Industrial applications of computed tomography

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ABSTRACT

The number of industrial applications of Computed Tomography (CT) is large and rapidly increasing. After a brief market overview, the paper gives a survey of state of the art and upcoming CT technologies, covering types of CT systems, scanning capabilities, and technological advances. The paper contains a survey of application examples from the manufacturing industry as well as from other industries, e.g., electrical and electronic devices, inhomogeneous materials, and from the food industry. Challenges as well as major national and international coordinated activities in the field of industrial CT are also presented.

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1. Introduction

This paper gives an overview of the large and increasing number of industrial applications of X-ray Computed Tomography (CT) in the manufacturing industry as well as in other industries. The paper can be read as a natural continuation of the CIRP 2011 keynote paper describing the use of CT for dimensional quality control purposes: i.e. for traceable measurement and tolerance verification of dimensions on mechanical components [69]. X-ray computed tomography, sometimes abbreviated to XCT or iCT (i for industrial), is the method of using X-ray radiation to take a number of two dimensional (2D) images of an object in many positions around an axis of rotation. From these images, using software, a three dimensional (3D) model of the object’s external as well as internal structure is reconstructed and can be analyzed. Likewise in [69], X-ray CT is called CT in this paper, the main focus still being on dimensional metrology applications.

As reported in [69], the first CT scanner was built for medical imaging by Nobel Prize winner Hounsfield in 1969. Since 1980, CT became popular for material analysis and non-destructive testing (NDT) and detecting material defects. More recently, in 2005, CT technology entered the application field of dimensional metrology, as alternative to tactile or optical 3D coordinate measuring systems. CT is similar to magnetic resonance imaging (MRI), but where MRI uses non-ionizing radio frequency radiation to detect the magnetic resonance of hydrogen molecules, CT uses ionizing radiation and measures the absorption of X-rays. Consequently, the two techniques have different areas of application. CT is a useful tool for examining materials with high atomic number while MRI is extremely useful in examining soft biological tissues. Other 3D imaging techniques, using neutron sources, are currently being developed for soft materials, and a certain overlap in terms of methodology and applications can be expected. MRI imaging techniques are not considered and neutron source is only briefly mentioned in this paper.

Typical areas of use for CT in industry are in the detection of flaws such as voids and cracks, and particle analysis in materials. In metrology, CT allows measurements of the external as well as the internal geometry of complex parts. So far, CT metrology is the only technology able to measure as well the inner as the outer geometry of a component without need to cut it through and destroy it. As such, it is the only technology for industrial quality control of components having non-accessible internal features (e.g. components produced by additive manufacturing) or multi-material components (e.g. two-component injection molded plastic parts or plastic parts with metallic inserts). CT can be considered as a third revolutionary development in coordinate metrology, following the introduction of tactile 3D coordinate measuring machines (CMMs) in the seventies and that of optical 3D scanners in the eighties.

The number of industrial applications of CT is large and rapidly increasing. After a brief market overview, the paper gives a survey of state of the art and upcoming CT technologies, covering various types of CT systems, scanning capabilities, and technological advances. The paper contains a survey of application examples from the manufacturing industry as well as from other industries, e.g., electrical and electronic devices, inhomogeneous materials, and from the food industry. The paper aims at giving a detailed overview of the numerous and different applications of CT for industrial purposes in the light of industrial application...
requirements. The paper also addresses limitations and problems of state of the art CT. Challenges as well as major national and international coordinated activities in the field of industrial CT are also presented.

An overview of the advantages and disadvantages of using CT for dimensional metrology is shown in Fig. 1.

![Fig. 1. Advantages and disadvantages of CT. Adapted from [81].](image)

2. CT market overview

After developing the first CT (called EMI scan) for human-medical purposes in the early seventies of the last century by the research branch of the British EMI (a British multinational music company) the usage increased rapidly. The technology has improved enormously and the number of implemented systems increased vastly. Application in industry like NDT for the inspection of technical objects for pores and inner defects were opened and developed in the eighties, but brought only smaller contributions to the number of implemented systems. Moreover the disadvantage of the conventional 2D X-ray systems being film based could be overcome by highly advanced digital systems with 2D X-ray detection pannels and computer evaluation. The use in two-dimensional defects (flaws) testing and completeness check in electronic production, i.e. printed circuit boards (PCBs) as well as surface mount technology (SMT), was developed and has led to a significant increase in application of CT systems. The application of CT for three-dimensional measurements was investigated but failed due to lack of accuracy. In the early years after the millennium, the 3D-accuracy and traceability problem was overcome with a keen solution applying a conventional 3D-coordinate measurement system for calibration and traceability, and a new method for performing and evaluating measurements with good accuracy. The first coordinate measuring machine with X-ray sensor facility, developed by Werth Messtechnik, was presented to the market during the international fair “Control” (Stuttgart, Germany) in 2005 [140]. Fast and accurate (in the range of microns) holistic measurements of the entire workpiece with several hundreds of tolerances (even inside of hollow workpieces) were now possible. That has incentivised several vendors of metrology systems to develop new CT systems and led to new and innovative investigations of research institutes, while the number of implemented CTs for dimensional measurements blew up. Nowadays the application of CT in industry covers quality control dealing primarily with dimensional metrology and flaw detection. Today digital X-ray systems are common in the medical applications, but industrial digital X-ray inspection systems are still a nascent market [103]. The development of CTs in medicine can be seen as precursor for X-ray systems in industrial market. Nevertheless the needs and requirements in industry for CT metrology are quite different to those in medical fields (mainly accuracy and traceability). Fig. 2a shows that the market for industrial digital X-ray inspection systems was estimated by Frost and Sullivan [34] for 2009 to be 344.2 million US$, for 2011 US$ 399.5 million [87]. The forecast for 2014 is 450.6 million US$ [34] and for 2016 is US$ 509.4 million [87]. According to other sources [34] the industrial X-ray inspection systems market is predicted for 2017 to be US$ 591.9 million. That is a Compound Annual Growth Rate (CAGR) from 2009 to 2017 of about 7%, what is significantly higher than the CAGR in general.

The global geographical distribution of installed systems in 2009 is shown in Fig. 2b. Most installations are in North America, Europe and Japan. Future market development will be driven mainly by India and China, not to forget Russia, Brazil and South Africa (BRIC-states). The trends in the market for industrial CT can be seen in two regards:

Applications in existing branches are expanding due to new requirements in the technological leading areas like aerospace, automotive and transport industry. The new drivers are product safety and economics. In production the overall productivity and efficiency of manufacturing processes are to be improved. Safety of components must be increased as recent disasters caused by failures in materials and parts are demonstrating. Economics of production processes can be improved by replacing conventional CMMs by CTs. New more comprehensive and more flexible solutions will support increasing the market with such applications. In electronics and microelectronics we are faced with new challenges in increasing economics and inspection comprehensiveness. Innovative systems will be able to check the completeness of devices, of critical devices – with suitable systems – also of each soldering point, even of new devices with hidden soldering points like ball grid arrays (BGAs). A considerably high number of CT systems will be necessary to supply the demand of adaptable solutions.

New markets can be identified. An emerging new large market is the food industry. Integration of CT in packaging lines can check the content of – vacuum – sealed packages, cans or preserving jars just before delivery. Inclusions of contaminants like glass, metal, stone and other can be detected. If tightly focused they can even be eliminated. Moreover, in butcheries and meat processing factories, each piece of meat can be tested for the content of hidden fat and bones and the price can be calculated accordingly. Counting the number of such companies or maybe even butcher shops demonstrates the volume of a market referring to this. Another emerging market will be in security related utilizations. Against the background of the fear of terrorism attacks checking cargo, luggage and even complete containers will get more importance. Detecting explosives and other dangerous materials and devices will be required not only for airports and ship terminals but also for railway stations, public buildings like court houses, schools and attractive tourist sightseeing sites as well as factories and company sites. A wide upcoming market can be seen in the area of new materials like metal foam and CFRP (carbon fiber reinforced plastic) and other composites, where CT will allow new technical solutions. Testing procedures for those materials as well as for testing components have to follow the technology leading to a significant market share of industrial CTs.

