Multisensor Coordinate Metrology

Dimensional Measurement Using Optics, Probes, and X-ray Tomography

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Contents

The Changing World of Coordinate Metrology 4

Sensors 8
Optical Sensors .............................................................. 11
Tactile Sensors .................................................................... 39
X-ray Tomography Sensor .................................................... 52

Machine Design and Areas of Application 56
Coordinate Measuring Machines with X-Y Stage .................. 56
Coordinate Measuring Machines with Guides in a Single Plane . 59
Bridge-Type Coordinate Measuring Machines ....................... 62
Coordinate Measuring Machines with Rotary Axes ................ 67
Coordinate Measuring Machines for Two-Dimensional Measurements... 71
Coordinate Measuring Machines with X-ray Tomography Sensors ...... 73
Coordinate Measuring Machines for Special Applications .......... 76

Metrology Software 77
Measurement with the Graphical Interface .......................... 78
Programming Complex Measurement Sequences .................. 79
Comparing with CAD Data ............................................... 81
Measuring with CAD Data ............................................... 85
Automatic Mode ............................................................ 87

Special Metrological Characteristics 89
Sensors and Machine Axes ................................................. 89
Machine and Workpiece Coordinates .................................. 91
Measuring while Moving .................................................. 95
Multisensor Systems ....................................................... 97
Calibrating the Sensors .................................................... 99
Probing Force ............................................................... 102

Measurement Accuracy 105
Resolution ........................................................................... 106
Specification and Acceptance Testing ............................... 109
Measurement Uncertainty .................................................. 115
Temperature Effects ......................................................... 119
Measurement Process Capability ...................................... 124

Outlook 129

Bibliography 130

The Company behind this Book 131
Sensors

When selecting sensors, the conditions of the workpiece such as the size of the features to be measured, precision requirements and sensitivity to contact must be taken into consideration. Selection of the sensor (or sensors, for multisensor applications) must therefore be done with the measurement task in mind. Economic aspects such as measurement time and costs also play an important role.

The sensors vary a great deal in their mechanical, optical, electronic, and software design, leading to very different properties. Understanding the principles and characteristics is helpful for optimal use. The sensors may have their own measuring range (measuring or scanning sensors) or may only detect a threshold value (trigger sensors) (Fig. 3). The direction of sensitivity of the sensors may be limited to one or two coordinate axes (1D, 2D sensors) or may cover all three axes (3D sensors) (Fig. 4). The measured values of the axes that are not evaluated by the sensor are given by the sensor position (e.g. the location of the measurement axis of the center of the probe tip for 1D probes or the location of the object plane for image processing). Sensors can measure single points (point sensors), contours (line sensors), or surface regions (area sensors) (Fig. 5). All these properties can be found in nearly any possible combination (see Fig. 57, p. 90).

Fig. 3: Trigger (left) and measuring sensors (right)

D Deflection
S Signal course
M Measurement range

Fig. 4: One-, two-, or three-dimensional sensors: principle representation of the kinematics without measurement systems
a) Parallelogram spring
b) Mounting cylinder

Fig. 5: Measuring points, lines, or surface regions
Capturing contours by scanning

Scanning contours, for example for measuring form and position tolerances, is possible with measuring sensors (scanning probe, optical distance sensors) when combined with suitable control of the machine axes. Trigger probing systems also offer this function, in principle, but require very long measurement times. When scanning with an image processor, several images are automatically merged during contour tracking to form overall images and contours. The size of the contours that can be scanned is limited not by the sensor, but by the measuring range of the coordinate measuring machine.

Another significant criterion for differentiating the sensors is the physical principle of capturing the primary signal. The majority of sensors currently in use can be classified as optical or tactile (Fig. 6). For optical sensors, the information about the location of a measurement point is transmitted to the sensor from the object by light. Tactile sensors obtain this information by contacting the measured object with a probe tip, typically a probing sphere. With X-ray tomography sensors, the workpiece is penetrated by X-rays and its three-dimensional geometry is reconstructed from the X-ray images. The resulting volume data are then used to derive the location of the measurement points.

Optical Sensors

For decades, the human eye was the only available “sensor” for optical coordinate measuring machines, which included measuring microscopes and measuring projectors. Visual measurements led to subjectively induced measurement errors. These included parallax errors (viewing from an angle) and erroneous measurements of light-to-dark transitions (e.g. at edges) due to the logarithmic light sensitivity of the human eye. However, visual edge detection remains the last available alternative even for modern machines. It is used when the object structures to be measured are very difficult to see and the geometric features can only be found intuitively.

