Advanced X-ray computed tomography methods: High resolution CT, quantitative CT, 4DCT and phase contrast CT

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Abstract
During the last years, a number of novel X-ray imaging and data processing methods have been developed. This work gives an overview of some recent CT-developments:
1) High resolution CT: State of the art laboratory CT-systems are able to reach resolutions down to 0.7 µm (or even lower) and voxels sizes down to 50 nm. Several applications of high-resolution CT are presented and discussed.
2) Quantitative CT: In the beginning of industrial CT mainly images were generated for visual inspection. Nowadays software tools and methods are getting increasingly important to determine quantitative data from CT scans with reasonable accuracy. These quantitative values can be lengths, diameters, distances, fibre orientations, porosity values, parameters characterizing the 3D-microstructure, etc.
3) 4DCT or In-situ CT: Typical 4DCT and in-situ investigations include the thermo-mechanical behaviour (tension, compression, torsion at different temperatures) of materials, phase transitions, physical reactions (e.g. melting, sintering, diffusion...), chemical reactions, etc. CT is one of the most powerful methods for in-situ investigations of a material since it generates the complete 3D information without, in most of the cases, affecting the studied system.
4) Phase contrast CT: X-ray computed tomography phase imaging methods can be classified into propagation based methods, interferometric methods and other techniques. In this presentation, we compare an interferometric method based on the Talbot-Lau interferometer with propagation based phase contrast CT-methods and discuss the possibilities and restrictions.
5.) Further trends: In addition we report on further trends and methods such as XXL-CT / Robot-CT, In-line CT/High speed CT, coupling of CT with material simulation, application of new X-ray sources and detectors (e.g. photon counting detectors), application of multi-energy techniques, etc.

Keywords: X-ray computed tomography, grating interferometer, phase contrast, new CT-methods, quantitative CT, robot CT

1. Introduction and Motivation

X-ray computed tomography (CT) has become very important as a 3D imaging and measurement method for various domains, e.g. materials science, biomedicine, security services [1-5]. CT is a non-touching, non-destructive method which reveals the complete 3D-geometry of a specimen including inner surfaces. For research CT is an excellent tool to support the development of new materials, new processes and new parts, but it is also used for quality control and failure analysis. Some rough estimates of the worldwide industrial CT-market in 2015 are:

- 2000-3000 CT-systems for non-medical applications worldwide
- >30 CT-suppliers including small companies and big international enterprises
- >10 CT-Software companies (e.g. Volume Graphics VGStudioMax, FEI Visualization Sciences Group Avizo, …)
- Several CT-standards are available: VDI/VDE 3630 for metrology and DIN EN 16016-1:2011 for non-destructive testing, ASTM E 1695 (Standard test method for measurement of CT system performance) and ASTM E 1441 and ASTM E 1570 (Standard practice for CT), ISO 15708-1 and 2 for non-destructive testing. In addition the ISO TC 213 WG 10 is working on future ISO 10360-standards for CT applied to metrology [1,2,5].
The industrial CT-market is a steadily growing market but the full potential for industry is not yet tapped. There are many useful applications which still have to be discovered. Since CT is applicable for a widespread variety of materials and the achievable resolutions are adequate for a large number of applications, CT is the method of choice in many domains:

- The original and still the most important application area of CT is non-destructive testing (NDT) and materials characterization. While for NDT internal structures like shrink holes, material inclusions or cracks, are of special interest, in materials science the 3D-characterization of different phases and/ or filler materials are crucial [1,2,3,6].
- The second major application area of CT is metrology for dimensional measurements of 3D geometry features, mainly in the field of quality control. The primary interest in metrology is the measurement of crucial distances, wall-thicknesses, diameters and the 3D-geometry of inner and outer surfaces in general as well as the evaluation of their tolerances.
- Another important application area of CT is reverse engineering and rapid prototyping: A computer aided design (CAD) model is extracted from a CT scan, which allows for reproductions and duplications of components by means of rapid prototyping techniques [4,5].
- CT is also beneficial in the field of virtual prototyping. In virtual prototyping using CT, digital models of scanned prototypes are generated. CT for virtual prototyping enables improvements of the geometry of prototypes in the preproduction phase. In addition, modelling and calculation of material properties can be performed based on CT data, e.g., for the design of filler media or for the design of fibre-reinforced polymeric parts [1,2,3].
- Further applications of high resolution CT are found in the fields of biomedical sciences for applications, where the resolution of typical medical CT systems is not sufficient anymore [19,20].
- Many other useful applications of CT are found in the fields of security, geology, the arts, or archaeology [1,2].

