3D RECONSTRUCTIONS OF MICRO-SYSTEMS USING X-RAY TOMOGRAPHIC METHODS

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Abstract: During the last years tomographic X-ray investigation methods have been transferred from research centers to industrial labs and have been used for research and development as well as quality control. At the moment 3-dimensional tomographic methods are introduced into production for process survey and in-line control. Furthermore there is a trend towards highly accurate tomographic systems with resolutions down to several microns or even several hundreds of nanometers resulting in new demands for those systems.
Region of interest reconstruction methods have to be applied to objects with large expansion in two dimensions in order to achieve a high resolution within a small volume. For this purpose problem optimized scanning and reconstruction algorithms are necessary.
In this paper we present the state of the art of high-resolution industrial X-ray CT and laminography systems. As an example a new cost effective, small and fast tabletop mini 3D-CT system is shown. It allows the usage of µ-CT in many trades as e.g. seed production, or plastics, Al-casting or electronic industry. In combination with laminographic methods as tomosynthesis or swing-laminography this system can be used as well for the inspection of flat components. First results will be presented.

Introduction: High demands on the quality of materials and technical components require non-destructive testing methods for the optimisation of production processes. The wish to determine, characterise and measure voluminous defects requires fast non-destructive testing methods with a high geometrical and contrast resolution.
X-ray irradiation is well known as a non-destructive testing method for technical components. However using a simple irradiation technique there is no possibility to get any information about the depth of the imaged structures from a single projection. As early as twenty-two years after the discovery of X-rays it was mathematically shown that it is possible to calculate the density distribution of an object from its X-ray projections [1]. This led to the development of computed tomography (CT) in the medical field in the early 70^{th}. Since the 80^{th} CT is also used for the examination of technical objects. Two dimensional CT (2D-CT) with a line detector reconstructs with one measurement – a complete rotation of the object – one slice of the object. An examination of the whole volume of an object with two-dimensional CT (2D-CT) is very time consuming due to the fact that a large number of object slices have to be measured and reconstructed one after each other. For each measurement the object has to be completely rotated.
This difficulty can be overcome by the three-dimensional CT (3D-CT). Instead of a line detector a two-dimensional flat X-ray detector is used and only one rotation is necessary to obtain the information for the reconstruction of the whole object volume. So significant shorter inspection times can be reached compared with the situation in 2D-CT.
The three-dimensional distribution of the linear absorption coefficient can be reconstructed from the projections using mathematical reconstruction algorithms. Optimisation and parallelisation of such algorithms can lead to fast reconstruction methods, which are even suitable for the examination of random samples in industrial applications. Figure 1 shows the principle of a 3D-CT measurement geometry.