Generally, the measurement function of the eye is replaced by optoelectronic sensors. Like the eye with a measuring microscope, they act either orthogonally to the optical axis in the object plane (lateral sensors – image processing), or along the optical axis when focusing (axial sensors – distance sensors, see Fig. 6). Lateral measurement sensors determine the distance of object points from the sensor axis (sensor coordinates x, y in the object plane). To do so, the measured object is typically illuminated and the image is pro-
Sensors Optical Sensors

Projected onto the sensor by means of a lens (Fig. 7). Sensors in this group that measure only individual points allow automated “probing” of edges with good contrast. This means that they are only useful with transmitted light. Due to this limitation, such sensors are rarely used anymore. Today, primarily image processing sensors are used because they can measure many points in the image plane. Images with much lower contrast can be evaluated by considering adjacent structures. Sensors that measure laterally can only be used for measuring two-dimensional (2D) or stepped objects (2½D). To perform a true three-dimensional (3D) measurement of a workpiece with optical sensors, an additional method for measuring along the third coordinate axis is required. The sensors discussed here are known as axial measurement sensors or distance sensors, because they measure the distance between the sensor and the surface of the workpiece. These distance sensors function by different physical principles that can be roughly classified as “time-of-flight” or “angle-based” methods (see Fig. 6). The time of flight of a light beam travelling from the sensor to the object and back cannot be determined directly for such short distances, so an interferometer is used. Triangulation and focus methods use the angular relationship between the measurement beam and the sensor, or the aperture of the optics and the working distance to measure distances (Fig. 8).

The advantages of optical sensors for applications arise from measuring without contact. This means that fragile workpieces, as well as those with small features, can be measured. Plastic parts, functional optical surfaces, flexible sheet metal parts, and micromechanical components (implants, watch parts) are good examples. With non-contact measurements, the difficulty of fixtureing small or elastic components can be reduced or eliminated. Many measurement points can be captured very quickly or even simultaneously with optical sensors. Compared with other sensors, they therefore have significantly shorter measurement times. For this reason, they are also used in production control for a wide range of workpieces.

Image Processing Sensors

Due to its wide range of potential applications and good visualization of the object and features being measured, image processing is standard on most optical and multisensor coordinate measuring machines. Like the image generated by a measuring microscope for visual measurement, the measured object is imaged by a lens onto a matrix camera and

Fig. 7: Principle construction of a laterally measuring sensor with optical imaging
a) Sensor
b) Lens
c) Measured object
d) Lighting

Fig. 8 (opposite): Distance method
a) Interferometer (time of flight): the distance to the object can be determined by interference from the difference in time of flight between the reference and measurement beams.
b) Triangulation (angle): the distance to the object can be determined from the position of the light spot in the measurement field and the known triangulation angle (sensor arrangement according to the Scheimpflug principle to prevent defocusing).
c) Focus method (angle): the distance to the object is determined from the focal state represented by the contrast; defocusing depends on the aperture angle.
Optical Sensors

Sensors captured, as shown in a simplified view in Figure 7 (p. 12). The electronics in the camera convert the optical signals into a digital image. That image is used to calculate the measurement points with appropriate image processing software. The light intensity distribution in this image is analyzed. The performance of image processing sensors is significantly influenced by the individual components such as lighting system, imaging optics, semiconductor camera, signal processing electronics and image processing algorithms [1, 4].

Imaging optics with a telecentric lens produce the lowest measurement uncertainties. The telecentricity keeps the image scale effectively constant when the distance to the object is varied within the telecentric range of the lens (Fig. 7). An aperture is used to ensure that only those beams of light that are nearly parallel are used to generate the image for each image point. This is particularly important for lenses with very low magnification. They have great focal depths, which means that the object can only be roughly brought into focus. The best quality can be achieved with telecentric lenses with fixed magnification.

For most applications, it makes sense to combine high and low magnification levels. Low magnification, with a large field of view, allows the workpiece to be easily located even if it is only roughly positioned on the measuring machine. Features with less tight tolerances can be measured very quickly “in the image”. There may also be requirements to measure features with tight tolerances using high magnification with high precision and small fields of view. A lens turret can switch the lenses to set various magnifications. The disadvantage is that the position repeatability is often insufficient when changing optics. Two or more lenses can also be combined by splitting the imaging beam path. Due to the loss of light when splitting the beam, however, certain features may be too dark to be measured. Because only two different magnification levels are typically needed, another elegant approach is to switch between two separate image processing sensors with different magnifications arranged next to each other. They can be simply positioned by the precise machine axes that are already available. The magnification of common telecentric lenses ranges from 0.1× to 100×, with a field of view from 100 mm to 0.1 mm.