This contribution aims to give an overview of some trends and development in the field of industrial X-ray computed tomography. Some of the most important trends and advanced CT-methods for industrial applications are summarized in Table 1.

<table>
<thead>
<tr>
<th>Trend</th>
<th>Method</th>
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<tbody>
<tr>
<td>Higher resolution</td>
<td>Micro-, Sub-micro and Nano-CT with &lt; (1 µm)^3 voxel size</td>
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<tr>
<td>Extraction of quantitative data,</td>
<td>Quantitative CT, application of advanced image processing methods for</td>
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<tr>
<td>CT as a measurement tool</td>
<td>CT data including reconstruction, denoising, segmentation, feature</td>
</tr>
<tr>
<td></td>
<td>extraction, feature characterization, visualization, etc.</td>
</tr>
<tr>
<td>Observation of a process</td>
<td>4DCT/In-situ CT (mechanical loading, solidification, etc.)</td>
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<tr>
<td>New modalities of CT imaging</td>
<td>Phase-contrast CT (Propagation based phase contrast CT, grating</td>
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<td></td>
<td>interferometer CT, crystal interferometer CT and analyzer based</td>
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<tr>
<td></td>
<td>imaging)</td>
</tr>
<tr>
<td>Scanning of bigger parts</td>
<td>XXL-CT and Robot-CT for parts and products &gt; 3 m</td>
</tr>
</tbody>
</table>
Higher speed | In-line CT/High speed CT with an inspection of < 1-5 minutes per part
---|---
CT as a tool for materials science and product development | Coupling of CT with material simulation and FEM (finite element method)
Elemental / Spectral imaging | Application of multi-energy techniques, photon counting detectors, X-ray fluorescence tomography, etc.

Table 1 gives an idea of some of the main current trends, but there are several others in hardware and software for CT like the development of:

- new X-ray tubes: 600 kV - 800 kV-tubes, liquid metal jet tube etc.
- new detectors: photon counting detectors (Medipix, Timepix,..) etc.
- new reconstruction and scanning geometries (e.g. algebraic reconstruction, discrete tomography, laminography)
- advanced CT-data processing methods

2. Results and Discussion

2.1 Micro-, Sub-micro and Nano-CT

Laboratory cone beam X-ray computed tomography is one of the most promising and the most common methods for non-destructive and full 3D-characterizations of materials and components. In recent years, industrial CT devices have been continuously improved to achieve higher resolutions and higher accuracies. It is now possible to reach resolutions below 1 µm and voxel sizes below 0.1 µm. Table 2 gives an overview of commercial CT-devices with resolutions below 1 µm and macroscopic field of views (FOV), this means that the specimen can have a diameter of approximately 1 mm. This relatively large FOV is a big advantage for practical usage and sample handling compared to devices like the Xradia 810, which has a FOV of 65 µm and is listed in the table in addition.

Table 2: Overview of laboratory sub-micro and nano-CT-systems with resolutions and voxel sizes <1 µm.

