X-ray Tomography in Industrial Metrology

Precise, Economical and Universal

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This book was produced with technical collaboration of Werth Messtechnik GmbH.

Special thanks to Prof. Marc Kachelriess, Erlangen, for technical advice.

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From Clinical CT to Industrial Measuring Machine

1970s: first CT machines for medical use

X-ray tomography, also known as computed tomography (CT), can be used to completely capture spatially extensive objects, including their internal structures for metrology purposes. The Austrian mathematician Johann Radon (1887–1956) laid the mathematical foundation for this process in the beginning of the 20th century, with the Radon transformation that bears his name. The use of X-ray technology in the form of two-dimensional radiographic images has long been an established part of medical diagnostics. The Nobel Prize winners Allan McLeod Cormac and Newbold Hounsfield made substantial contributions to the development of 3D tomography machines for medical use. The first commercial machines were available in the 1970s. Today, this technology is indispensable in medical practice [1].

1990s: inspection using X-ray tomography

At the start of the 1990s, X-ray tomography was also being used more frequently for inspecting technical objects. Workpieces were checked for voids, inclusions and missing features. It became possible, for the first time, to inspect the internal structures of workpieces in a non-destructive manner. Over time, special machines were developed for these new applications. These machines were also used for the initial attempts at determining workpiece dimensions using X-ray tomography. The attainable accuracy, in the range of a few hundredths of a millimeter,
was still very low. So, broad application for metrological purposes was not yet possible. Especially the deviations of the measured dimensions from the absolute correct value were very large.

The accuracy problem was overcome by a fundamentally new approach and the use of coordinate measuring technology. The first X-ray tomography machine sufficiently accurate for industrial applications was presented to the public in the spring of 2005 (Fig. 1). This new class of coordinate measuring machine makes it possible to completely measure even complex components with several hundred dimensions and internal structures in a relatively short time of less than 20 minutes. The accuracy ranges from a few microns for standard applications to fractions of a micron for precision measurements. The use of these devices leads to significant acceleration of process chains and increases productivity for the user.
X-ray Tomography for Industrial Metrology

The use of X-ray tomography in industrial metrology is fundamentally different from medical CT. In order to take radiographic images from various directions, the X-ray unit (radiation source and sensor) in a medical CT machine is rotated around the stationary patient. For industrial X-ray tomography, however, the X-ray unit is generally stationary and the workpiece is rotated in the beam path. The objects to be examined in the industrial field contain materials which require radiation parameters that are different from those in medical applications. The requirements for resolution and precision also differ. As a rule, the radiation exposure of the object being examined is not a problem in industrial applications. This means that greater radiation intensities can be used than those in the medical field.

Basic Principle of X-ray Tomography

X-ray tomography uses the ability of X-ray radiation to penetrate objects. An X-ray tube can be considered almost a point source of X-rays. The X-rays pass through the measured object to reach the X-ray sensor. On the way through the object, a part of the radiation is absorbed. The longer the penetrated length of the object, the less radiation escapes from the opposite side of the object. The absorption also depends on the type of material. This
Machine Technology and Design Variations

When designing coordinate measuring machines with X-ray tomography, the specific requirements of the application must be considered. The maximum size of the measured object and the required precision play an important role. The most suitable X-ray technology and machine mechanics must be selected depending on the material and size of the objects to be measured. A decision must also be made as to whether the measuring machine is to be used as a single-purpose machine for one family of parts, or as a flexible measuring machine for a variety of measurement tasks. Whether multisensor equipment makes sense or not should also be addressed.

X-ray Source

The tubes used to generate X-rays are a core component of X-ray tomography machines (Fig. 15). They operate on the basic principle of electron beam tubes. Free electrons are generated in a vacuum by thermionic emission, and accelerated by an electrical field generated by voltage between two metal electrodes, so that an electron beam is formed. In an X-ray tube, this electron beam impinges on the metal surface of the target. If the acceleration voltage is high enough so that the kinetic energy of the electrons is sufficient, then X-rays, a form of high-frequency electromagnetic radiation, are produced. The frequency range of
The X-rays generated depends on the voltage between the cathode and the anode of the tube (the cathode voltage) and on the target material. The radiation from an X-ray tube can be considered as a flow of photons of various frequencies. Because the energy of a photon is proportional to its frequency, the selected electrical voltage of the X-ray tube affects the frequency and thus the energy of the photons. This is important when selecting the X-ray tube, because certain materials can be measured optimally only with a relatively low level of radiation energy. Other materials, however, can be penetrated only by high-energy radiation, and therefore require a higher cathode voltage. In practice, the maximum voltage depends on the type of tube and is between 90 kV and 450 kV. To measure typical plastic parts, a voltage between 90 kV and

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**Fig. 15:**
The core components of tomography:

a) 225 kV microfocus X-ray tube
b) High precision, air bearing rotary axis
c) X-ray sensor with about 2000 × 2000 pixels

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**Cathode voltage affects the radiated spectrum**
130 kV is sufficient. If parts that contain metal are to be measured, a higher voltage is required. Synchrotrons can generate X-rays with higher energy than those produced by X-ray tubes. They are currently used only in scientific applications due to their high cost. High-frequency synchrotron radiation can be used for penetration and tomography of very large metal objects, such as complete engine blocks.

