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X-ray Tomography in Industrial Metrology

Precise, Economical and Universal

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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,

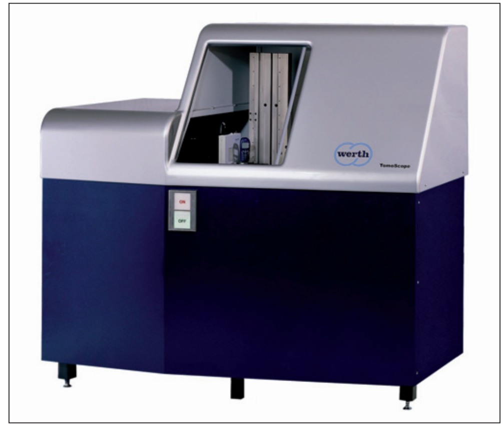

Fig. 1: Werth TomoScope® 200: the first coordinate measuring machine with X-ray tomography – multisensor capabilities optional

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.

2005: first coordinate measuring machine with X-ray tomography

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 workpiece is rotated

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

Absorption of the X-ray beam represents the penetrated workpiece length

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

process is analogous to the creation of a shadow image of a partially transparent object by illuminating it with a point source of light. The brightness levels in the X-ray image correspond to the transparency of the penetrated areas and thus depend on their material density.

Cone beam tomography captures objects in three dimensions

The cone-shaped X-ray beam produces two-dimensional radiographic images of the object. The X-ray tomography sensor creates these images in an analogous manner to the image sensor in a digital camera. It provides the images in digital form for further analysis. In order to use tomography on an object, several hundred to a few thousand of such two-dimensional radiographic images are made in sequence. The sequence is made with the measured object in numerous accurately known rotated positions (Fig. 2). The three-dimensional information about the measured object is contained in the digital image sequence thus generated. Using suitable mathematical methods, a volume model that describes the entire geometry and material composition of the workpiece can be calculated from this sequence. Due to the beam shape, this process is called *cone beam tomography*.

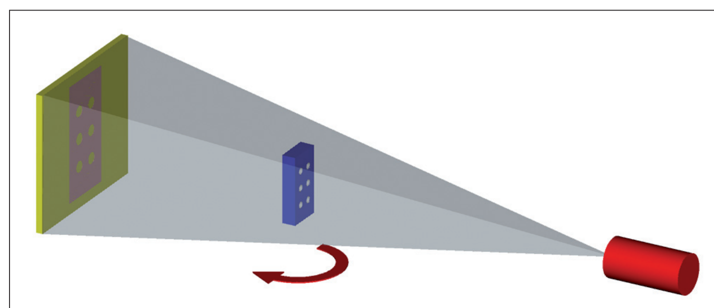

Fig. 2: Principle of X-ray tomography

Measurability of smaller structures using rastering

ter tomography a voxel size of 0.25 mm is achieved with 800 voxels per 200 mm of part length. To calculate a feature (e.g. a radius) several measurement points, and thus several voxels, are always required. The smallest structures that can be practically measured in this example are about 1 mm to 3 mm in size. With quintuple rastering (five positions along the rotary axis), for example, about 4800 voxels are captured per 200 mm of part length with a voxel size of 0.04 mm. The smallest structures that can be measured are thus approximately 0.15 to 0.5 mm.

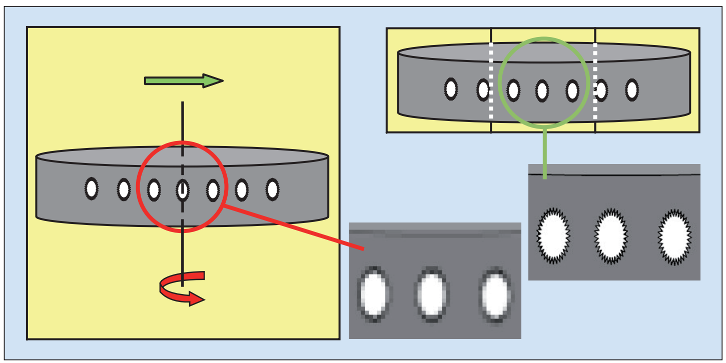

Fig. 14: Raster tomography perpendicular to the rotary axis

If the diameter of the enveloping circle of the measured object is larger than the sensor size in the workpiece plane (e. g. disc shaped parts), the rastering must be done perpendicular to the rotary axis (Fig. 14). For compact measured objects, raster tomography can also be done in both directions at once.

