25 Years Industrial Computer Tomography in Europe

Authors: Christoph Sauerwein, Martin Simon, Hans Waelischmiller GmbH,
Schießstattweg 16, 88677 Markdorf, Germany

Abstract

In recent years X-ray computed tomography (CT) has received a growing interest in industry. Most of the mathematical and physical basis for CT has been developed many decades ago and are still valid. Already 25 years ago pioneers were applying X-ray CT to inspect and examine industrial objects.

Since then, advances especially in sensor technology and computer hardware have led to dramatical changes in CT hardware. Together with refinements of the CT reconstruction algorithms and their implementation in modern object oriented software environments and fast PC hardware it was possible to enhance the resolution and reduce the scan and reconstruction time. Especially the development of 3D CT systems based on cone beam reconstruction algorithms has improved the acceptance of CT technology for industrial applications.

Besides the classical NDT application CT is becoming more and more a versatile tool for defect detection, dimensional measurement and is even entering the field of reverse engineering. Due to this advanced technology a multitude of applications in various fields has become possible, such that CT is now an indispensable instrument in many fields of industrial product development and manufacturing.

This paper presents an overview on the development of industrial CT systems and technologies which includes advances in system concepts and a cross-section on a variety of applications.

Introduction

Only few years after the first medical X-ray computer tomographs found entry into hospitals, this new technology was also used for non-destructive testing. First of all medical scanners were used, then specific industrial tomographs were developed and adapted to the respective testing objects.
In line with the rapid development of computers and various X-ray detectors also the design and layout of the CT systems changed. By way of examples we wish to present the major steps of development of CT systems and the range of various applications of the past 25 years, thereby making no claim to be exhaustive.

From Medical to Industrial Tomograph

At the end of 1977 to early 1978 MBB in Ottobrunn near Munich (today: Eurocopter) started to make their first CT investigations on helicopter rotor blades [1]. At first the CT-installations in Munich hospitals were used. Then, in 1993 a (medical) CT-Scanner of their own was procured; to this day this scanner is in use for systematic investigations on cracking and analysis of crack progression. On the basis of the CT-results and the new investigation opportunities due to CT, rotor blades could be developed whose internal structure was considerably more complex than those of former blades (refer to Fig. 1).

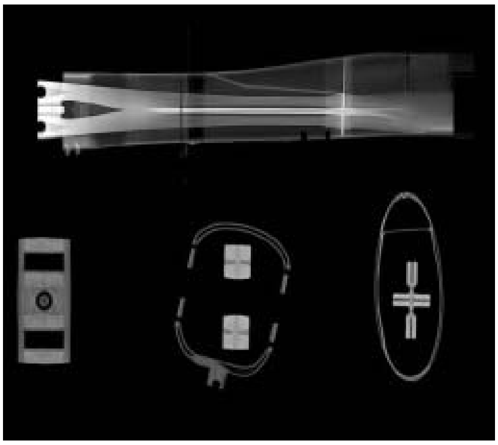


Fig. 1: Complex rotor blade (Eurocopter)

As concerns the systems technology, it is interesting to learn that from 1978 to date the measuring and reconstruction times have dramatically decreased in spite of increased matrix values. (Refer to Table 1)

Table 1:

Year	1978	1980	1993	Today
Type	EMI 5050	EMI 7020	GE Light Advantage	Medical Scanner
Matrix	320	512	512	512
Time/Layer	600 sec	100 sec	14 sec	2 sec

In 1978 the Bundesanstalt für Materialforschung und -prüfung (BAM) (Federal Institute of Material Research and Testing) in Berlin initiated the development of a tomograph exclusively for technical applications. The first version was completed in 1983. It was equipped with a Co-60 source and 32 individual detectors and operated in the rotation-translation-mode [2]. This scanner enabled to show the contents of radioactive waste drums in spite of strong casing (refer to Fig. 2).

Fig. 2: First CT-Scanner of BAM

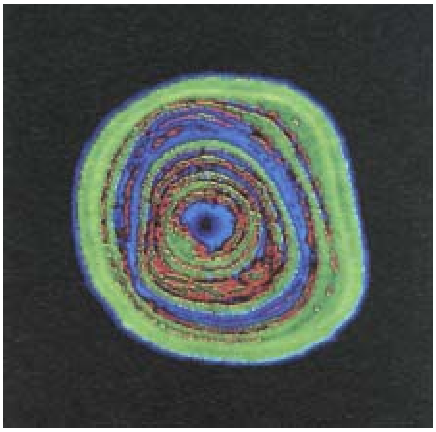
Based on this lab experience and their own development, systematically pursued since 1981, in 1990 the Sauerwein company have supplied a drum scanning installation to the Technical University Munich, which, to this date is used for services. The installation is provided with 30 individual detectors for digital radiography, transmission tomography and emission tomography, as well as a gamma spectrometer for isotope selective gamma scanning [3].