<table>
<thead>
<tr>
<th>CT-Device</th>
<th>Best resolution [µm]</th>
<th>Minimum voxel size [nm³]</th>
<th>Max. Sample size [mm]</th>
<th>Ref./ Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE phoenix nanotom m</td>
<td>~1.0</td>
<td>300</td>
<td>250 x 240</td>
<td>[<a href="http://www.ge-mcs.com/download/x-ray/phoenix-x-ray/nanotom_m_s_DE_GEIT-0113">www.ge-mcs.com/download/x-ray/phoenix-x-ray/nanotom_m_s_DE_GEIT-0113</a>]</td>
</tr>
<tr>
<td>Bruker Skyscan 2211</td>
<td>~0.9</td>
<td>100</td>
<td>Diameter: 204 Length: 200</td>
<td>[<a href="http://www.skyscan.be/products/2211">www.skyscan.be/products/2211</a>]</td>
</tr>
<tr>
<td>Zeiss Xradia 510 Versa</td>
<td>~0.7</td>
<td>70</td>
<td>up to 300</td>
<td>[<a href="http://www.xradia.com/versaxrm-510">www.xradia.com/versaxrm-510</a>]</td>
</tr>
<tr>
<td>NanoXCT</td>
<td>-</td>
<td>50</td>
<td>several mm</td>
<td>[<a href="http://www.nanoxct.eu">www.nanoxct.eu</a>, demonstrator available at RayScan]</td>
</tr>
<tr>
<td>Zeiss Xradia 810 Ultra</td>
<td>~0.05</td>
<td>16</td>
<td>0.065 (FOV)</td>
<td>[<a href="http://www.xradia.com/zeiss-xradia-810-ultra">www.xradia.com/zeiss-xradia-810-ultra</a>]</td>
</tr>
</tbody>
</table>
As examples, Fig. 1 shows some high resolution images. The left picture in Fig. 1 shows a radioscopic picture generated by the NanoXCT-system demonstrating the ability to resolve 150 nm JIMA lines and spaces. The right picture in Fig. 1 shows a cross-sectional image of a wood chip measured with Nanotom at a voxel size of (0.5 µm)³. The cell structure of the wood can be clearly recognized. The thickness of a cell wall is about 2 µm.

2.2. Quantitative CT - Application of Advanced Image Processing methods for CT data

Industrial CT currently transforms from a qualitative diagnostic tool to a quantitative characterization method. Regarding quantitative characterization CT is increasingly used as a measurement device for metrology and for extracting quantitative data in the following areas:

- Pore evaluation of metallic and polymeric foams
- Porosity of metals and polymers
- Fibre orientation, diameter and length of fibre reinforced polymers
- Fibre bundle characterization of technical textiles
- Quantitative data concerning the 3D-structure of inhomogeneous metals or other materials (e.g. interconnectivity, sphericity, etc.)
- Phase identification
- …

In these areas and also others CT-data is used to extract quantitative data. For example, the CT-data of glass fibre reinforced polymers can be processed to extract fibre orientation and fibre length distributions [9]. To do so, the CT-data is processed by several consecutive steps: pre-processing, segmentation, medial axis extraction, individual fibre extraction including cluster analysis and final fibre characterisation [9]. Figure 2 shows fibre length distribution functions of polypropylene granules with 10, 30, 40, 50 and 60 wt.% of glass fibres (PPGF). It is clearly recognisable that the fibre length distribution function is shifted to lower values with increasing fibre content. With higher fibre content more fibres will be broken during the manufacturing (compounding) process.
The right picture of Figure 3 shows a second example for quantitative CT, it’s a high resolution cross-sectional CT-slice of as-cast MgZn6Zr1-alloy (=ZK60) modified with 2.5 wt.% RE (rare earth metals) [10]. CT clearly shows the 3-dimensional structure of the material. The microstructure is formed by a matrix of globular α-Mg grains reinforced by a highly interconnected network of intermetallics along the grain boundaries, originated from the preferential segregation of Zn and RE elements into the liquid phase during solidification. The average dendritic cell size is 150-200 μm, and two distinct morphologies of intermetallic phases are observed: one smooth and another one lamellar, which appears to be eutectic-like. It can also be seen, that the grey values of the intermetallic phases are different, the grey values of the lamellar-like phases are significantly higher. The ZK60+2.5 wt.% RE was compressed at temperatures between 250 °C and 350 °C to investigate the thermo-mechanical behaviour. It can be clearly recognized that damage is found in the form of cracks in the intermetallic phases after deformation at 350 °C. The cracks visible at 250 °C are much smaller. The increase of cracks and of porosity with the compression temperature are shown together with the intermetallic interconnectivity in the right picture of Figure 3. At 350 °C the volume fraction of porosity (cracks) is as high as 5.5 %. The interconnectivity of the intermetallic phases decreases slightly with increasing temperature.
2.3. 4DCT/In-situ CT

4DCT or in-situ CT summarizes different kinds of CT-methods where a process is monitored without (or hardly) affecting the specimen [3]. Typical processes to be investigated using 4DCT are static and dynamic load processes (e.g. tension, compression, torsion,...), the thermo-mechanical behaviour of structural materials, phase transitions, physical reactions (e.g. melting, sintering, diffusion,...), chemical reactions and similar. The main challenge for in-situ CT is the optimal combination of a suitable in-situ setup (e.g., a loading stage) with a CT-device, so that the experiments produce reliable and reproducible results. One has to take into account that the CT-measurement time can be quite long especially at high resolutions and the speed of the process might be rather high so that the process cannot be monitored reliably or if the process is interrupted, relaxation effects might occur. A typical experimental set-up for interrupted in-situ tensile tests is shown in Fig. 4 (left) together with a typical result of such a scan before mechanical loading (right) [11].