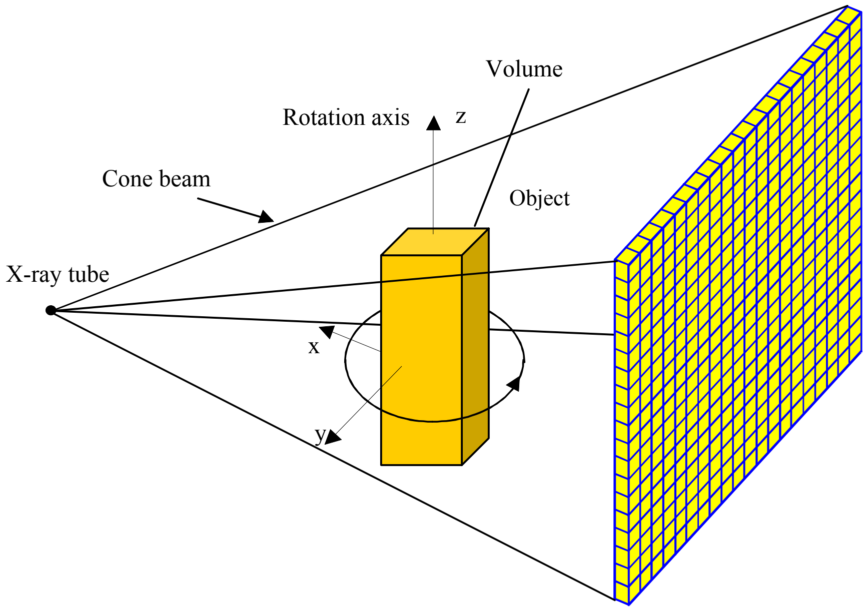

Fig. 1: Principle of a3D CT geometry

As seen CT allows a 3D imaging of objects, but with the restriction that the object has to be irradiated from 360 degrees. In case of flat components, e.g. multilayer printed circuit boards, this is not always possible because of high absorption and limited access.
In contrast to that laminographic methods are able to deal with such a situation. This allows the determination of the position of inner structures even for flat objects. In principle laminography uses a relative motion of the x-ray source, the detector and the object. The x-ray source and the detector are either moved synchronously on circles or are simply translated in opposite directions as shown in Figure 2. Alternatively one of these components can remain stationary and the object is moved. The locations of the projected images of points within the object move also.
In case of classical laminography one uses an integrating detector and only the points from a particular slice, the so called focal slice, will be projected always at the same location onto the detector and therefore imaged sharply. All other object structures will be permanently projected at different locations. They aren't imaged sharply and will be superimposed as a background intensity to the focal slice. This principle of superimposing projections is also called tomosynthesis. The main disadvantages of classical laminography are the reduction of contrast resolution caused by the smearing of the background intensity, the complicated mechanical scanning system and the fact that in each measurement only one slice is imaged sharply. All other slices have to be inspected consecutively by displacing the object vertically.

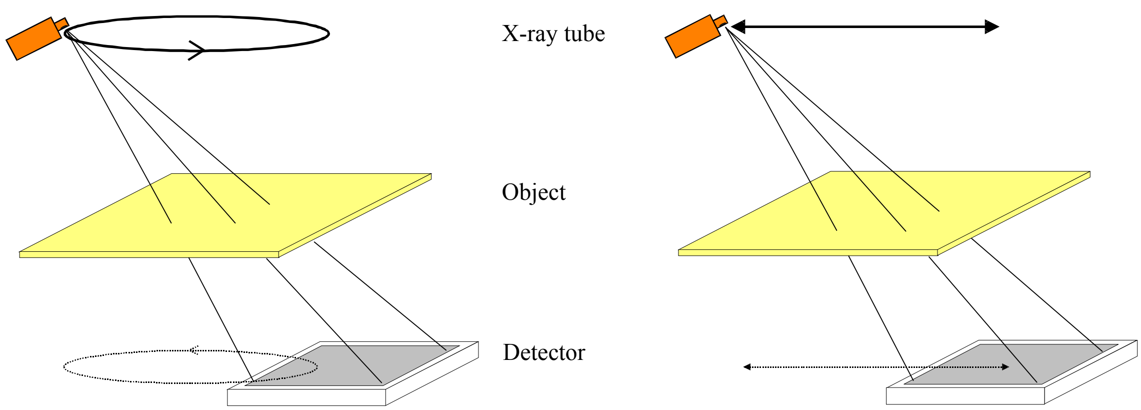

Fig. 2: Principle of rotational (left) and translational (right) laminography

Digital laminography allows to overcome at least the last restriction. A digital X-ray detector is used instead of an integrating film so that a series of discrete projections can be stored on a PC. The data of all object layers can be obtained with only one measurement by resorting them, see Figure 3. Because of this it becomes possible to examine the whole volume of an object within acceptable times [2].

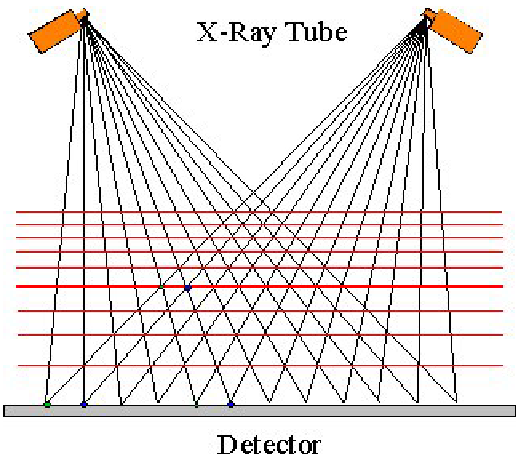

Fig. 3: Principle of digital laminography

Moreover one is able to reconstruct the projection data measured under many angles using mathematical reconstruction algorithms like the Algebraic Reconstruction Technique (ART). This leads to a higher contrast resolution and overcomes the smearing out effect of simple tomosynthesis. But it should be mentioned that this reconstruction technique needs more time [3]. A certain method of laminography, that can be done with the conventional setup of a CT system, is the so called swing laminography. The flat object is rotated between the X-ray tube and the digital X-ray detector, but instead of scanning 360° the object is typically rotated with angles Θ of about 90° (Figure 4). This allows a placement of the object just in front of the tube and leads to a very high resolution and a region of interest measurement. The reconstruction can be done with ART. This method allows the upgrade of every conventional CT system.