A zoom optic provides greatest flexibility. Conventional zoom optics move the lens packages to change magnification by means of curved guides in a barrel (Fig. 10a). The mechanical positioning errors caused by moving the lenses results in a loss of accuracy. This can be reduced in several ways. The simplest, but very time-consuming

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**Telecentrics for constant image scale**

Fig. 9: Non-telecentric images (left) change sharpness and image scale as the object distance changes. With telecentric imaging on the object side (right), in contrast, the images have nearly constant scale.

- a) Sensor plane
- b) Virtual image plane
- c) Telecentric diaphragm

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**Switching lenses – changing magnifications**

**Zooming – adjusting magnifications**
method consists of repeated calibration after every change of magnification. Alternatively, high repeatability when zooming can be achieved using motorized linear guides with very low positioning error (Fig. 10b). The mechanical curves are replaced by corresponding mathematical functions in the control software. In addition to different magnifications, this also allows different working distances to be selected. In practice, magnifications from 0.5x to 10x and working distances from 30 mm to 250 mm can be achieved. By selecting the magnification appropriately, the best compromise between the measuring range of the sensor and the measurement uncertainty can be achieved. The working distance can be adjusted largely independently of magnification to meet the requirements of the measuring strategy. This will allow for the most precise measurements and the best image quality with standard working distance or measurements at longer working distances to avoid collisions.

Lighting systems are the basis for every optical measurement and provide the necessary contrast to measure any feature. The easiest features to measure are on the outside edges of workpieces. In this case, transmitted light can be used (Fig. 11a). Flat objects provide ideal measurement conditions. On the other hand for edges on prismatic or cylindrical objects, the interaction of lighting, workpiece and imaging beam path must be given more attention. The aperture of the lighting system and the lens must be matched to each other and to the application. Maximum flexibility is provided by transmitted light units with selectable aperture. Panel light sources can be
used with a mask with many small-aperture holes to create a large collimated light source (Werth FlatLight, see Fig. 47, p. 72).

It is rare that all features can be measured using transmitted light in a practical application. Therefore, additional incident light illumination systems are typically used. There are two different types: The bright field incident light (Fig. 11b) is projected onto the measured object parallel to the optical axis of the imaging beam path. Ideally, this is done directly through the imaging lens system. This type of illumination causes direct reflection on metal surfaces, for example, that are perpendicular to the imaging beam path. The measured object is shown as lighted. Inclined surfaces reflect the light away from the lens and therefore appear dark. The dark field incident light impinges on the measured object at an angle to the imaging beam path. Depending on the angle of the workpiece surface, the light is reflected into the lens (light) or away from it (dark). The type of lighting can be selected to optimize the contrast of structures of interest on the object. In the simplest case, ring-shaped arrangements of light-emitting diodes (LEDs) are used for the dark field incident light. By connecting various diode groups, the object can be illuminated from different spatial directions and thus optimally adapted to the measurement task (Fig. 11c). Using MultiRing® illumination (Fig. 11d) in combination with zoom optics with a variable working distance (see Fig. 10, p. 16), it is possible to vary the lighting angle to the optical axis over a wide range. Additionally, the working distance to the objects can be long enough for measurement without collision.

Figure 12 shows examples of the effects of different types of lighting. The light sources can be controlled by the user or can be controlled by the measurement software in automatic mode. To measure automatically under practical conditions, variable material surfaces such as metal surfaces with different degrees of reflectivity, or differently colored plastic parts have to be considered. By using a closed-loop light control the lighting will be automatically adjusted until the light reflected by the surface of the workpiece matches the values of light specified by the measuring program. A mathematical correction of the illumination characteristics (light intensity relative to the setting in the user interface) allows CNC programs to be used with various lighting hardware that have different illumination characteristics. This may be on different machines or after a machine repair. The images of the object are typically captured with CCD or CMOS cameras. For many years the advantage of CCD cameras relative to their competitors of CMOS design was their high signal quality. The latest generation of CMOS sensors has achieved comparable or even better signal quality. The cameras have from about 700 to 5000 pixels (picture
Cameras generate digital signals

Filters improve the image

The simplest method for determining the measurement points derives the intersection points of predefined lines with the visible contours in the image of the object (commonly called “Edge Finder”). This is repeated sequentially at many locations in a previously specified analysis region (window). The result is a large number of measurement points that are combined into a group within the window. However, a separate one-dimensional analysis is performed to determine each individual point. The extensive two-dimensional information contained in the image is thus not considered. This is a disadvantage, particularly when measuring in incident light. False contours from surface structures, blowouts and dirt can be detected and compensated only to a limited degree.