![Fig. 4. On the left picture the in-situ tensile/compression stage mounted on the turntable of the Nanotom-CT device is shown. The right picture depict a typical cross-sectional CT-image of a glass fibre reinforced polymer specimen before mechanical loading was applied. Voxel size: (2 µm)^3.](image)

The damage mechanisms can be clearly detected by CT analyses. The main mechanisms are fibre pull-out, fibre fracture, fibre-matrix debonding and matrix cracks. The next figure shows these typical damage mechanisms. The CT-resolution is high enough so that the different mechanisms can be distinguished clearly and a quantitative classification is possible as shown in Fig.5.

![Fig. 5. Cross-sectional CT-images of typical damage mechanisms in glass fibre reinforced polymers: 1.) Matrix cracks, 2.) Fibre breakage, 3.) Fibre pull-out, 4.) Fibre/matrix debonding. The CT-measurements were performed in an in-situ loading stage at 90 % failure force and with a voxel size of (2 µm)^3 [11].](image)

2.4. Phase-contrast CT
Emerging CT-technologies that provide more insight than conventional attenuation based tomography are called phase contrast CT-techniques. They can mainly be divided in four different methods: Propagation based phase contrast CT, Talbot Lau grating interferometer CT, crystal interferometer CT and analyzer based imaging. We will concentrate in this work on the first two methods [12, 13].

2.4.1 Propagation based phase contrast CT
A conventional cone beam CT-system with a polychromatic X-ray source without any X-ray optics can show phase contrast effects when the focal spot size of the tube is low enough. If the focal spot size is around 1 µm or below the spatial coherence length is high enough so that phase contrast effects occur. The maximum spatial coherence and maximum phase contrast can be obtained when the wavelength is large, the focal spot size is small and the source-object distance is large. The influence of propagation based phase contrast on the resulting CT-data and on the detectability of details are shown in Fig. 6. Here the object-detector distance (ODD) is increased from 189 to 486 mm, which results in an increase of the phase contrast and detail detectability.

![Fig. 6. Cross-sectional CT-data of a carbon fibre reinforced polymer sample at different object-detector distances: 189 mm at the left picture and 486 mm at the right picture. Voxel size was constant and set to (2.75 µm)^3 [12].](image)

![Fig. 7. Grey-value profile along a pore from Fig.3 within the CFRP with different object-detector-distances ODD (left picture) and phase contrast values versus object-detector-distance (right picture) [12].](image)

The increase in phase contrast with increasing distance between the object and the detector can be seen also in the grey value profiles along a certain pore. This is shown in the left graphic of Fig. 7. The corresponding phase contrast values for the various distances between
the object and the detector are shown in the right graphic of Fig. 7. The phase contrast values were calculated from the upward and downward overshooting of the grey value profiles across the edges of a pore within the specimen.

2.4.1 Interferometer phase contrast CT

One of the most important and most recent innovations in X-ray technology has emerged by the introduction of the Talbot–Lau grating interferometry (TLGI) [11,14]. In 2002, the Talbot-Lau effect was first utilized for X-ray imaging using monochromatic synchrotron radiation [11,14,15]. The additional use of a source grating enabled the introduction of this technique to polychromatic X-ray sources in 2006 [6]. A Talbot-Lau interferometer is formed by three transmission gratings combined with a state-of-the-art X-ray apparatus with low coherence. TLGI provides three complementary characteristics in a single scan of the specimen:

1) Attenuation contrast (AC) due to absorption
2) Differential phase contrast (DPC) due to refraction
3) Dark-field contrast (DFC) due to scattering

AC provides information on the attenuation of the X-ray beam intensity through the specimen and it is thus equivalent to conventional X-ray imaging. DPC is related to the index of refraction and image contrast is thus achieved through the local deflection of the X-ray beam. DFC reflects the total amount of radiation scattered at small angles, e.g. caused by microscopic inhomogeneities in the sample represented by particles, pores, and fibres. Depending on the micro-structure, the scattering has a preferred direction perpendicular to the local orientation, which is reflected by the measured dark-field signal [17,18].