Machine Technology and Design Variations

Machine configuration adapted to the measurement task

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

How an X-ray tube works

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

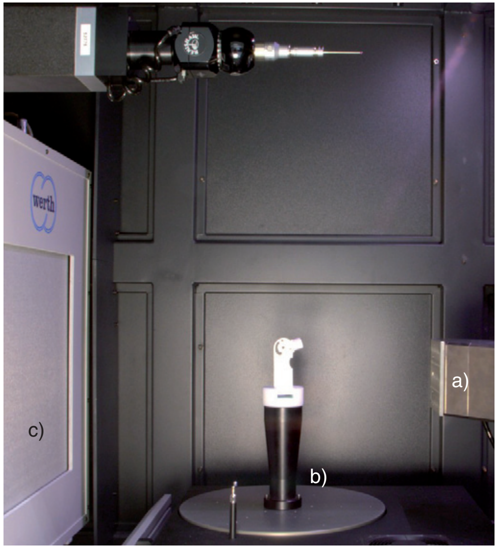

Fig. 15:
The core components of tomography:
a) 225 kV microfocus X-ray tube
b) High precision, air bearing rotary axis
c) X-ray sensor with about 2000 × 2000 pixels

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.

Cathode voltage affects the radiated spectrum

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

130 kV is sufficient. If parts that contain metal are to be measured, a higher voltage is required. Linear accelerators can generate X-rays with higher energy than those produced by X-ray tubes. They are currently used only rarely due to their high cost. High-energy radiation produced by accelerators can be used for penetration and tomography of very large metal objects, such as complete engine blocks.

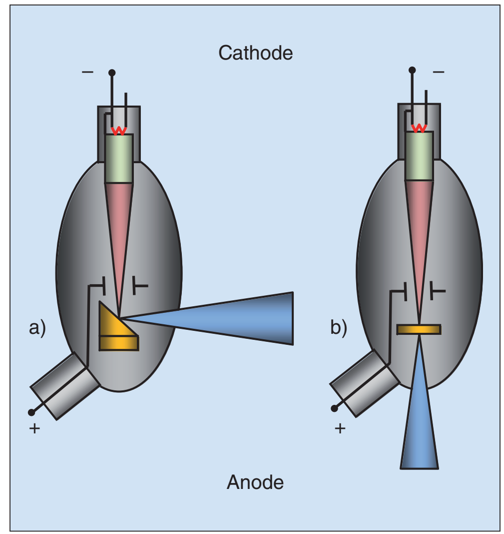

Fig. 16:
Principle of X-ray generation: The heated cathode emits electrons in a vacuum. They are accelerated by the electric field between the cathode and anode. When they impact the target, the electron radiation is converted to X-rays.
a) Reflection target
b) Transmission target

The target determines the usable X-ray spectrum

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 in conjunction with the available minimum focal spot size.

Reflection targets for short measurement times

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, but at the cost of lower resolution. The minimum focal spot size that can be achieved with a reflection target tube is a few microns. This is sufficient, in principle, for many measurement tasks, where a structural resolution in the micron range is seldom required. With sub-voxeling, nevertheless, measurement errors of less than 1 µm can be obtained. The decisive disadvantage of reflection targets, however, is that small focal spot sizes can be achieved only with very low power and thus longer measurement times (typically 5 µm at 5 W).

Transmissions targets for high resolution

Transmission targets are penetrated by the X-rays, which 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. Also using transmission targets, the focal spot size depends on the power setting. In recent years, however, transmission target tubes have been developed that greatly reduce this effect in comparison with reflection target tubes. It is thus possible to achieve a small focal spot even at medium power levels (typically 5 µm at 25 W). Very high requirements for resolution can thereby be met even for larger workpieces and relatively short measurement times. For lower resolution requirements and higher power levels, deliberate defocusing is used to limit the power density at the target and thus to increase its service life.

Open and closed tube styles

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 by hermetically sealing the vacuum chamber. Closed X-ray tubes are available as reflection target tubes for voltages up to about 150 kV. These tubes can be used over a service life of several years without maintenance. After this period, the complete X-ray tube must be replaced.

Maintenance of X-ray tubes

Microfocus X-ray tubes with voltages above 150 kV and transmission target tubes are built as open systems, because the wear on the electrodes is higher and thus regular maintenance is required. For open X-ray tubes, the vacuum is generated by a separate vacuum pump during operation. This makes it possible to open the X-ray tubes for servicing. Considering the maintenance costs of open systems and replacement costs for closed systems, the cost to operate both types of tubes is similar. Newer systems with transmission target and *monoblock design* (tube, vacuum pump, and high-voltage generator in a single unit) provide the advantages of both designs and allow good resolution at high power with low maintenance costs.