The targets of X-ray tubes are fundamentally classified as reflection targets and transmission targets (Fig. 16). The difference when using reflection or transmission targets is in the available radiation power, and therefore the measurement time and the minimum focal spot size.

In a reflection target (also referred to as a direct emitter), the X-rays are reflected by the target. This design provides greater heat...
dissipation allowing higher power and thus shorter measurement times. A preferably rectangular aperture bounds the generated X-ray cone to a pyramid shape and adapts it to the size of the sensor. The minimum focal spot size that can be achieved with a reflection target tube is a few microns. This is sufficient for ordinary measurement tasks, because a resolution of less than 5 µm for structures is seldom required. Nevertheless, with sub-voxeling and other optimization, measurement errors of just a few tenths of a micron can be obtained.

Transmission targets are penetrated by the X-rays, and are therefore thinner than reflection targets. The X-rays are propagated in the direction of the electron beam. X-ray tubes with transmission targets have the advantage that the thin target produces a smaller beam diameter (focal spot) and thus a higher resolution is achievable. However, also using reflection targets, the focal spot size depends on the power setting. A small focal spot can be obtained only at low power. This is a severe limitation on practical use. It makes sense only for micro parts with very high resolution requirements. If the measured objects are greater than a few millimeters in the beam direction, then either a very long measurement time must be accepted, or the X-ray tubes must be operated at a higher power level. In the latter case, the focal spot will be larger due to physical constraints. A certain intended defocusing is also performed at higher power levels to limit the power density at the target and to avoid destroying it.

X-ray tubes are available in both open and closed designs. In a closed X-ray tube, the
vacuum is generated once, by the manufacturer, and is maintained for the long term by hermetically sealing the vacuum chamber. The use of closed X-ray tubes generally makes sense for voltages up to about 150 kV. In this case, the tubes can be used for a service life of several years without maintenance. Once the service life has expired, the complete X-ray tube must be replaced. X-ray tubes with focal spot sizes in the micrometer range, which are operated at voltages above 150 kV, are typically open systems. The wear on the electrodes of such tubes is so great that they require regular maintenance. For an open X-ray tube, the vacuum is generated by a separate vacuum pump during operation. This makes it possible to open the X-ray tubes for servicing to regenerate the vacuum by operating the vacuum pump. Considering the maintenance costs of open systems and replacement costs for closed systems, the cost to operate both types of tubes is similar.

The construction of an X-ray tube is very complex in detail. In addition to the electrodes and the target that have been mentioned, it also has a large number of components for focusing the beam, electrode heating, and other functions (Fig. 17).

Due to the required measurement accuracy, the temperature plays a prominent role [3] when using X-ray tubes in coordinate measuring machines. Because X-ray tubes in general have a low efficiency level, there is a relatively large power loss. This is removed from the measuring machine by a suitable liquid cooling system with heat exchangers.
Rotary Axis

In principle, it makes no difference whether the X-ray source and the sensor rotate about the measured object or the measured object is rotated in the beam path. For metrology applications, the preferred machine design has a stationary X-ray unit and a rotary axis for the workpiece. This type of machine can be manufactured with high precision at reasonable cost.
cost. Thus, proven components from coordinate measuring technology can also be used. The properties of the rotary axis with respect to radial runout, axial runout, and indexing error directly affect the measurement results. For example, a deviation in angular measurement of one arc second, at a radius of 200 mm, causes a tangential measurement error of about 1 µm. However, this does not allow a direct conclusion concerning the achievable measurement error for tomography, because there are other influencing factors. Apart from radial and axial deviations, the wobble of the rotary axis and the effects of other machine components must also be considered. This means that precise rotary axes must be used, particularly for measuring machines with a large measurement range, and especially for workpieces with large diameters. For smaller diameters, the requirements are somewhat lower. Also, the rotary axis must be capable of ensuring the required precision when loaded with the weight of both workpiece and holding fixture.