Process Tomography

Whilst with industrial tomographs the testing object is usually placed on a rotary table, the process tomography, analogous to medical scanners, requires rotation of the radiation source and the detectors around the process to be investigated.

The first installation of this type was developed by Habermehl and Ridder in the years 1976 - 1978 [4] in order to investigate water conveyance in trees, thus analysing the mechanism of tree death due to acid rain. This way it could be shown that in damaged trees the outer (younger) rings carried considerably less water than the center rings, whilst in healthy trees the complete cross section participates in the water conveyance. (refer to Fig. 3)

Fig. 3: Mobile CT-Scanner MCT 3



CT slice

In the early eighties Sauerwein has put 3 such mobile CT-installations with Cs-137 source and 3 scintillators into operation, which were then used by forestry institutes for investigation of proliferation of red ring rot or to predefine the stability of city trees.

In the same way the stability of telegraph poles or steel reinforcement in bridge piers could be examined by those mobile tomographs. However, already early on mobile tomographs were used to localize deposits in pipe work of chemical installations in operation and define the free cross section with the aim to take appropriate timely countermeasures and prevent costly downtime.
Starting in 1999, the mix of processes of quasistationary 2-phase flows were investigated at the Research Center Karlsruhe by means of a 3-D tomography, using a two-dimensional flat panel detector of amorphous silicium [5].

From 2D to 3D-CT

In order to achieve fast dedicated use of CT together with highest possible image quality, the early nineties provoked the development of CT-detectors on the basis of X-ray image amplifiers. What it mattered was a combination of fast radioscopy with high resolution CT - in order to avoid time consuming scanning of large objects in 2D-CT. The combination detector Gammascope CT developed by Sauerwein and patented in 1991 enabled to define by a high resolution radioscopy image, in which positions of the testing object a 2D-CT section image would have to be taken. To this end the initial image of the image converter was read out by a diode line with 1024 elements, in order to achieve high local resolution and, thanks to the dynamics of the line - at the same time an excellent density resolution. In 1992 a CT-system with this detector and two X-ray tubes (450 kV and 225 kV microfocus) (refer to Fig. 4) was installed at Mercedes in Stuttgart and successfully used for a great variety of applications within the vehicle component development and systematic investigation on component failure as a function of mileage [6].

Fig. 4: CT-Scanner at Mercedes

Almost at the same time Europe's first 3D-CT system (refer to Fig. 5) was developed within a joined project sponsored by the BMFT together with the BAM, still used to this day for numerous spectacular investigations. An X-ray image amplifier, read out by a high resolution, cooled CCD camera is used as a detector. Hence it is possible to make use of the complete radiation cone, defined by the X-ray source and the detector surface, such that only one rotation of the object is required for data acquisition.

Fig. 5: First 3D-CT-Scanner (Sauerwein/BAM)

Advantages of 3D-CT as compared to 2D-CT with regard to time saving in data acquisition are evident. In addition, only with direct 3D-CT is it ensured that local resolution in all three directions in space is equally good.

Nevertheless it took until the end of the nineties that 3D-CT systems were procured by industrial companies. This was encouraged by the development of highly efficient, moderately priced computers, allowing for reconstruction of the 3D-results to keep up with the data acquisition. The introduction on the market of so-called flat panel detectors on the basis of amorphous silicium of higher dynamics than X-ray image amplifiers and easier handling due to their flat design, also helped.

Since then a number of companies offer CT-systems, the majority of them procuring the actual CT-know how from external sources.

Dimensional Evaluation and Reverse Engineering

Originally, industrial CT was developed with the aim to investigate density distribution and to scan components with respect to material or jointing faults. The important feature of CT to provide orthoscopic, unambiguous images of the complete internal structure of each testing object, moreover enables to use the geometry information from the interior.