![Fig. 2. Market data. (a) Trend in annual revenue for industrial X-ray inspection systems market [34,79,87]; (b) global distribution of totally installed CT systems. Based on [121] and referred to Frost & Sullivan 2011-03-24.](image)
Altogether it can be forecasted that the CAGR of this technology also in future will be increasing faster than average CAGR of economics.

3. CT scanning technologies

CT scanning technologies were reviewed in [69], with details on technical systems and components, including X-ray sources, X-ray detectors, kinematic systems, and other hardware and software technologies. In this section, an up-to-date overview is given, with focus on: (i) types of CT systems, (ii) scanning capabilities and (iii) technological advances.

3.1. Types of CT systems

Many different types of CT systems are available today: from small devices which can be attached inside a Scanning Electron Microscope (SEM) to large machines used for CT scanning of tall and heavy parts. The most relevant categories of CT systems are listed in the following.

3.1.1. Clinical CT

In clinical CT scanners, the X-ray unit (which carries source and detector) is continuously rotated around the object or patient (which remains stationary or is slowly translated horizontally along the axis of the rotating unit) to obtain tomographic images representing slices of the scanned body. In over four decades of medical applications, several generations of clinical CT scanners have been developed, ensuring a continuous increase of performances [51].

3.1.2. Material analysis and industrial CT

CT systems for material analysis and other industrial applications such as non-destructive testing are fundamentally different from clinical scanners. In these systems the object is rotated in the X-ray beam, while the X-ray source and the detector remain stationary. In addition, since the dose of radiation transpiring the object is normally not critical in industrial CT, greater radiation intensities can typically be used than those applied in clinical CT. Furthermore, because resolution and accuracy requirements are different, scanning parameters usually differ significantly from clinical CT [57,61]. Resolution and accuracy can also be adjusted by moving the axis of rotation supporting the object either closer to the source (higher image magnification and pixel resolution, but more blurring) or closer to the detector (sharper images, but less resolution) [69]. This is normally not possible with clinical scanners where the rotation axis is centered between source and detector. Unlike clinical scanners, most CT systems for material analysis or industrial use apply cone beam geometry and flat panel detectors as it yields hundresfold reduction in scanning time (multiple slices measured in one rotation) and good image quality [40]. However, systems with fan beam geometry and linear detectors are also used, especially for reducing scatter effects when large thicknesses need to be penetrated using high voltage tubes.

3.1.3. Dimensional metrology CT

In conventional metrology (e.g. tactile coordinate measurement) the measurement must be planned taking into account every feature. CT introduces a paradigm shift toward holistic measurements of workpieces. Since the dimensional measurements are performed on a virtual model, the data acquisition (CT scan) and evaluation can be done at different times and different locations. In dimensional metrology applications, special attention is paid to accuracy and traceability of measurement results [69]. In order to enhance the accuracy of CT measurements, metrological CT systems are designed involving principles and technologies for CMMs. For example, metrological CT machines can be constructed using high precision mechanical guideways and thermally stable structures. CT can be utilized in multisensor CMMs, enlarging here the flexibility and applicability [27]. Fig. 3 shows an example of a multi-sensor CMM including CT sensor, tactile (touch-trigger) probe and stable granite base. Fig. 4 shows an example of a metrological CT system with liquid cooled micro-focus source and therinally controlled cabinet. The thermal stability of the system and the cooling of both source and detector may greatly reduce the thermal effects on measurement accuracy [88,93,108,113]. CT systems for dimensional metrology have to be tested according to standard procedures and guidelines in order to ensure conformance with metrological performance specifications. The German guideline VDI/VDE 2617-13 is currently considered as the fundamental document for specification and verification of CT systems used for coordinate metrology and it forms the main basis for future development of ISO standards [129].

Fig. 3. Multi-sensor CMM including tactile and CT sensors and stable granite base, shown without its X-ray protection housing [140].

Fig. 4. Metrological CT system with liquid cooled micro-focus source and thermally controlled cabinet [89].

3.1.4. Robot operated CT

In order to automate loading and unloading of the workpiece to be scanned, CT systems can be integrated with robots. Fig. 5 shows an example of robot operated CT. Other solutions for reducing time of workpiece handling are discussed in Section 3.3.1.

Fig. 5. CT system integrated into the manufacturing line by means of automated robotized loading [14].

3.1.5. SEM CT

Specific CT devices can be attached in a standard Scanning Electron Microscope (SEM), allowing 3D imaging of small samples with resolution down to 500 nm, without compromising the
regular imaging capability of the SEM [10]. These devices utilize the X-ray radiation which is produced by a metal target hit by the electron beam in the SEM. The X-ray radiation is then acquired by a dedicated camera mounted on the side window of the SEM specimen chamber (Fig. 6). The object is rotated within the X-ray beam using a rotation stage installed in place of standard specimen holders.

3.1.6. Large scale CT

The main restriction in CT scanning of large parts is connected with the material attenuation coefficient, which limits the maximum accumulated material thickness that can be penetrated, as discussed in Section 3.2.3. In order to increase the maximum penetrable thickness, X-ray tubes with high voltage are employed.

Commercial standard tubes are typically limited to 450 kV, but special tubes up to 800 kV are also available today [118]. For higher energies, linear accelerator X-ray sources are also used (Section 3.1.7). Another important issue to be taken into account when scanning large parts is the need of large detectors. In alternative, stitching of multiple X-ray projections or multiple CT reconstructions can be performed, using various procedures [76]. Other methods for measuring large parts are for example digital laminography and other techniques briefly discussed in Section 3.1.8.

3.1.7. Linear accelerators and synchrotron CT

Even though the most common X-ray sources are based on electron guns [69], other possibilities exist to accelerate electrons against a target to produce X-rays. Linear accelerators and synchrotrons in particular, despite being very expensive sources, offer specific advantages with respect to common electron guns.

Linear accelerators (LINAC) greatly increase the velocity of electrons or other charged particles by subjecting them to a series of oscillating electric potentials along a linear beamline. Thanks to their high energy, linear accelerators can be used for penetrating very thick and/or high absorbing parts, up to meters of concrete or metal. Fig. 7, for instance, shows a linear accelerator used for non-destructive testing of large steel castings. X-rays can also be generated by synchrotrons, which are special particle accelerators, hosted in large facilities, as shown for example in Fig. 8. Synchrotron CT devices are available at nearly all synchrotron facilities. Their radiation has the following relevant properties: monochromatic, high coherence, high collimation, high brightness and intensity, low emittance, and wide tunability in energy/wavelength [17,95].

3.1.8. Digital laminography and other techniques

In CT the object have to be irradiated from all angular directions (360°). This is not always possible, for example in case of limited access to the component or in case of large flat objects, due to high absorption of the object in at least one direction. In order to overcome this problem, different techniques can be used, such as laminography and tomosynthesis [60].

Digital laminography is a valid solution for scanning flat parts. In this technique, images of planes above and below the plane of interest are blurred out by reciprocal movement of the X-ray source and detector, to show a specific layer more clearly. Source and detector can be moved for example on circular orbits around the same axis, so that only the points in one plane of the object, the focal plane, project to the same position on the detector while the points in all other planes are blurred. The result of the inspection is the image of the focal plane, which represent a section of the object, with superimposed burred images of the other planes. This technique can be applied for example to the inspection of multilayer printed circuit boards, welding seams on large parts and aerospace components [42,70]. Motionless laminography is a variant of digital laminography, where multiple detectors are used to avoid the movement of source and detector. Fig. 9 shows an example of motionless laminography applied to the inspection of aircraft wings.

3.2. Scanning capabilities

The key capabilities of CT for industrial applications are briefly discussed in the following.
3.2.1. Resolution

Many factors influence the spatial resolution of CT reconstructions, including: focal spot size of the X-ray source, performance of the detector, magnification, number of projections, reconstruction algorithms, and data post-processing. The focal spot size is particularly important in determining the image quality. Systems with focal spot size larger than 0.1 mm are typically referred to as conventional CT or macro CT. Microfocus systems (μCT) have a spot size down to one or few micrometers. Nanofocus systems (nanoCT) may reach sub-microscopic spot size, currently down to 0.4 μm [48,60]. Synchrotron CT (sCT) can reach 0.2 μm resolution, and by applying Kirkpatrick–Baez optics (sCT + KB) can currently go down to 0.04 μm resolution [106]. Fig. 10 shows typical ranges of spatial resolution for the tomographic systems considered above.