X-ray Sensor

X-ray sensors are available both as line sensors and area sensors (Fig. 18). From a purely geometric standpoint, line sensors would be perfect. Synchronized movement of the X-ray source and the line sensor relative to the measured object in the direction of the rotary axis can ensure that the section plane through the object is always perpendicular to the rotary axis. The disadvantage of this fan beam tomography is that each section plane needs to be captured individually in every ro-
Area sensors are better

For this reason, area sensors that capture several section planes of the measured object at once, according to the number of lines on the sensor, are typically used. The disadvantage of this cone beam tomography with circular motion, however, is that the captured object section planes, except for the center one, are not perpendicular to the rotary axis. This causes fundamental measurement errors during the mathematical reconstruction of the volume data from the 2D radiographic images. Depending on the precision requirements, these must be corrected.

Smaller cone angle reduces measurement errors

The smaller the cone angle, the lower these measurement errors. This means that it makes sense to design high precision machines with
a greater distance between the X-ray source and the sensor. However, this reduces the efficiency of the X-ray tubes, because the usable part of the available beam cone is smaller. Depending on the desired accuracy, the machine manufacturer must find the optimal compromise (Fig. 19).

Industrial X-ray tomography machines typically use area sensors with a scintillator (Fig. 20). The scintillator converts the X-rays that strike the sensor into light. The high-energy photons of the X-rays excite particles of the scintillator material as they pass through it. These particles then emit light in the visible frequency spectrum. This makes it possible to use conventional silicon based photosensitive elements to record the image.

The individual pixels of an area sensor are not exactly identical in sensitivity. This difference is automatically eliminated in practice by calibrating the sensor under bright and dark X-ray illumination and applying auto-

Fig. 19:
Werth TomoScope® HV 500: Coordinate measuring machine with X-ray tomography for the most stringent requirements with a small cone beam angle (distance from focal point to sensor approx. 2.5 m); measurement range: length up to 800 mm, diameter up to 700 mm; length measurement error MPE E: (4.5+L/100) µm, L in mm
motic software correction. Typical area sensors (see Fig. 15, p. 20) have about $1000 \times 1000$ or $2000 \times 2000$ pixels. The dimensions of the pixels are between 50 and 400 µm. The size of the sensor determines the largest possible object that can be measured “in the image” at low magnification without using raster tomography. For the same cone angle, a larger area sensor requires a larger measuring machine than a smaller sensor. Large sensors therefore make sense only if a large measurement area is required.

The image scale between the object plane and the sensor (usually, but not entirely accurately, referred to as the magnification) is in principle greater for large sensors with large pixels, because a greater distance is needed to form an image of the object for the same cone angle size. However, this is only an illusionary advantage. The image scale must always be considered in conjunction with the pixel size of the sensor. The size of the voxels in the object plane is critical for the resolution and thus the measurement error. With the same number of pixels, a smaller sensor using less installation space provides the same resolution in the object plane as a

Fig. 20:
Matrix X-ray sensor with scintillator: The X-ray image is converted into an image in the visible spectrum by the scintillator (a). The photo sensor array (b) converts this into electronic signals.
Quality and precision, together with innovation, have formed the basis for over 60 years of successful corporate growth at Werth Messtechnik GmbH. The first console profile projector set ergonomic standards in 1955. From the 1960s through the 1980s, measurement projectors with the Werth Tastauge, probe eye, and digital travel measurement were developed into CNC coordinate measuring machines by Werth Messtechnik. The first multisensor coordinate measuring machine, the Inspector, with integrated image processing and laser distance sensors followed in 1987. The introduction of the VideoCheck® product line in 1992 was the cornerstone for further corporate growth. Early integration of PC technology and a strictly modular concept enabled high performance at acceptable prices. Werth Messtechnik grew to be the largest European provider of optical and multisensor coordinate measuring machines by a wide margin. The integration of linear drive technology in coordinate measuring machines and sensor developments like the Werth Fiber Probe and the Werth Zoom confirmed the claim that Werth Messtechnik GmbH is the worldwide technology leader in this market segment. With the TomoScope®, Werth presented the first machine developed especially for coordinate measuring technology with X-ray tomography. Innovative solutions improved the accuracy of this measurement principle to the level of coordinate measuring technology. Complete integration of all functions required for tomography in the WinWerth® software package has provided simple, timesaving, reliable operation.

Double digit annual growth rates for nearly two decades have enabled the development of a highly motivated team. Over 200 employees in Germany, along with sales and service support organizations in every important industrial country, ensure that Werth Messtechnik will continue to provide cutting edge coordinate measuring technology in the future with optical sensors, multisensors, and X-ray tomography with outstanding quality and excellent service.