Fig. 8 shows results of a carbon fibre reinforced polymer (with a porosity around 4%) scanned with Talbot Lau grating interferometer CT. Fig. 8 displays the CT axial slices of the linear absorption coefficient $\mu$, the refraction coefficient $\delta$ and the linear scattering coefficient $\varepsilon$. Here, only the larger macro pores appear, whereas the resolution does not allow seeing the small micro pores within the fibre bundles. In the absorption CT slices, the fibre bundles themselves cannot be distinguished from the epoxy matrix and they appear with limited contrast in the phase contrast CT pictures. However, the fibre bundles are by nature heterogeneous and thus lead to a strong scattering signal. Consequently, the bundles parallel to the section plane appear clearly in the cross-sectional picture of the scattering coefficient in the form of white stripes (right picture).

Fig. 8. Cross-sectional CT pictures of the CFRP sample with absorption contrast (left picture), phase contrast (picture in the centre) and dark field scatter contrast (right picture). Voxel size was (44 µm)$^3$ [17,18].
Figure 9 shows cross-sectional CT pictures of a mole with the modalities absorption contrast, phase contrast/refraction and dark field scatter contrast of a mole. In the pictures the breast of the mole including the lung and the backbone is visible. Within the absorption data the bone has the highest contrast and the lung is almost not visible. In the dark field image the lung and the bone have a similar contrast since the dark field signal is caused by microscopic inhomogeneities in the mole represented by pores and fibres.

Fig. 9. Cross-sectional CT pictures of a mole with absorption contrast (left picture), phase contrast (picture in the centre) and dark field scatter contrast (right picture). The CT-data were acquired with a Talbot-Lau desktop interferometer. Voxel size was (11.4 µm)³.

2.5. XXL-CT and Robot based CT

CT is not only used for small parts but there is also an increasing demand to scan large parts such as containers, whole cars and aeroplane wings. For such applications the geometrical and X-ray penetration have to be overcome. Therefore CT-systems with linear accelerators and X-ray energies up to 10 MeV-range and robot based CT-systems are under continuous development. Aside the generation and detection of photons in the MeV range itself, the achievable image quality is limited using standard detectors due to the dominating absorption effect of Compton scattering at high energies. Especially for CT reconstruction purposes these effects have to be considered on the development path from classical 2D radioscopy to 3D imaging. Most high energy CT applications are therefore based on line detectors, which allow shielding against scattered radiation in order to increase imaging quality but with the drawback of time consuming large volume scan capabilities. Fig. 10 left image shows such an XXL-CT set up. Here a 9 MeV linear accelerator is used as X-ray source, the turntable has a diameter of 3 m and it handles specimens with a weight of up to 10 tones. The X-ray detector is a line detector array with a length of 4 m and a pixel pitch of 400 µm. With such a system entire cars and shipping containers can be scanned with a reasonable quality. Similar “large” CTs can be found at EMPA/CH, BAM/GE and different places in the US.

Fig. 10. XXL-CT set up (left) and prototype of the robot based XCT system “Robo CT” both at Fraunhofer IIS (right image, www.iis.fraunhofer.de/en/them/blogpruef.html/category/etc/tags/iis/XXL-CT)
Other approaches to scan big parts are robot based CT and the application of laminographic methods. Especially regarding robot based CT (Fig. 10, right picture), which shall be applied for non-destructive X-ray inspection of large and bulky objects like aircraft fuselages or fins, large detectors with high sensitivity at low energies are of utmost importance in order to provide quantitative means for testing carbon fiber reinforced components.