3.2.2. Scanning speed

Contrary to coordinate measuring machines, in CT systems the scanning time is independent from the number of features to be measured on the object (see Fig. 11). On the other hand, the scanning time depends on a number of parameters, including: exposure time, number of projections and performance of data processing [69]. Typical scanning time for industrial CT systems with cone beam currently ranges from few minutes to one or few hours [26]. However, innovative techniques are available for faster scanning, as discussed in Section 3.3.1.

3.2.3. Measuring range

As discussed in Section 3.1, very different types of CT systems exist today: from desktop CT with reduced measuring volume to large scale CT. The dimensions of the object that can be scanned in these systems is limited by the measuring volume between source and detector, and depends also on: applied magnification due to the cone beam geometry, maximum penetrable material thicknesses (see Section 3.2.4) and the capability of the CT system to apply advanced scanning procedures, such as region of interest scanning (see Section 3.3.2), extended field of view scanning (see Section 3.3.3) and helical scanning (see Section 3.3.4).

3.2.4. Maximum penetrable material thicknesses

The maximum accumulated material thickness that can be penetrated by X-rays depends on the material attenuation coefficient and the X-ray photon energy. Typical values for common materials are given in Table 1; complete tables and graphs are available in literature [22,90]. Before scanning, the object should be oriented as to reduce the maximum penetrated material thickness. Optimal part orientation should also minimize the variation of penetration depth during object rotation, in order to avoid pixels saturation or extinguishment in X-ray projections [81,137].

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>X-ray range (kV)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel/ceramic</td>
<td>130–150</td>
<td>&lt;8 &lt;25 &lt;40 &lt;70</td>
</tr>
<tr>
<td>Aluminum</td>
<td>190</td>
<td>&lt;30 &lt;50 &lt;90 &lt;150 &lt;250</td>
</tr>
<tr>
<td>Plastic</td>
<td>225</td>
<td>&lt;90 &lt;130 &lt;200 &lt;250 &lt;450</td>
</tr>
</tbody>
</table>

Source: [26].

Note: The values in this table are maximum thicknesses producing low signal-to-noise ratios; with smaller thicknesses the transmitted intensity increases.

3.2.5. X-ray dose

While reducing the radiation dose per scan is particularly relevant in clinical and biological CT, the effects of X-rays exposure on the scanned object are often negligible in industrial CT. However, in some cases the X-ray dose must be limited to avoid degradation of materials, for example in the case of highly exposed polymers [13], and to prevent specific effects, such as color modifications in gem stones [102]. Safety of CT operators is ensured through appropriate shielding of the X-ray system [85].

3.2.6. Multi-material scanning capabilities

The capability of analyzing multi-material objects is frequently demanded in several industrial applications. CT is definitely capable of providing interesting solutions to this demand, as clearly demonstrated since the earliest clinical CT scans in the 1970s. However, CT scanning of multi-material objects presents also significant difficulties, due to different X-ray attenuation by different materials and to specific image artifacts [132]. CT manufacturers offer different solutions to facilitate measurements of multi-material objects through multi-spectra scans, including: multi-material targets (e.g. different materials on an indexable head), dual-source CT and energy-sensitive sandwich detectors [36]. Further details on advanced solutions for multi-energy scanning are given in Section 3.3.5. Another issue that needs particular attention when performing CT measurements on...
multi-material parts is the identification of adequate thresholds for correct surface determination. This issue as well as further considerations on multi-material scanning are discussed in Section 3.2.6, along with specific examples concerning multi-material assemblies.

3.2.7. Accuracy
As for other coordinate measuring systems [21,141], the measurement uncertainty of CT depends on the specific object to be measured and the specific parameters chosen for the measurement process. The factors that influence the measurement accuracy are listed and discussed in [69]. Recently several new studies have been conducted on uncertainty evaluation and accuracy enhancement of CT dimensional measurements [19,30,50,54,82,86,135].

The results of the first international inter-laboratory comparison of CT systems used for dimensional metrology, which was concluded in 2011 [15], show that sub-voxel accuracy is definitely possible for CT dimensional measurements on calibration artifacts. In particular, the comparison showed that measurement errors in the order of 1/10 of the voxel size are reachable for size measurements, while measurements of form are more affected by the influence of CT data noise [15,18]. The achievable accuracy using CT on real industrial parts is investigated in the CIA-CT international comparison described in Section 6 of this paper [4]. A general description of the accuracy of CT in achieving traceable measurements is a complex issue that is still a matter of investigation [69,121] but a first indication can be provided here based on specific investigations [4,15]. Fig. 12 illustrates the expanded uncertainty of CT measurements assessed from comparisons with reference measurements obtained on CMMs.

3.2.8. Software capabilities
Data processing plays an important role in CT technology, with increasing demands on high-performance computing. The general capabilities of software for CT data reconstruction and analysis were described in [69]. In specific industrial applications of CT, specific software capabilities may be requested, especially for CT data analysis.

To this end, several software solutions are now available on the market, allowing task-specific analysis of CT data, including for example: fiber composite material analysis (Fig. 13), wall thickness evaluation, porosity and inclusion analysis, comparison to nominal CAD geometry, coordinate metrology, etc.: see examples in [69]. As a general conclusion concerning scanning capabilities Table 2 illustrates the possibility of performing measurements using CT compared to tactile and optical CMMs.

<table>
<thead>
<tr>
<th>Tactile</th>
<th>Optical</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeform geometry</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High aspect ratio</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Soft material</td>
<td>✓</td>
<td>See Fig. 10</td>
</tr>
<tr>
<td>Micrometric detail</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fast measurement</td>
<td>✓</td>
<td>See Fig. 10</td>
</tr>
<tr>
<td>Internal detail</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

3.3. Technological advances
Industrial CT is rapidly evolving, with continuous improvements in both hardware and software components. Some of the main technological advances are presented in the following.

3.3.1. Fast CT scanning
Thanks to recent advances in CT components and computing power, several manufacturers of industrial CT systems have recently proposed fast CT scanning solutions, capable of inspecting industrial parts in few seconds [9,11,92]. Due to their scanning speed, these systems can be used for in-line inspection of products. For instance, Fig. 14 shows a fast in-line CT system for inspection of castings, with typical scanning and inspection speed of 5–10 mm cross-section per second, allowing a complete scan and analysis in 10 s for small automotive parts (e.g. small pistons or chassis
components) and in 80–90 s for larger engine components (e.g. cylinder heads) [11].

Another advanced solution in fast CT scanning is the possibility of scanning moving parts, obtaining three-dimensional CT reconstructions that capture the movement over a period of time. The result is a dynamic volumetric dataset (i.e. a CT volume model that includes time and motion), called 4D CT scan that can be reproduced like a movie (see Fig. 15). The University of Leuven developed a rotating in situ compression unit that was integrated in a CT scanner. It allows 3D visualization of the progressive compression and collapse of e.g. scaffold or lattice structures (beam-like 3D structures): see Section 4.2.3 [64].

![Fig. 15. 4D CT reproducing the movement of a screw [91].](image)

3.3.2. Region of interest scanning

When a specific detail of a larger object needs to be reconstructed at a higher resolution, then region of interest (ROI) CT scanning can be performed. ROI scanning comprises a range of different methods that allow measuring specific regions (volume portions) without reconstructing the whole object [60,73,76]. Fig. 16 shows an example of a particular ROI scanning, where the object is first scanned entirely at a lower magnification (coarse resolution) and then the region of interest is scanned at a higher magnification (fine resolution), so that the higher magnification region is reconstructed taking into account also the voxel information from the coarse voxel volume [26].

![Fig. 16. Example of ROI scanning on electric razor blades: (a) CT acquisition of the whole object, (b) CT acquisition of a portion with better resolution (higher magnification), (c) CT result for the whole object, (d) CT result for the high resolution region [26].](image)

3.3.3. Extended field of view scanning

Several methods are available for extending the CT scan field of view [52,76]. They may be needed when a portion of the scanned object is positioned outside the scan field-of-view (SFOV) and hence the line integrals corresponding to those regions are not projected into the detector. If the object is larger than the SFOV, methods are available for extending the SFOV by combining multiple projection images taken at different positions of the object, which is translated laterally [76]. If the object is longer than the SFOV in the direction of the rotary axis, the extended reconstruction may be obtained by stitching several CT volume reconstructions [26]. Extended field of view scanning is useful also for enhancing the obtained resolution.