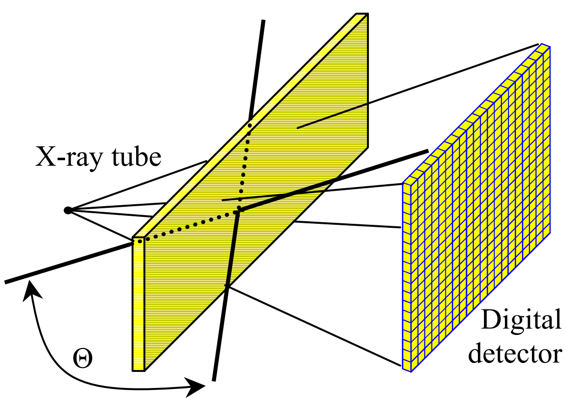

Fig. 4: Principle of swing laminography

Results: Modern demands on CT are fast measurements with high geometrical and good contrast resolution, with as low costs as possible. Unfortunately this are mainly opposed requirements what is clarified in Figure 5.

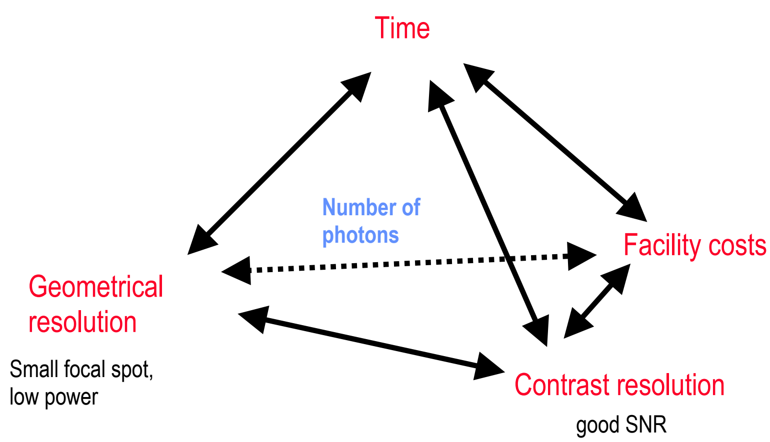

Fig. 5: Boundary conditions of a CT measurement.

In order to achieve a broad acceptance and application of 3D-CT in industry, considerable developments and optimizations have been necessary. A lot of work has been done to optimize the reconstruction algorithms, in order to be online with a fast measurement. Table 1 shows the state of the art of 3D-CT using simple Pentium IV PCs for the reconstruction.
Furthermore the Fraunhofer Development Center X-Ray Technology actually developed diamond based high power transmission targets for high resolution µ-focus applications, that allow an order of magnitude higher photon output compared with conventional transmission targets. These new targets help to enhance contrast resolution and safe measurement time. First prototype X-ray tubes are developed together with industrial tube manufacturers.
Figures 6 to 10 give an impression of the potential of high resolution 3D-CT and thus of the achieved improvement of CT during the last few years. Measurements with voxel sizes below 5 µm and measurement times of several minutes are state of the art.

Reconstructed volume	Views	Image Data [GByte]	Volume Data [GByte]	Measure-ment Time [min]	Reconstruction time, one PC	PCs for online-reconstruction
511 x 511 Pixels 450 Slices	400	0.2	0.225	2 – 15	Online	1
1023 x 1023 Pixels 900 Slices	800	1.8	1.8	15 - 60	50 min	1 - 3
2047 x 2047 Pixels 1800 Slices	1600	6.4	14.5	30 - 120	580 min	5 - 20

Table 1: typical measurement and reconstruction times for 3D CT measurements, referring to 3.0 GHz Pentium IV PCs

