systematic errors (A) are substantial. Thus, the sources of systematic errors must be very carefully attended to in the design, construction and calibration of a video measuring system.

As the value of L becomes smaller, as is the case when measuring micro parts, constant errors (B) become more significant, therefore the imaging optics, cameras calibration standards and image processing and motion control algorithms must be suited to this level of precision.



An orthogonal reference setup checks for orthogonality errors.
Source: View Micro-Metrology

of 1/16 of a pixel for a 4 bit exponent or 1/64 of a pixel for a 6 bit exponent and hence may be ignored. Here it has been included for the purpose of completeness only.

- **Errors due to temperature, pressure and humidity.** In applications with accuracies of the order of a micron, it is essential to keep the temperature controlled within ±2 F. Although well-designed measurement systems are built from materials with low and generally similar thermal coefficients, where two dissimilar materials are physically connected, temperature changes can induce stress and deformation. At the micron level even small changes in temperature can have measureable impacts on both systematic and constant errors.

  Ignoring thermal stress induced errors, the worst case error due to temperature deviations has been estimated to be about 4.38 microinches per inch per degree F or 4.38 microns per meter per degree F, assuming steady state conditions and no transients. Therefore, it is advisable that the materials for which measurements are to be carried out in the system be thermally soaked in the same room for about 24 hours, preferably in a controlled environment with temperature of about 68 F ±2 F, before any attempt is made to carry out calibration or repeatability studies on the measurements.

Nearly 30 years experience with video measurement systems has shown that achieving high accuracy and precision requires much more than clever integration of components. High accuracy begins with comprehensive understanding of the sources of error in measurement systems, and their effect on the overall accuracy and uncertainty of the resulting measurements. With this understanding, we can apply sound design and careful manufacturing techniques to produce systems with exceptional accuracy and repeatability, which provide many years or reliable service. **Q**

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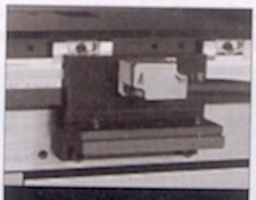

Shown is a typical scale and reader head arrangement. *Source: View Micro-Metrology*

QUALITY ONLINE

For more information on video measurement, visit ww.qualitymag.com for the following:

- *"Advanced Video Measurement Solutions"*
- *Q-cast Podcast: Video Measurement*
- *"Select the Right Video System"*