3.3.4. Helical scanning

Helical scanning (also improperly called “spiral scanning”) involves simultaneous rotation and translation of the object along the rotation axis, so that the relative movement of the X-ray source and detector to the object describes a helix. This procedure has several advantages such as elimination of Feldkamp artifacts [69] and increase of resolution along the axis of rotation. It can also be used for scanning elongated objects that cannot fit into a single exposure [76].

3.3.5. Multi-energy scanning and color CT

In multi-energy CT, the analyzed materials can be differentiated by using several advanced scanning methods, which basically can be classified in two main approaches: (i) exposing the object to different X-ray spectra and (ii) employing energy-resolved detectors. The first approach may be implemented in several ways: different spectra can be obtained for example by varying the scanning parameters (e.g. the source voltage, or the power, or even just the current – which actually does not affect the spectrum but can help to achieve better signal-to-noise ratios [67]), or different target materials (e.g. using multi-target heads), or different sources (e.g. using dual-sources CT systems, with two different tubes) [36]. For the second approach, energy-sensitive photon-counting detectors are needed. Their ability to resolve energies allows energy-selective imaging with a single X-ray exposure [136]. CT systems equipped with such detectors are often referred to as “Spectral CT” or “Color CT” [1].

3.3.6. Phase contrast and dark field imaging

Phase contrast and dark field imaging can be used to visualize small details and increase image contrast within structures that otherwise would appear uniform. Phase contrast imaging differentiates between structures under analysis by exploiting differences in the refractive index of materials and highlighting small details of differing refractive index [99]. Dark field imaging uses scattering from sub-micron structures in the sample, offering a powerful contrast mechanism to reveal subtle structural features of an object [98]. The main advantage of these methods compared to normal absorption-contrast X-ray imaging is enhanced contrast that makes it possible to see smaller details and improved soft tissue contrast [119], see Fig. 17.

![Fig. 17. Conventional X-ray radiograph of a spectacle case (top) compared with dark-field X-ray radiograph [126].](image)

Other 3D imaging techniques, using neutron sources, are currently being developed for soft materials, as illustrated in Fig. 18. Other 3D imaging techniques require the use of large-scale facilities such as neutron sources or synchrotron sources which provides opportunities beyond those achievable from laboratory
X-ray sources. Neutron imaging provides unique, and complimentary opportunities compared to X-ray imaging and are especially well suited for biological materials, or when very high penetration power is required (i.e. for imaging of engine blocks) [58,59]. When it comes to synchrotron X-ray sources, the high intensity of such X-ray beams allow e.g. for ultrafast x-ray imaging [8,109], Fig. 19, and multi-modal imaging of polycrystalline materials [72]. In order to facilitate industry access to such advanced imaging facilities, dedicated imaging centers linking industry with major facilities are starting to emerge. Examples are e.g. the Manchester X-ray Imaging Facility [127] and the DTU Imaging Industry Portal [123].

4. Industrial application fields and requirements

4.1. Introduction

Nowadays, the manufacturing industry is facing the challenge of shorter product life cycles and growing product varieties. This demands highly cost and time efficient product development and production processes. Improvements in production technologies (e.g. injection molding) allow the manufacturing of complex parts with freeform surfaces and a huge amount of different features, which have to be inspected. On the one hand advanced materials, such as fiber reinforced plastics, enable new product developments, but on the other hand require new measurement and testing methods. Testing the conformity of the product characteristics in every production stage with accurate and time efficient measurement technologies can contribute to reduce waste and costs during the manufacturing. In this context industrial X-Ray Computed Tomography (CT) offers a large variety of applications in the entire development and production chain. CT delivers a holistic volumetric model of the workpiece that can be used for versatile inspection tasks and dimensional measurements as well as for reverse engineering applications. The CT has the capability to non-destructively determine the inner and outer geometry of workpieces.

Fig. 18. Conventional X-ray radiograph of a camera (left) compared with radiograph using neutrons [96].

Fig. 19. Historical development of fast X-ray tomography. Open symbols denote synchrotron sources, while filled ones represent laboratory sources, red squares denote white beam and black circles monochromatic beam scanners. Adapted from [77].

Fig. 20 presents an overview of different fields of application for the CT technology in the industrial domain. CT measurements can be evaluated voxel based or surface based. Voxel based, qualitative evaluation can be classified in visualization and non-destructive testing (NDT). Quantitative, surface based evaluation comprises digitization and dimensional metrology. The need for traceability increases with the complexity of the task. Simple visualizations do not require absolute measures. For metrology applications traceability is crucial. Fig. 21 shows a flow chart of a typical dimensional CT measurement process while Fig. 22 depicts use of the substitution method to achieve traceability of CT measurements [53,69].
Visualization refers to the function testing of assembled workpieces. It is a qualitative, visual conformity inspection of the interplay or the existence of components. It allows the analysis of function or even malfunction under real working conditions. Non-destructive testing is a qualitative testing method. It encompasses the issues of defect analysis and material characterization. Defect analysis focuses on the visual inspection of manufactured workpieces in terms of pores/blisters, voids, inclusions and cracks. Defect analysis is widely applied in casting and forming industry and injection molding industry to assure the quality of workpieces. Weak spots (e.g. regions of high pore density) can be identified easily. Material characterization focuses on the determination of intended material properties. Typical applications are the analysis of fiber orientation, alignment and density in compound materials and pore size and pore density in foams (here pores are a defined material characteristic). In both cases the results can be used for instance to improve the manufacturing processes concerning molding die geometry and molding process parameters or to distinguish between good and bad parts (see Section 4.2.5, Fig. 42). Digitization describes the capability to generate and evaluate virtual models of workpieces from CT measurements. It can be structured in simulation and reverse engineering. Simulation is a widely used and powerful technique to predict or investigate workpiece properties and behaviors. The object of interest needs to be modeled to perform the simulation. Instead of using a simplified model (e.g. CAD data), the CT provides detailed models of real workpieces. For example finite element simulations (FEM) can be used to investigate heat transport or mechanical stress. In reverse engineering applications surfaces of the virtual model are extracted and reconstructed for CAD applications. Reverse engineering enables to recover lost drawings, capture prototypes or to build spare parts. The CT opens up new possibilities in the product development. Metrology comprises any dimensional measurement on CT data. According to the German guideline VDI/VDE 2630 Part 1.2 [130] the dimensional metrology aspect is differentiated in nominal/actual comparison, tolerance analysis and wall thickness analysis. Nominal/actual comparison is an analysis and color coded deviations visualization of the geometric deviations between a CAD model or a reference workpiece (nominal data) and a measured workpiece (actual data). It allows a holistic, non-feature based evaluation. Tolerance analysis comprises dimensional, shape, form and position tolerances, determination of compensating elements, regular geometry and sculptured surfaces. In contrast to conventional coordinate measurement, the measurements are performed on the virtual model. Wall thickness analysis determines a characteristic number in the volumetric model. Dimensional CT measurements can be used for quality control throughout the whole product development and manufacturing cycle.

4.2. Manufacturing industry

Since about 2005 the manufacturing industry started showing great interest in CT technology for quality control purposes:

- The rising complexity of components and products, with high function integration, has led to components with more complex, often internal, features that cannot be controlled on dimensions and tolerances in a non-destructive way with tactile or optical CMMs. Control of complex assembled products also call for CT: one need to look inside the assembled product to detect mismatches (e.g. undesired gaps or collisions between individual components of the assembly, possibly due to unwanted deformations of those components enforced by the assembly). Measuring the components of an assembly separately (even if within specs) does not guarantee proper functioning of the assembled system.
- Techniques like plastic injection molding with metallic inserts, two-component injection molding or other production methods yielding multi-material components also requires CT for non-destructive quality inspections (geometry, dimensions, fitting, porosity).
- New production methods, in particular additive techniques, have favored designing and producing components with internal cavities that cannot be produced with traditional methods and cannot be measured on tactile or optical coordinate measuring machines.
- Not to the least, people start recognizing that CT has the unique possibility to apply for a double quality check in one step and one measurement task: e.g. checking dimensional quality (precision) and checking material quality (e.g. porosity, weld quality, etc.) can be done using the same CT measurement data.