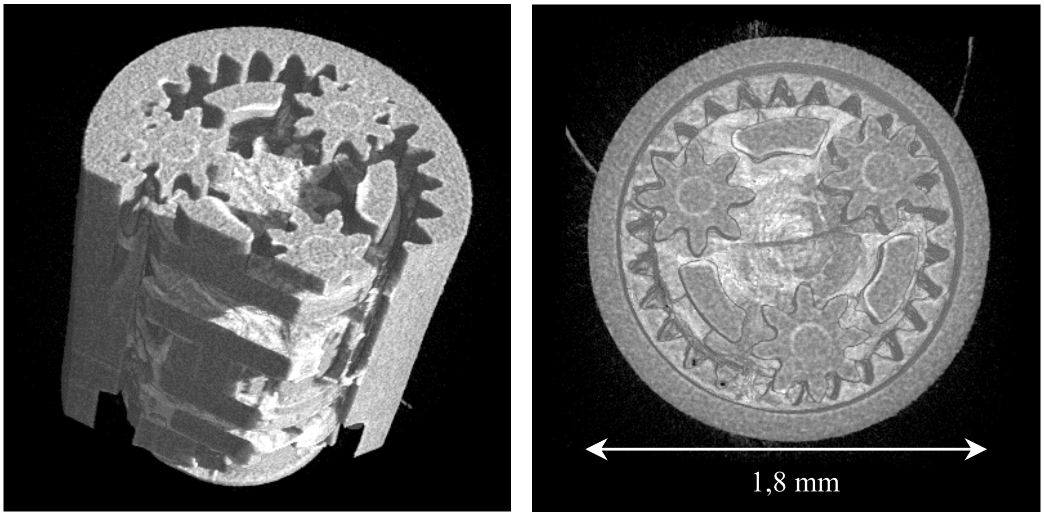

Fig. 6: 3D-CT of a plastic gear box of a medical endoscope, 3 µm voxel size

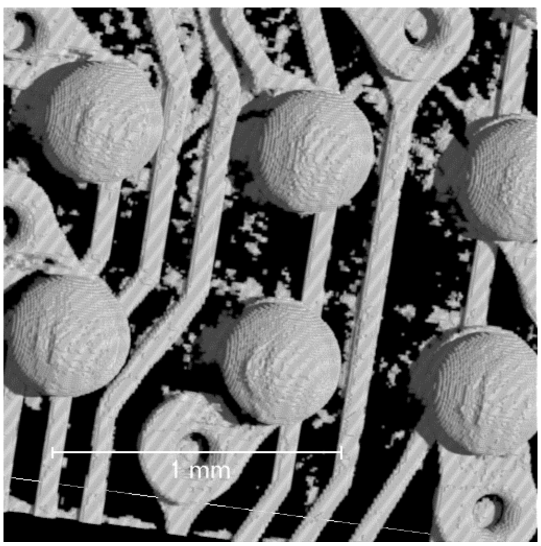

Fig. 7: 3D-CT on a micro ball grid, 3 µm voxel size

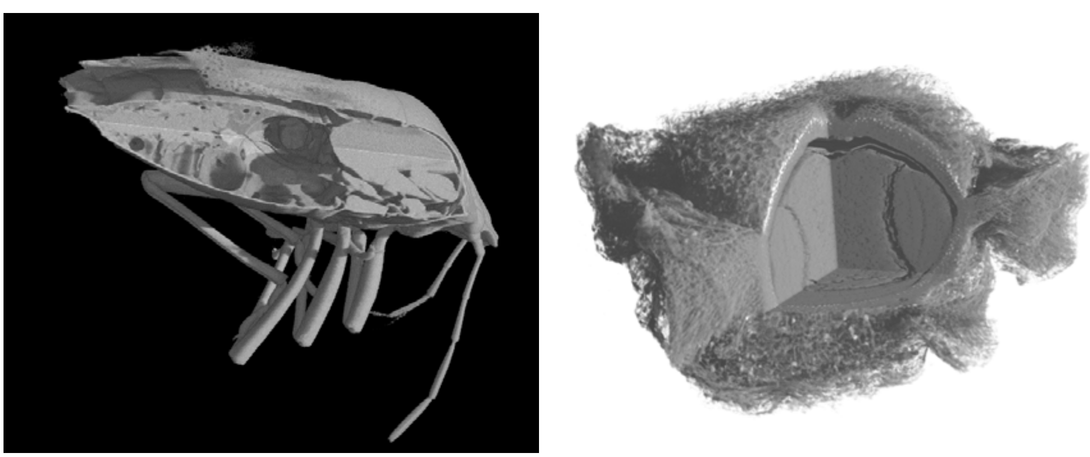

Fig. 8: CT on low absorbing biological samples; bug measured with 10 µm voxel size (left) and seed of a sugar beet measured with 5 µm voxel size (right)