2.6. In-line CT/High speed CT

CT has become an important tool within the last ten years in the field of process development and random inspection in serial production. This is due to the unbeatable ability of non-destructive evaluation of inner sample structures. Thereby, acquisition and reconstruction times were reduced from hours to minutes in the case of standard geometries. Future optimizations of the method will result in scanning times of less than a minute, so that a true three dimensional CT testing will be available for series production. The main benefit compared to existing 2D systems will be the exact location and characterization of defects in space, leading to further reduction of rejections in production. Cycle times lower than 1-5 min or even lower than 1 min are mainly possible by:

- Using the preliminary knowledge of the specimen for optimized measurement trajectories/strategies and projections
- Using the preliminary knowledge of the specimen for efficient defect detection and/or geometrical analysis
- Optimization and parallelization of CT data evaluation pipelines optimization of measurement trajectories and projections
- Increasing the tube power and using better detectors

Typical applications are void detection in Aluminum parts, detection of cracks and inclusions in plastic parts, mixed material assembly analysis in multi-material components, metrological analysis of different parts etc. In-line CT suppliers comprise companies such as Carl Zeiss metrology, GE Sensing & Inspection Technologies, Yxlon International and North Star Imaging.

2.7. Coupling of CT with material simulation

The digital nature of a tomographic image enables the generation of digital models (e.g. finite element models (FEM)), which precisely represent the material’s microstructure. Voxel-based CT datasets are therefore converted into finite element meshes, assigning appropriate boundary conditions and material properties [18]. The results can be used to study the material’s effective bulk properties, failure modes, and constitutive behaviour under known load conditions. This allows a new level of understanding of the intrinsic material behaviour in order to develop a simulation model, which may then be further applied to arbitrary load cases and geometries. The digital three-dimensional data obtained from CT can be converted into finite element meshes in several ways. The most straightforward methods involve converting voxels directly into trilinear hexahedral elements or extract a triangle mesh (STL-data) from the CT data. An example for the use of CT data for finite element simulation [19] is shown in Fig. 11. In the left picture an experiment for in-situ CT tensile loading of a GFRP-sample is shown. The fibre extraction pipeline, developed in [9] extracts start and end points of each fibre in the investigated volume, which can be used to create an FEM-simulation model. If load is applied to this virtual specimen one can calculate precisely and visualize forces on the fibres (see right picture).
As shown in Fig. 11 an additional application of CT for simulation is the evaluation and verification of materials models. CT can be used, e.g., to measure the size and distribution of inclusions to be compared with materials simulations [19]. Using CT can also provide important information about damage initiation and progression (in the form of cracks or local delamination) for the development and verification of material models. Another example in this context is the comparison of measured fibre orientations of a GFRP-sample with process simulations for injection moulding.

![Fig. 11. Schematic representations of a fibre-reinforced tensile sample investigated by in-situ CT (left). The dataset was quantitatively evaluated and used for FEM-simulation of the forces (right). The colours represent the strength of the calculated forces [19]](image)

### 2.8. Further trends in industrial CT

There a huge number of further trends and new developments [20]. We can only mention a very few. These trends comprise aspects like:

- New x-ray tubes: 600 KV- and 800 kV-tube (COMET), 750 kV-tube (Nikon), metal jet tube (Excillum),…
- New detectors: photon counting detectors (Medipix, Timepix,…), 4 K x 4 K detector (Perkin Elmer…),…
- Improved and new reconstruction algorithms and scanning strategies (e.g. algebraic reconstruction, statistical reconstruction methods, discrete tomography, laminography, tomosynthesis)
- Improved and new methods for measurement artefact reduction
- Improved and new methods for more accurate CT-simulation
- Advanced CT-data processing methods including denoising, segmentation, feature extraction, feature characterization, visualization etc.
- Elemental CT /spectral imaging by application of multi-energy CT, K-Edge Imaging and X-ray fluorescence tomography
- Multimodal Imaging by combination of X-ray CT with other imaging methods
- And of course new applications of CT in industry (non-destructive testing, 3D-material characterization and metrology) and science
3. Summary and Conclusions

X-ray computed tomography is still an emerging technology with many applications which are not yet known. The main trends are: Better resolution, better accuracy – more quantitative values, faster, bigger, coupling of CT with material simulation and better reconstruction, artefact reduction, simulation, image processing and visualization methods. In this review we have reported on different aspects and trends of industrial CT like:

- High resolution CT
- Quantitative CT
- 4DCT or In-situ CT
- Phase contrast CT
- CT of big parts: XXL-CT / Robot-CT
- In-line CT/High speed CT
- Coupling of CT with material simulation
- Application of new X-ray sources and detectors, application of multi-energy techniques, photon counting detectors etc.

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