The latter is illustrated in Fig. 23 [69] showing three quality checks done with the same CT data: (i) control of form and geometrical deviations, (ii) thickness verification and (iii) control of material density/porosity. This and other examples (e.g. thermoforming, folding and welding of plastic honeycomb panel) were already given in [69].

![Image](https://via.placeholder.com/150)

**Fig. 23.** Reconstructed CT model (a), control of geometry (b), wall thickness analysis (c), and porosity inspection (d) of car inlet fan.

4.2.1. Casting and forming industry

The aforementioned benefits of CT quality control are of particular importance to the foundry or metal forming industry where checking for material flaws (pores, inclusions, etc.) is at least as important as checking for dimensional quality.

Castings often depict internal cavities (produced with cores) that also call for dimensional CT measurements: see Fig. 24. Forming of hollow components is also coming up as a way to reduce mass and weight in the transportation industry: e.g. hydro-formed hollow camshafts or hollow constructed crankshafts [120]. An example of an aluminum casting measured with CT was given in the CIRP keynote paper of 2011 [69]. That casting had been split into several segments, provided with reference spheres, as to be suited as a reference object for accuracy verification of dimensional CT measurements on castings [7]. Fig. 25 shows a CT quality control process for turbine blades. The blades were measured on a Nikon Metrology 450 kV scanner equipped with a linear X-ray detector. Individual dimensions are checked within several sections and are used to provide a global Fail/Pass evaluation of the blades.

CT measurements of a 3-cylinder head of a combustion engine are shown in Fig. 26 (notice the steel bushings inserted in the aluminum cylinder head). The CT measurements were aimed for reverse engineering and redesigning the cylinder head in order to
solve a problem of overheating and cracking of the head. It involved following steps:

- Scanning of cylinder head on 10 MeV CT scanner and 2D reconstruction (BRP-Rotax GmbH & Co).
- 3D reconstruction and STL meshing (Materialize Mimics® software).
- Segmentation of different materials and internal structure (Materialize Mimics® software).
- Re-meshing for FEM and CFD (Computational Fluid Dynamics) (Materialize Mimics® software).
- CFD calculation (Star-CD®).
- (Re)design using STL-based CAD systems (Materialize 3-matic® CAD software).

4.2.2. Machining (subtractive manufacturing)

Machined parts call for CT for dimensional check of internal features: for such parts, material quality control is less of an issue, while external features or cavities that are fully visible externally can better be measured using traditional CMMs equipped with tactile or optical probes (e.g. laser stripe scanners in case multiple measuring points are desirable as in CT measurements). Internal features of machined parts calling for CT inspection mostly involves small/long internal channels (drilled, bored, tapped, laser machined, etc.) or small re-entrant cavities (milled, EDMed, etc.) whose dimensions cannot be measured with traditional means: see Figs. 27 and 28. In quite some cases the purpose is not only to check for geometry, form and dimension of the cavities, but also to check for undesired burrs at intersecting holes: see Fig. 29. Fig. 30 gives examples of micro parts that cannot be measured with classical CMM.

Material removal machining processes, being still the most precise manufacturing processes, are also the most demanding in terms of accurate dimensional measurement. The accuracy and uncertainty of dimensional CT measurements is however counteracted by typical phenomena as X-ray beam hardening, gray-value edge thresholding, etc. This is illustrated in Fig. 31, where a precision pin (04 mm) inserted in a hollow stainless steel stepped cylinder (see dimensions Fig. 31a) was measured on a 225 kV CT device (Nikon Metrology MCT225). The hollow stepped cylinder
was produced on a precision lathe (Mori Seiki NL2000Y/500) and calibrated on a Mitutoyo FN904 CMM. The pin was a calibrated pin (tolerance ±1 μm) [125]. Fig. 31b demonstrates that optimizing the beam hardening (BH) correction reduced the non-systematic dimensional errors on the inner pin diameter (i.e. error neglecting the systematic offset of about 3 μm) from 7 μm to 2 μm. Similarly, Fig. 31c demonstrates a reduction of the average outer cylinder edge offset by around 3 μm (typically from 5 μm to −2 μm) and of the inner hole diameter by 8 μm (from −13 μm to −5 μm): see arrows. Proper BH correction reduced the overall dimensional errors (both systematic and non-systematic) to within 5 μm.

4.2.3. Additive manufacturing

Additive manufacturing (AM) offers unique possibilities for producing parts with internal cavities or lattice structures that are impossible to produce with other manufacturing techniques. Hence, many AM parts feature such internal geometries that allow optimizing the component’s, weight, shape and strength: Fig. 32. AM definitely calls for CT quality control as it is the only method to perform non-destructive dimensional measurement of inner features and non-destructive density/porosity verification, which is a critical issue in AM.

An example of an AM nozzle with conformal helix cooling channel is given in Fig. 32.

Fig. 34 gives an example of a component made from to parts produced by selective laser sintering of nylon powder (white components) and assembled by gluing (black glue). Blue ink was poured inside the glued components. It demonstrates that the parts are leaking (see blue area on left picture). CT scanning revealed that this is due to interlayer porosity (see right picture). To check the performance of AM in producing thin lattice structures for lightweight aerospace components or porous medical scaffolds for bone regeneration, several such lattice structures were manufactured by selective laser melting and tested with a CT scanner (Philips HOMX 161) [64]. The rotation allows taking 360° X-ray pictures of the scaffolds being gradually compressed, and to reconstruct 3D CT images of the collapsing scaffold, while recording compression force versus deformation and calculating local stresses. Fig. 36 depicts the compression unit and some CT images and visual picture of a collapsing scaffold.

4.2.4. Injection molding

CT is particularly suitable to investigate injection molded polymer parts, thanks to the good X-ray penetrability of these materials. Scan tasks typically encompass run-in and trouble shooting by part geometry comparison with CAD model (Fig. 37), identification of QC measurements, and defect analysis. Check of a molded part geometry is relevant with respect to the CAD model, between single cavities, among different molds, between different materials, and after exposure to heat treatment and wear [2]. Challenges are often encountered in terms of: results

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**Fig. 29.** CT check for undesired burrs at intersecting holes: (a) object front view, (b) object top view, (c) 3D CT model showing burrs.

**Fig. 30.** CT measured of micro milling cutter Ø0.4 mm (left) and of micro holes Ø4.00 mm down to 0.25 mm (right).

**Fig. 31.** CT measurements of calibrated steel pin inserted in stainless steel step cylinder.

**Fig. 32.** Examples of AM parts with internal features and lattice structures.
depending on fitting method, datum system interpretation, flash and mold lines, rough surfaces, rounded corners, and large variations in wall thickness. As an example, a flash easily observed under the microscope can be invisible to CT, Fig. 38.

Often, mold approval, or mold validation, is a major production issue. Typically, validation of injection tools in connection with process run-in is carried out verifying critical features on parts from the different cavities using tactile CMMs, but companies are investigating the possibility of validating molds from CT measurements. Currently, 90% of the use of CT within the Prefilled Device Quality Control Department at Novo Nordisk A/S (DK) is related to mold approval, while 10% are special tasks, such as, e.g., scanning of a subassembly in order to check if click springs are assembled correctly [116]. A similar example is found at LEGO A/S (DK) where the verification department is responsible for measuring and testing of LEGO elements from new production molds [29]. The test results are used as a basis for approval and release of new elements – therefore of molds – and are an important contribution in the value chain of mold manufacturing. The LEGO elements are measured either by the use of Coordinate Measuring Machines or manual measuring equipment. The idea is to measure as many elements as possible using measuring machines, but today around 75% of the features are still measured manually. However, many elements feature complex geometries and require CT scanning: these elements feature high aspect ratios and hidden positions, where measurements by common means are not possible. The verification department has recently invested in a CT scanner, which will further support quality control of the molds.
The difference in measuring many parts can be appreciated considering Fig. 39 which compares a set-up with several items ready for CNC measurements on a tactile CMM with a multiple part holder for use in a CT scanner. An important application area concerns insert molding (where plastic is injected around an insert, usually metal), outset molding: (similar to insert molding but here a metal sheet surrounds some plastic elements), and overmolding, (where another plastic is injected around a plastic product or around a part of the plastic product). In the case of different similar materials (e.g. two plastics) or dissimilar materials (metal and plastic), CT is usually challenging, as addressed later in Section 4.2.5.