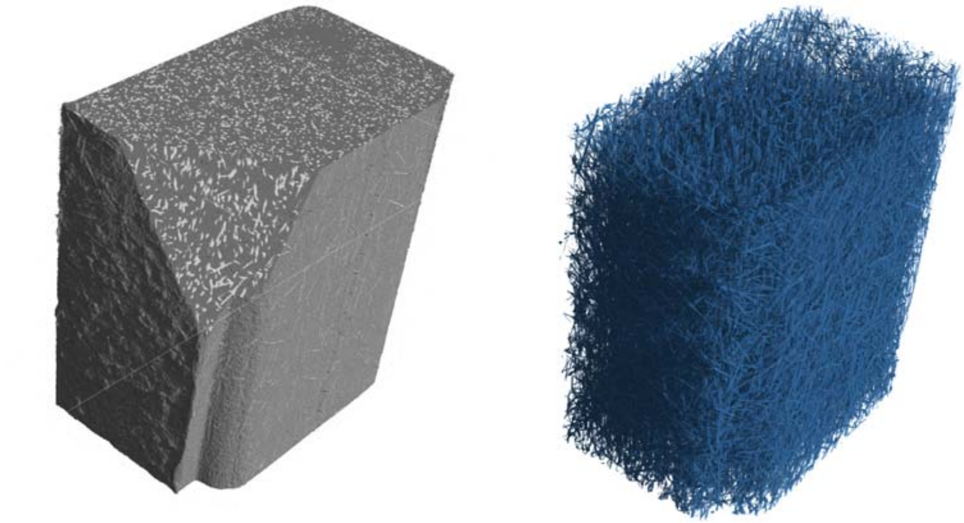

Fig. 9: 3D-CT on low absorbing fibre enforced plastics, 4 µm voxel size

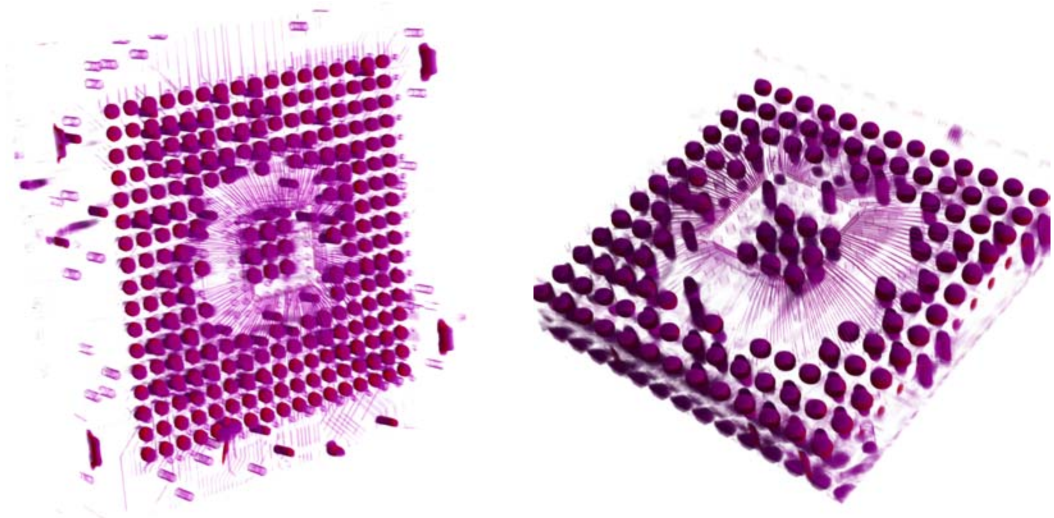

Fig. 10: Swing laminography with an angle of 90°of a Pentium IV chip, 15 µm (left) and 8 µm (right) voxel size

Discussion and Outlook: There are several developments in the field of industrial CT. Figure 11 shows the basic configuration of a high resolution 3D-CT table top system that allows the examination of small plastic, light metal or biological samples as seen before. Due to its cost/performance ratio it fulfils the requirement to promote the application of X-ray CT in the industrial production as well as in research and development.

Furthermore fully automatic 3D-CT systems with very fast measurement and reconstruction times of less that 15 seconds in combination with an automatic online 3D analysis, are developed in order to achieve a 3D inline inspection that could replace the currently common inline inspection with X-ray irradiation [4].

The development of better detectors and improved targets for X-ray tubes opens the door for applications that need even higher resolutions as shown within reasonable times. This offers new possibilities for non-destructive testing, as well as for the application of 3D-CT as a tool for dimensional measurement, which currently is object of research.

The combination of CT with laminographic methods as the swing laminography will enlarge the spectrum of applications.

Fig. 11: Movable 3D-CT table top system

Conclusions: The state of the art of industrial 3D-CT has been shown. 3D-CT is no longer only a method for laboratories but can as well be used as a powerful instrument in the industrial production processes. Combination with laminographic methods even enlarges the area of application. The development of small, cost effective systems will abed the propagation of CT in industry.

References:

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