In contour image processing, the entire image is evaluated within a measurement window. Contours are extracted within this image using suitable mathematical operators. Each pixel on a contour corresponds to one measurement point. The measurement points are strung together like a chain of beads. This makes it possible to detect and filter out artifacts when measuring (contour filter), without

Contour image processing for reliable measurement

Fig. 13: Image processing methods
a) Original image: contour detection disturbed
b) Improved with image filter: contour detection correct
c) Erroneous measurement due to contamination
d) Correct measurement including form error with contour filters

Fig. 14: Contour image processing compared with single-point edge detection
a, b) Single-point edge detection: correct measurement with exact edge position (a), erroneous measurement when edges are shifted (b)
c, d) Contour selection in a larger window allows the edges to be found reliably in various positions.
changing the shape of the contours (Fig. 13c, d). For practical applications, it is important that several contours can be differentiated within a captured region (Fig. 14c, d). Modern systems interpolate the coordinates of the measurement points within the pixel raster in an additional step (subpixeling: Fig. 15) enabling higher metrological resolution and accuracy [5].

Contours that are larger than the field of view of the lens being used can be combined into an entire image using automatic contour tracing in conjunction with the CNC axes of the coordinate measuring machine (contour scanning). This scanning method is well suited for checking relatively large contours, such as on punching tools. For this application, both punch and die profiles of the tools are captured directly and can be compared with each other or with the CAD data set.

Another method for capturing larger areas of the workpiece is raster scanning. A complete image of the workpiece surface or perimeter is produced by joining images from different sensor positions in a common raster (Fig. 16). Using re-sampling, new pixels for an overall image are calculated from the partial images eliminating positioning deviations. The resulting image can be analyzed by the image processing software, just like measurements “in the image” (see Sensors and Machine Axes, p. 89). Raster scanning can be done very quickly with continuous image capture while moving in OnTheFly® mode (see Measuring while Moving, p. 95).

Image processing was initially suitable only for measuring two-dimensional features. The scope of application therefore included mainly two-dimensional workpieces such as flat sheet metal, films, circuit boards, sliced aluminum profiles, rubber or plastic extrusions, prints, stamping dies, lead frames or chrome masks. The same sensor hardware (optics, camera technology, etc.) can also be used with focusing methods (see Focus Variation Sensors, p. 25), to create the commonly used base sensor type for multisensor coordi-

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Fig. 15: From the original image to the calculated best-fit element

a) The image processing sensor “sees” the object as a gray scale image.
b) The pixels in the gray scale image are converted into digital amplitudes.
c) A threshold operator calculates a pixel contour from the digital image.
d) For every point of the pixel contour, a “subpixel point” is interpolated from the adjacent gray scale values.

e) The subpixel contour is used to calculate a best-fit element, for example, using the Gaussian method.
f) Display of the result in the gray scale image for visual observation.

Raster scanning: resolution independent of the measurement range

Fig. 16: Raster scanning: Several adjacent image regions (eight areas divided by yellow lines) are captured in sequence and merged. By setting measurement windows (green rectangles) and an optional search vector (yellow arrow), contours and geometric elements (in the example circles) and features (diameters) are calculated.
nate measuring machines. By combining both methods in one sensor hardware, many three-dimensional measurement tasks can also be addressed. A major area of application is the measurement of functional dimensions on plastic parts, such as the spacing between snap tabs and the geometry of sealing grooves and plug cavities. Additional application examples are stamped components made of sheet metal, watch components, furniture hardware, fuel injector nozzles, printer heads, tools, and turned components.

To improve the flexibility of image processing sensors for three-dimensional measurements, a rotating and tilting camera head can be used. The standard types of illumination and an automatic interface for the fiber probe are integrated in the head (see Tactile-Optical Scanning Probes, p. 45). A rotary/tilt unit, such as those used with tactile sensors, allows the sensor to be oriented spatially relative to the workpiece. An additional interface can be used to automatically exchange various optical or tactile sensors (Fig. 17).