CT can be used also for dimensional verification of micro components produced by micro injection molding [94]. Specific calibration artifacts can be used in connection with CT scanning of micro components [17,78].

Other plastic components that can be measured effectively by CT are polymeric prosthetic joint components, where CT is particularly useful for measuring the geometry of worn bearing surfaces and quantifying wear volumes, with reduced uncertainty in comparison to CMM measurements [16,19,20,117].

Injection molding is not limited to polymers but can also involve metal [104]. Metal injection molding (MIM) is, e.g., practiced at Grundfos (DK), where CT is used to detect manufacturing defects, Fig. 40 [65].

4.2.5. Assemblies

X-ray CT is a unique tool for inspection of assemblies (Figs. 41–43). It allows visualizing the various components of the assembly in the assembled state. This is essential as separate inspection of the individual components of an assembly (even if they all are within specification) does not guarantee proper functioning of the assembly.

An example of fit assembly analysis is given in Fig. 42. The aim was to investigate a number of plastic actuators and inserts that should fit together and to detect why some pairs of actuator-insert did not fit while others did. Another example is given in Fig. 44.
Fig. 43. Example of a complex multi-material assembly: drug delivery device (insulin pen) including components of different polymeric materials. Courtesy of Novo Nordisk A/S [116].

Fig. 44. Assembly of two threaded components: (a) real parts, (b) CT measurement, (c) reconstructed CT model, (d) cross section thru right part of CT model showing invisible contact planes. Courtesy of Nikon Metrology/X-Tek, Belgium/UK.

It concerns the assembly of two bolds made of the same material. As it can be seen from the cross section thru the reconstructed model (Fig. 44d), the CT measurements does not allow to identify the horizontal fitting plane between the two bolts as they fit quite well together. This might be a problem when measuring an assembled system.

4.2.5.1. Multi-material assemblies. Assemblies consisting of different materials are often encountered in measurement tasks using X-ray CT. Multi-material assemblies are inherently problematic for X-ray CT:

- It is often a dilemma when setting up the scanning parameters if multi-material assemblies consist of both light plastic and dense metal parts. Low energy X-ray beams are essential for detecting small details and creating sufficient contrast especially for the lower density material; High energy X-ray beams are necessary for penetrating and revealing internal structures of denser parts. Dual energy CT (DECT) is often applied for solving this problem: it utilizes different X-ray spectrum in order to optimally characterize multi-material components [49]. It is facilitated in two different ways: dual detector and dual exposure/source techniques [105]. The dual detector technique is capable of creating two datasets in one scan by using a multi-layer detector; each layer is sensitive to a different energy band. The dual exposure/source method consists of two separate CT scans, one with high energy X-ray and one with low energy X-ray. An example is shown in Fig. 45.

Fig. 45. Example of dual energy CT. Connector with encapsulated metal parts (left) and its 2D X-ray projection images acquired using high (middle) and low (right) X-ray energies [67].

Fig. 46. Example of the typical workflow of multi-energy image stack fusion [67].

A connector with encapsulated metal parts is scanned using different X-ray energies. In the last step, X-ray projection images acquired with different X-ray energies are combined. Fig. 46 demonstrates a working pipeline using multi-energy image stack fusion in CT dimensional metrology [67].

- Surface determination is undoubtedly another main difficulty for industrial CT when dealing with multi-material assemblies. The global thresholding technique (defining material surface using a single gray value: iso-surface) does not work, because using such method for multi-material surface determination would create “imaginary” layer of less attenuating materials around the edge of more attenuating materials. As demonstrated in Fig. 47, an “imaginary” layer of aluminum is created between steel and air at the bottom [46].

Fig. 47. Voxel model containing three materials (steel, aluminum and air) and gray value profile along the arrow. Due to the limitation of iso-surface technique, an “imaginary” layer of aluminum is created at the bottom interface between steel and air [46].

In order to get more accurate material edges, local adaptive thresholding is necessary. As described in Fig. 48, this technique starts from a rough global contour assessment (defined by single gray value) and searches for the steepest gray value change in its neighborhood: the final material edge is then defined locally at the highest gradient. This method accounts for local gray value variations caused by e.g. beam hardening artifacts and scattering noise.

However, the local adaptive thresholding method also has its limitation, as shown in Fig. 49, where a set of steel and ZrO2 end gauges has been fitted together. Because the X-ray attenuations of
both materials are similar, their peaks in the gray value histogram merge with each other (see Fig. 49b). Fig. 49c depicts the 3D model generated by local adaptive (left) and global (right) thresholding. Neither of these two methods could make clear distinction between steel and zirconia. Moreover, a lot of noise is observed around the ZrO₂ part when the local thresholding method is applied. In this case, local adaptive thresholding is more easily affected by noise (low S/N ratio). Despite of the difficulties in selecting scan settings and in material surface determination, industrial CT has already proven its power in both qualitative (e.g. void detection, porosity or density observation) and quantitative (e.g. CAD comparison, dimensional measurements) assessments for multi-material assemblies. An example of void detection and defect analysis for a lamp assembly is given in Fig. 50. The aim was to check for voids in the sealing layer and to find out the reason for air leakage. Another example on inspection a multi-material car headlamp assembly using industrial CT is given in Fig. 51. The lamp filament is inspected using region of interest scanning (ROI, see Section 3.3.2).

Fig. 48. Working principle of the local thresholding method demonstrated on a reconstructed slice [124].

Fig. 49. Problems in segmenting multi-material assemblies which consists of materials with similar X-ray attenuation.

Fig. 50. (a) Lamp assembly with glass welded feet plate, (b) 2D X-ray projection image, (c) reconstructed CT slice, (d) 3D CT image.

Fig. 51. Example of CT inspection of car headlamp assembly: complete assembly (top left), selected components (top right), lamp component (bottom left), and ROI CT of lamp filament (bottom right).

4.2.5.2. Example of mechanism analysis. Besides static assemblies, CT is an excellent tool to analyze mechanisms and to check why mechanisms may fail (Fig. 52). Here again, analysis of the individual components of mechanisms may not reveal problems. CT allows visualizing the mechanism in 3D and visualizes e.g. why it blocked: e.g. where an unwanted collision between components occurred.

Fig. 52. Analysis of watch mechanism.

4.2.5.3. Examples of complex assemblies. Fig. 53 shows a complex electro-mechanical assembly. It consists of a plastic injected component with many metallic inserts (4 cylindrical aluminum screw holders and 27 copper connector pins) and in which 12 induction coils are mounted. The part was measured on the CT scanners of KU Leuven, with and without the coils. In the latter case, appropriate thresholding allowed a clear segmentation of geometrical of the plastic, aluminum and copper components. Comparison of individual dimensions and full model comparison (CAD compared) was made between measurements done with a
4.3 Other industries

4.3.1 Electrical and electronic devices

The wide range of applications for the CT in the electronic industry can be subdivided into the areas of components (packaging), connecting processes and complex structures. Electronic devices contain electronic components and printed circuit boards (PCB). In electronic component manufacturing, for instance, semi-conductors or inductors are encased in supporting cases to prevent physical damage and corrosion. Since CT enables to visualize inner structures in assembled state which are not accessible for conventional measurement technologies, it can be used for failure analysis and quality assurance. Due to the size of components, CT machines with nano or micro focus tubes are generally used to reach sufficient resolution. Typical tasks on semiconductors are detection of broken bonds or inspection of ball bonds. The detection of void size and void distribution in IC’s or void detection on solder surfaces of power transistors is done. As an example a surface-mount device (SMD) inductor type 0805 (2.0 mm × 1.2 mm) is shown in Fig. 55. The left image shows a 2D X-ray projection of the conductor. The different layers overlap. The right image shows the 3D CT model [107,108]. The front cap is partially removed and the coil is clearly visible.