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

Heat is dissipated

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.

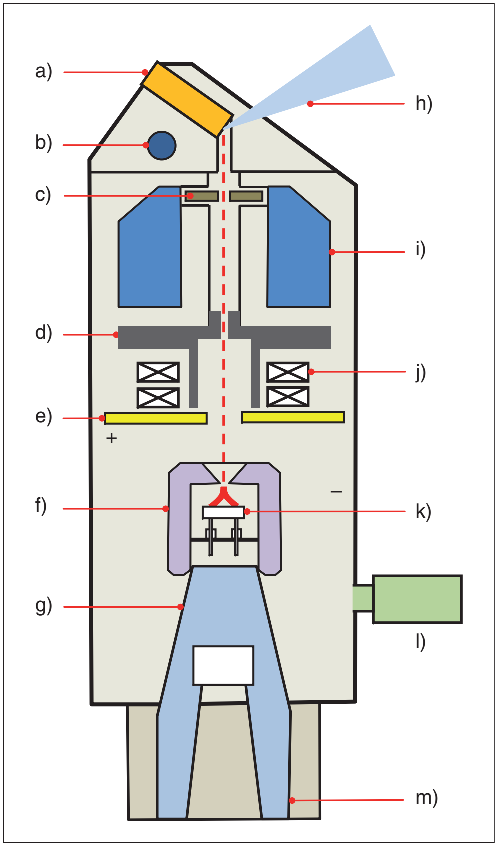

Fig. 17:
Schematic of a 225 kV microfocus X-ray tube with open construction:
a) Reflection target
b) Water cooling
c) Centering aperture
d) Shutter target
e) Anode
f) Grid
g) Isolator
h) Usable beam cone
i) Focusing coil
j) Centering and deflecting coils
k) Filament/cathode
l) Vacuum pump
m) High voltage cable connector
(Source: Viscom AG, Hannover, Germany)

Rotary Axis

The measured object is rotated

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. Thus, proven components from coordinate measuring technology can also be used.

The rotary axis greatly affects precision

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-

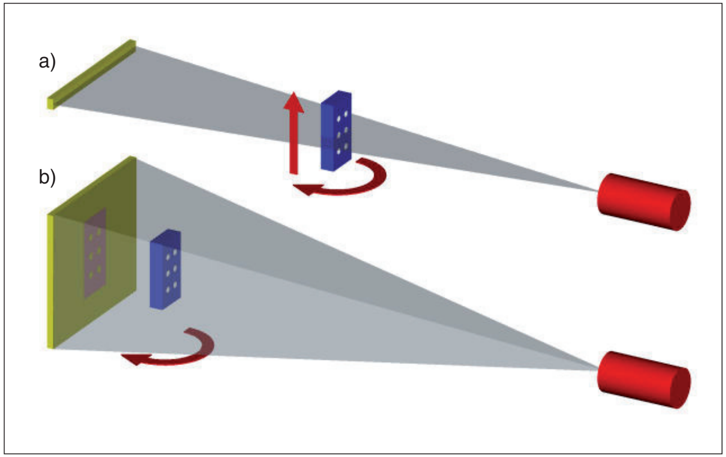

Fig. 18: Tomography using a line sensor (a) and an area sensor (b)

tary position. Compared to using an area sensor with, for example, 1000 lines, this would require 1000 times the measurement time if all other parameters are equal. The energy of the X-ray source is utilized much less efficiently, because only a single fan of the beam cone is used.

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).