Focus Variation Sensors
In the simplest version of the focus variation sensor, the measurement point is found by the distance between the object and the sensor. The same hardware components are used for this as for image processing. When moving the sensor along the optical axis, a sharp image is generated in only one position. If the sensor is out of focus, blurry images will result. The contrast can be used as a characteristic value for the state of focus of an image. If the focal plane of the sensor is moved along its optical axis within a range containing the object surface plane, then the contrast value reaches its maximum when the focal plane corresponds to the object plane. The location of the point on the surface can be determined from this sensor position (Fig. 18). This point can then be brought into focus by positioning (autofocus).

The sensitivity of the method described is influenced primarily by how far the apparent focal range extends along the optical axis. This range, also known as depth of field,
Contour measurement in workpiece coordinates

Contour probe into a probe rack. The integration of the tactile-optical contour sensor in a coordinate measuring machine allows fully automatic contour measurements over a large measuring volume. Other advantages are the high precision of positioning the measurement in the workpiece coordinate system and the ability to scan in any direction. This is not possible with classic contour profilometers. The measured data are evaluated for roughness, dimensions, shape and location using software functions. Application examples include: profile measurement of gear teeth segments, embossed sheet metal, profile sections of extruded materials with small geometries, roughness of stamped and punched parts at defined positions, and injection-molded parts.

X-ray Tomography Sensor

X-ray tomography, also known as Computed Tomography, or CT, allows the geometry of workpieces to be captured completely, regardless of their complexity. Both internal and external geometries are captured. Industrial computed tomography had previously been limited to material inspection due to the lack of sufficient precision. This changed through combining X-ray tomography with principles of coordinate metrology in 2005 (Fig. 36). Due to its short measurement times, CT provides significantly faster measurement, acceleration of process chains, and increases productivity for workpieces with many features.

X-ray tomography utilizes the ability of X-ray radiation to penetrate objects. As it passes through an object, part of the impinging radiation is absorbed. The longer the length of the object, the less radiation escapes from the opposite side of the object. The absorption also depends on the material. An X-ray detector captures the penetrating X-ray radiation as a two-dimensional X-ray image. With detector sizes ranging from approx. 50 mm to 400 mm, a large portion of the measured objects can be captured in a single field of view even at high magnification.

Several hundred two-dimensional X-ray images are made in sequence, with the measured object in various accurately rotated positions (Fig. 37a). The object is located on a high-precision rotary axis for this purpose. The three-dimensional information about the measured object contained in this series of images is extracted using the appropriate mathematical process. It is made available as a voxel volume, consisting of many individual voxels. Each voxel (from volume and pixel) embodies the absorption properties, or density, of the measured object or the surrounding air for each defined location in the measuring volume. Similar to two-dimen-
Sensors

X-ray Tomography Sensor

1. Introduction of X-ray Tomography

2. Principles of X-ray Tomography

3. Applications of X-ray Tomography

4. Conclusion and Future Trends

Fig. 37: X-ray tomography: The radiation originating from an X-ray point source passes through the measured object and reaches the area sensor. Images are taken in various rotary positions.

a) Low magnification
b) Higher magnification
c) Raster tomography

Automated correction of molds
In 2011, Werth Messtechnik GmbH celebrated its 60th anniversary. Quality and precision combined with innovation form the foundation of a successful corporate history. The company’s first profile projector set ergonomic standards in 1955. When they were digitized, measuring projectors took on the functionality of a coordinate measuring machine at the end of the 1960s. In 1977 with the Werth Tastauge, the first glass fiber sensor became available for measuring projectors. This principle has become established around the world for measuring with transmitted light. In 1980, the first optical CNC coordinate measuring machine was also brought to market by Werth Messtechnik.

Sensor developments like the Werth Fiber Probe and the Werth Zoom and the world’s first integration of X-ray tomography in a multi-sensor coordinate measuring machine in 2005 confirm Werth Messtechnik’s leadership in this market. Modern developments in the field of software such as BestFit, ToleranceFit®, or WinWerth® AutoElement complete the picture.

Stable growth rates for over several decades have allowed the building of a highly motivated team. Around 250 employees in Germany, as well as sales and service support points in every important industrial country, ensure that Werth Messtechnik will continue to provide cutting-edge coordinate metrology in the future, with the best quality and excellent service.

Bibliography