Multilayer PCB’s consist of various layers with circuit paths. A multilayer PCB fitted with SMD components is shown in Fig. 56. The carrier material was removed in the CT image to allow the detection of short circuits that can be caused by etching defects, broken circuit paths in the different layers, defective plating of through holes or measurement of layer offsets and annular ring width. Also the analysis of laser drilled bore holes can be performed (wall thickness and bore quality). The electronic industry uses a variety of connecting processes. The most common process for PCB assembly is soldering. During the solder process defects like missing solder fillets, solder bridges or non-wetting defects can occur. CT allows NDT for hidden defects, for example the void detection on mounted ball grid arrays (BGA). Fig. 57 shows solder balls of a BGA. Pores in the solder balls are colored in red. Some thin bond wires are also visible [84]. Voids and blisters on the contact zone of components and PCB can be analyzed.

Another widely used connecting process is wire crimping. Fig. 58 shows the 3D model of a crimp connection. In this case the task is to determine the number of ingoing and outgoing strands. One can easily count 19 ingoing and 17 outgoing strands in the three slices on the right side. Due to overlaps, this would not be visible on 2D X-ray projections. The density in the crimp zone can also be analyzed [108].

CT is the ideal tool for inspections of complex structures in the electronic industry. Fig. 59 shows a slice of an epilator which can be equipped with different heads. It shows an optional head on the
left and the standard head on the right side. The marked region shows the lock mechanism. The standard head fits well. The CT image reveals that the lock mechanism on the optional head does not catch due to dimensional deviations.

Fig. 60 shows a charger for an electric toothbrush. The marked region shows the position of the fuse. On the left side the charger is assembled completely. On the right side the fuse is missing.

4.3.2. Inhomogeneous materials

Fiber-reinforced plastics are widely used in lightweight construction. The mechanical properties depend significantly on the fiber orientation and the fiber/matrix composition. The CT is a perfect tool to determine fiber orientation and distribution (see Fig. 13), detection of agglomerations of fiber, voids and blisters in resin [62, 80, 97]. Fig. 61 shows a sample of a glass fiber compound material [108]. On the right side of the image the fiber mats and the resin filler are shown. Voids and blisters in the resin are clearly visible. On the left side of the image the resin is faded out. All eleven layers can be inspected separately. Compared to other measurement methods (e.g. 2D X-ray images) defects can be exactly located in the workpiece. This is a big advantage of CT especially for layer wise built material.

The CT technology offers a high potential for quality control and optimization in the wood industry. The knowledge about defects can be used to optimize the cutting process. The lumber value recovery could be improved by 6–10% [71]. A CT scan can reveal the location of internal log defects like branch knots, rot or decay, insect damage and cracks. Density, moisture distribution and ring width are other quality characteristics of wood that can be determined with CT [45]. Also the identification of heartwood/sapwood boundary or anomaly detection at glue line interfaces in engineered wood products is applications for the CT. As an example Fig. 62 shows a slice view of a subalpine fir log with several defects like branch knots.

CT is also used on fiber based natural materials. This category comprises wooden products like MDF, OSB, flakeboards and paper products e.g. laminates. To improve or develop new materials, one has to understand the characteristics and the microstructure. CT enables to visualize complex structures of fibers, splints and strand orientation. Correlation of density and pore distribution was analyzed by Standfest et al. [112]. Glatt et al. used CT measurements for the calculation of material properties and the modeling of material geometry. Their work focuses on meshes, fabrics and felts [39].

Fig. 63 shows a rolled up sample of wet knit ware. The water film can be clearly distinguished from the knit wear in the slice view on the left side. The right side shows the 3D view [115].
Another example of this type of product is shown in Fig. 64. On this sample of paper pore size, pore distribution and delamination were inspected. CT even offers a new possibility to examine the micro structure of paper and enables to design new materials [114].

Steel fiber reinforced concrete is widely used in civil engineering applications. Steel fibers improve the energy absorption ability of concrete. A substantial quality criterion is the uniformly distribution and orientation of fibers. CT and associated post processing enables to explore the fibers with respect to their main orientation, to classify and to statistically evaluate them [101].

4.3.3. Food industry

The food industry is also characterized by large volume production. As an example, the Danish Meat Research Institute (DMRI) which is a division of the Danish Technological Institute in Denmark supports with cutting edge technologies a yearly national production of over 20 million pigs and 15 million poultry. During the last years, the need for advanced measuring technology for flexible, automated production has increased in Denmark and other high cost countries. At the same time, the necessary technological development has become available with CT. Similarly to research institutes in Germany and other European countries [12,32,55,56,100,107,111,122], DMRI has been using CT for a number of years developing an on-line X-ray system for measuring meat-fat distribution in pig carcasses or pieces [24,25,133]. By measuring the distribution of meat, fat and bones in pork middles, it is possible to adapt the cutting according to current market prices. The weight Lean Meat Content (LMC) assessment is performed with the use of results from CT according to the formula:

\[
\text{weight} = V_{\text{fat}} \cdot \beta_{\text{fat}} + V_{\text{meat}} \cdot \beta_{\text{meat}} + V_{\text{bone}} \cdot \beta_{\text{bone}}
\]

where \(V\) indicates the volume and \(\beta\) the density of fat, meat, and bone, respectively. Preliminary studies have demonstrated potentials and realistic solutions, but have also clarified the extent and complexity of the challenges and risks. Fig. 65 shows a new CT scanner truck for online use in production and makes a decisive break with the normal understanding of CT technology, its use, speed and limitations.

The CT scanner enhances the existing facilities allowing optimizing and adjusting the cutting of each individual carcass according to current prices, quality demands and orders. Measurements result in the spatial distribution of meat, fat and bones and deliver an optimal recipe for automatic cutting of pork middles resulting in a return of investment for the slaughterhouse of less than 12 month. The CT scanners self-diagnostic and reporting capability generate a detailed operational status including function control. The on-line CT-scanner is characterized by:

- High capacity i.e. ability to measure 700 pork middles/hour.
- Cost effectiveness corresponding to 12 month return on investment for the slaughterhouse.
- A flexible platform for a broad range of applications.

A complete system coined “PigClassWeb”, for handling the large amounts of CT-scans acquired by the DMRI in R&D projects has been developed and implemented. Through advanced image analysis PigClassWeb enables DMRI and the slaughterhouses to perform virtual cuts in a reference pig. These cuts are automatically propagated to the whole population of pigs that are scanned, in such a way that the virtual cuts are anatomically similar for each carcass, irrespectively of size, weight and proportions.

The ability to very accurately estimate the weight of arbitrary cuts enables to report the yields of the cuts on the population as a whole, as well as on each scanned carcass. The user can access the application through a simple web-browser and adjust the settings of a specific cut through a view of the scanned reference carcass. For the simpler type of cuts the results are ready within seconds, when applying the cut on the whole population. PigClassWeb is scalable in the sense that future scans automatically are processed and included in the “Population of Virtual Pigs”. New types of cuts are currently in the pipeline to be included in PigClassWeb keeping it up-to-date and making it a very flexible tool for DMRI in R&D and for the slaughterhouses in the planning of their production. Fig. 66 shows the principle of an automated cutting line for pig carcasses, Fig. 67 shows an automated middle cutting line, and Fig. 68 illustrates the concept of virtual cutting of pig carcasses [25,33,47,133,134].

Besides the pork and poultry meat production, also the fish industry and, more recently, other food industries are providing CT applications. Here, new imaging techniques for on-line inspection of food products as well as application of X-ray CT in high-resolution studies of food products for developing high quality food are of interest. One of the promising aspect is to use new X-ray imaging modalities for detection of hard-to-find foreign bodies in food products. Refraction- and scattering-based contrast principles can be used to detect pieces of paper or insects in food as complementary to conventional absorption contrast which is used already today for detection of glass, metal or stones. Another example is determination of the distribution of ingredients in the product. These can be for instance nuts or berries in chocolate bars or holes in cheese, which are important quality parameters for the consumers. Fig. 69. The idea is to apply X-ray imaging using several modalities to obtain a quantitative measure for the distribution.
These two kinds of inspections are performed using radiography yielding 2D images but efforts concern also CT studies using synchrotron radiation facilities for inspecting food products at high resolution.