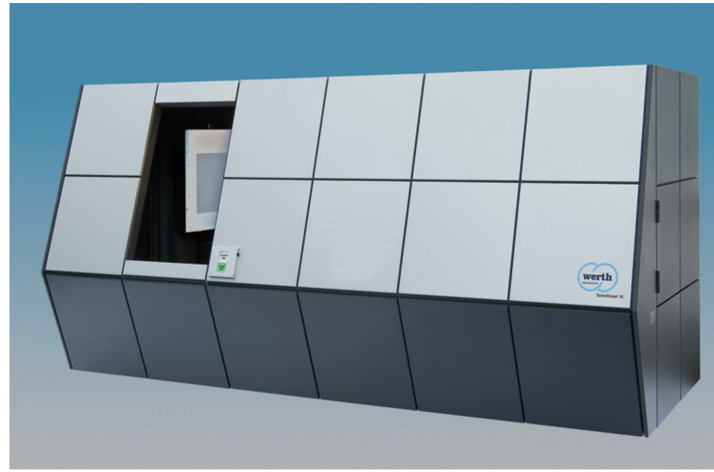

Fig. 19: Werth TomoScope® XL: Coordinate measuring machine with X-ray tomography for the most stringent requirements with a small cone beam angle (distance from focal point to sensor approx. 2.5 m); measurement range: length up to 800 mm, diameter up to 700 mm; length measurement error MPE E: (4.5+L/100) µm, L in mm

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-

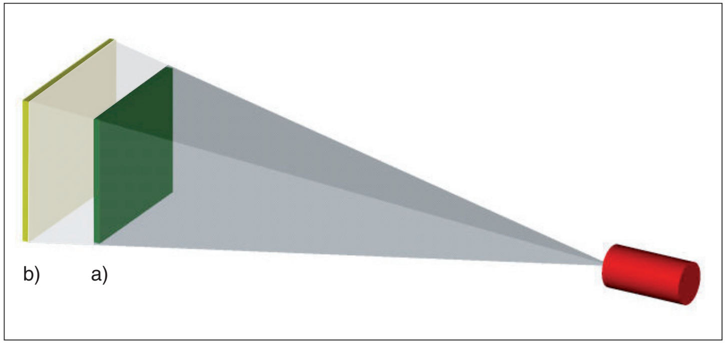

Fig. 20:
Matrix X-ray sensor with scintillator: The X-ray image is converted into an image in the visible spectrum by the scintillator (a). The photo sensor array (b) converts this into electronic signals.

matic software correction. Typical area sensors (see Fig. 15, p. 20) have about 1000 × 1000 or 2000 × 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.

Pixel size and image scale affect resolution

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 large sensor with a larger installation space (Fig. 21). The resolution can be increased by using a sensor with more pixels or by raster tomography.

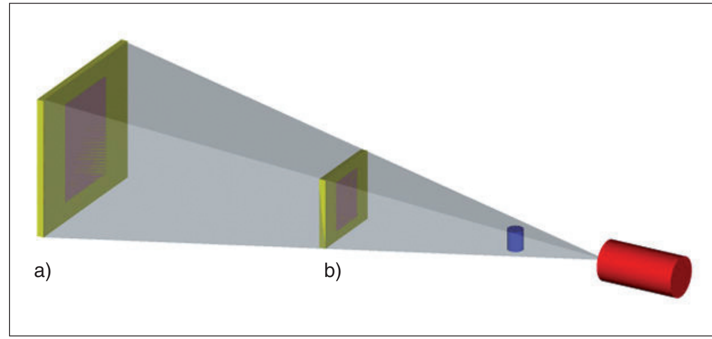

Fig. 21:
Magnification and measurement range for different sensor sizes – resolution is independent of the sensor size:
a) Large sensor
b) Small sensor

Linear Axes

Adjustability provides flexibility

If a measuring machine is not designed specifically for a dedicated application, but is intended to have flexibility, linear axes are needed in addition to the rotary axis. They serve to adjust the magnification to position the workpiece and to support rastering, among other things.

In the simplest case, only one linear axis is needed to shift the rotary axis along the X-ray beam path. This can be used to adjust the magnification and therefore the measuring range and the resolution (Fig. 22a). With this machine design, tomography can be performed only "in the image", that means the size of the components that can be measured is limited directly by the size of the sensor. It is also not possible to measure details at a higher resolution without moving the part manually.

To give the user the ability to position the workpiece optimally in the X-ray beam path, it must be possible to adjust the relative position

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The Company behind this Book

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In 2016, Werth Messtechnik GmbH celebrated its 65th 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.

In 1987, a multisensor coordinate measuring machine with image processing and an integrated laser sensor was presented with the name Inspector®. With the VideoCheck® product line, Werth pioneered the widespread use of digital image processing in the 1990s. Early integration of PC technology and a strictly modular concept enabled high performance at acceptable prices. Werth Messtechnik has developed into the largest European provider of optical and multisensor coordinate metrology.

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 the claim that Werth Messtechnik GmbH is the worldwide technology leader in this market. Modern developments in the field of software such as BestFit, ToleranceFit®, or WinWerth® AutoElement complete the picture.

Stable growth rates for almost three 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.