5. Challenges

Future demands and requirements in general metrology concern mainly:

- Faster cycle time for a measurement according to the cycle time of manufacturing.
- Better economy of the measurements process.
- Improved operability by workers.
- Enlargement of applicability range.

When considering the special technology of “CT dimensional measurement” its individual characteristics must be regarded:

- The accuracy must be significantly improved [15]. At the time being for normal standard applications one achieves an uncertainty in the range of a micrometer. But particularly for measurements of features with dimensions in micro- and nanometer range an uncertainty in the range of less than a tenth of a micron are necessary. That’s also a requirement if we compare this technology with optical or tactile coordinate measurement results.
- Larger workpieces as well as parts of higher density (e.g. machine parts, gear boxes, crank cases, engine blocks, even ship engines) must be possible to be inspected [139].
- Also other objects like trucks, containers for ocean freight, must be possible to be checked [139].
- More efficient X-Ray detectors must be developed with an improved signal-to-noise ratio in order to allow a smaller exposure integration time and faster measurement.
- X-Ray tubes with more energy (higher current) and with smaller focal spots will contribute to the measurement possibility of larger objects and/or to more precise results at lower integration time [44].
- Improved reconstruction algorithms (maybe with selectable options specific to the measurement task) may need fewer projections for accurate volume reconstruction: e.g. algebraic reconstruction, iterative reconstruction, use of prior knowledge about the object (e.g. from the product specification in the CAD-model or from the manufacturing process itself) may lead to more accurate results and/or to shorter reconstruction time [63,73,74].
- Task-specific measurement setups: selected combination of X-ray tube and detector, special trajectories for movement of detector and tube during data acquisition (robot CT, etc.) [37,110] and special correction techniques for industrial CT [6] will lead to improvements in economy and application bandwidth of CT in industry.
- Objects consisting of different materials (material mix CT) being measurable by use of different spectra, special imaging and reconstruction techniques [23,67,75].
- User assistance for reducing setup time and reducing measurement uncertainty [38,137].
- Determination of measurement uncertainty [66,68,69,131].

In a nutshell: CT in industrial applications will have to meet the measurement challenges of the future. Those are:

- Better resolution and accuracy e.g. by smaller focus spot. The resolution should be in the range of 10 nm and the measurement uncertainty for normal standard tasks in the range of 0.1 μm.
- Larger applicability range, particularly the possibility of measuring multi-component-parts, e.g. assembled electric and electronic components.
- Possibility of measuring parts of material mix like electronic components and assembled mechanical components.
- Larger measurement ranges for larger objects like freight, railway wagons, containers, diesel engines for ships, etc.
- For in-line measurements in the production line the shielding must be solved by labyrinths or other solutions.
- Better economy of CT measurements by less expensive instruments and by better workman friendly operation of the instruments. An unskilled worker should be able to make measurements after a one-day-course. The software must guide the operator and eliminate the risk of malfunction and maloperation.
- Characterizing the measurement uncertainty for the results in graphical representation (as false color or as hedgehog representation) will lead to an improved understanding of the results and a faster interpretation of the results.

6. Major coordinated activities in the field of industrial CT

The vast interest by academics and industrialists is reflected in a number of major coordinated activities in the field of industrial CT.
The “Center for Industrial Application of CT scanning – CIA CT” is an innovation consortium co-financed by the Danish Ministry of Science, Technology and Innovation that has run over the period 2009–2013, focusing on the industrial application of CT scanning for advanced 3D measurement, quality assurance and product development: see Fig. 70. The consortium has acted as a national competence center for industrial CT scanning through a number of research activities and initiatives, aiming to help the participating companies and Danish industry with the introduction of CT scanning as measuring technology along with research at international level. Project web site: www.cia-ct.mek.dtu.dk.

Another framework research project called “New X-ray Imaging Modalities for Safe and High Quality Food (NEXIM)” involving universities and several companies from the food industry is running in Denmark over the period 2012–2015 with a total budget of 4 M€ and involving 4 PhD and 6 postdoc projects [83].

Fig. 70. The vast field of industrial application of CT as illustrated by a CIA-CT cartoon: pig meat, mobile phone, hearing aid, insulin pen, Lego bricks [28].

The European Marie Curie Initial Training Network “INTERAQCT – International Network for the Training of Early stage Researchers on Advanced Quality control by Computed Tomography” involves 13 PhD and 2 postdoc projects over the period 2013–2017. The INTERAQCT project has been conceived as a pan-European industrial-academic initiative that will provide the unique and encompassing training environment required, by bringing together expertise from industry and academia in each of these domains (CT-equipment, CT-software, NDT, dimensional metrology, additive manufacturing, micro-manufacturing, composite manufacturing). The research will develop procedures for fast and accurate CT model acquisition, with special emphasis on multi-material parts. Furthermore, INTERAQCT targets quantification and improvement of the reliability of CT measurement results, by determining the probability of detection of material defects as well as by achieving metrological traceability. In addition, CT based quality improvement loops will be targeted for key emerging manufacturing technologies.

A number of conferences are devoted to the field of CT in Europe. Four annual CIA-CT conferences with international attendance have been held so far in Denmark. Since 2008, an international Conference on Industrial Computed Tomography is held in Wels, Austria www.3dct.at.

The first international interlaboratory comparison of CT systems used for dimensional measurements, called ‘CT Audit’, was carried out in the period from March 2010 to March 2011, involving 15 CT systems in Europe, America and Asia, operated by expert users. The project was organized and coordinated by the Laboratory of Industral and Geometrical Metrology, University of Padova, Italy. Four calibrated samples were chosen for circulation, representing a variety of dimensions, geometries and materials. The samples are shown in Fig. 71.

The “CIA-CT comparison – Inter laboratory comparison on industrial Computed Tomography”, organized by DTU Mechanical Engineering, Denmark, and carried out in 2013, has involved 27 participants from 8 countries. Instead of using reference artifacts for calibration and verification of CT scanners, this comparison has involved two real industrial parts commonly measured in industry, in terms of materials, dimensions and geometrical properties, as shown in Fig. 72: a plastic Lego brick and a metallic part of a medical device. Parallel circulation of 27 sets with the two items took place in spring 2013 and the final report was available in September 2013 [4]. An example of results is shown in Fig. 73. The comparison has shown that CT measurements on the small industrial parts that have been used can be divided in two groups. Group A with average measurement uncertainties in the range 6–15 µm, and Group B with average uncertainties in the range 14–53 µm, and maximum values up to 158 µm, compared to average uncertainties in the range 1.5–5.5 µm using CMMs. Fig. 74 illustrates the expanded uncertainty of CT measurements for different measurands on the two comparison items compared with reference measurements obtained on CMMs.

Fig. 71. The four CT Audit items enclosed in their cylindrical sealed boxes: (a) CT tetrahedron, (b) pan flute gauge, (c) PTB Calotte cube, (d) QFM cylinder [15].

Fig. 72. The two items used in the CIA-CT interlaboratory comparison of industrial CT scanners: plastic Lego brick and metal part from a medical device [4].

The CIA-CT audit – Inter laboratory comparison of medical CT scanners for industrial applications in the slaughterhouses was organized by DTU Mechanical Engineering in 2011–2012. Two synthetic phantoms were used instead of real pig carcasses. Each phantom consists of several polymer components made out of Polymethyl methacrylate (PMMA), Polyethylene (PE) and Polivinyl chloride (PVC). A comparison was made of volume measurement performance of different medical CT scanners in Europe. The phantoms circulated among four participants and a total of six medical CT scanners. Volume estimations were compared to
volumes determined by water displacement performed before the circulation and used as reference values [3].

7. Conclusions

The number of industrial applications of CT is large and rapidly increasing, as shown by the numerous and different application examples given in this paper from the manufacturing industry as well as from other industries, e.g. electrical and electronic devices, inhomogeneous materials, and from the food industry. The paper has also identified limitations and problems of state of the art CT in solving some of the industrial challenges. A number of major national and international coordinated activities in the field of industrial CT underline the strong industrial and academic interest.

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