Dimensional Measurement

By the end of the eighties this aspect made the CT-examination of turbine blades the center of interest. In operation, turbine blades are exposed to very high temperatures such that they must be provided with an ingenious system of cooling ducts in order to prevent burning out. CT is highly suitable for non-destructive geometric evaluation and measurement of the cooling ducts together with their diameter, their 3D-course and the residual wall thicknesses between the ducts, or rather to the edge. Therefore, also big manufacturing companies could not avoid using this technology. So, GE in Cincinatti (USA) has built a CT-installation of their own, and Pratt and Whitney in Canada have bought an American model. MTU in Germany first placed an order for an extensive study to Sauerwein, then verified the measurement results and their accuracy by destructive testing. Because of the excellent results they decided to use CT as a recurring procedure and therefore various CT services were used.

Geometric Comparison

Besides the point-by-point geometric measurement the thing to do would be to examine the complete volume of the testing piece for dimensional deviations. To this end the component is scanned in by means of a 3D-CT shot or a multitude of 2D-CT sections.

Then from the CT-data all internal and external material surfaces are extracted and compared with the CAD-model. The result can be represented by colour coding or numerically. This process comes in especially useful for the first article inspection of cast parts, where it is essential that the casting mould has got the correct surplus dimension in order to compensate for shrinking of the cast material when cooling down. Compared with conventional methods the CT first article inspection is often faster and less costly.

Since the early nineties services for this application are carried out by EMPA [7] in Dübendorf (CH). Later on also by Tomo Adour at Pau (F) and today in addition by Zeiss 3D in

Aalen (Germany). The both first mentioned institutes have participated in a European joined project "FATIMA" on the same issue, together with the end users and software companies from 1999 to 2002, where this process was further improved (refer to Fig. 6).

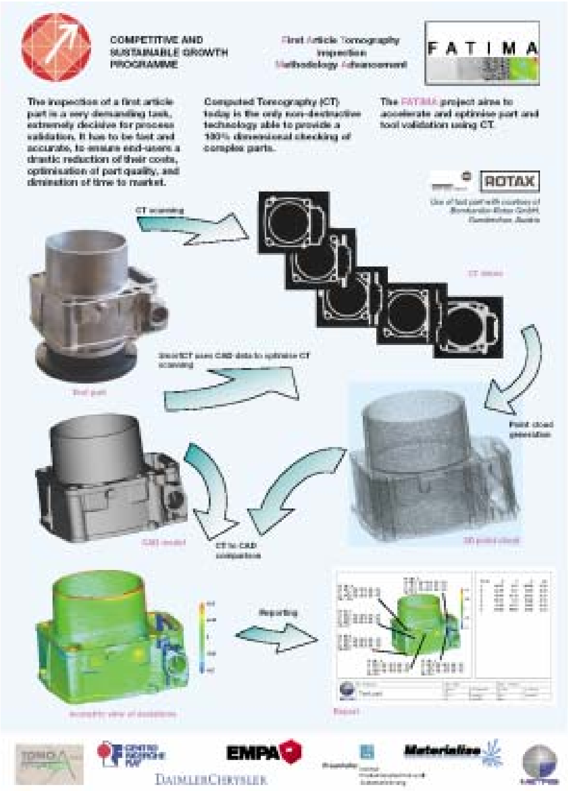


Fig. 6: Overview of FATIMA project

Reverse Engineering and Rapid Product Development

CT opens up interesting possibilities in so-called reverse engineering. This means, an existing product or model is three-dimensionally digitalized. All internal and external material surfaces are extracted from the CT-data and then reversed into CAD data. Thus, a 3D-CAD can be elegantly generated.

Using this procedure, a number of interesting applications were carried out by EMPA between 1997 and 1998 [7]. In order to produce new tools for the core manufacture of a water cooling jacket for a cylinder head a 3D-CAD data model was generated, as by then the manufacturer only had 2D-drawings at his disposal. In another case a motorbike racing motor was to be optimized, where, starting from an existing four-cylinder engine a three-cylinder engine of higher efficiency was to be developed in the most economical way. To this end a complete CT-data set of a cylinder was scanned and a CAD-data set generated. Involving the racing engine manufacturer the CAD-model was modified in order to improve the engine's efficiency. The thus modified volume model was used for planning and preparation of the casting process. Finally the CAD-data were used for control of a lasersintering process, whereby sand moulds and cores were fabricated without the usually required tools.

Industrial CT Today

Possibly today's most efficient X-ray CT system is Wälischmiller's RayScan 200 [8, 9].

The complete system is designed as a coordinate measuring machine, using high-quality, carefully matched components (refer to Fig. 7). So, for small components a local resolution of few micrometers is achieved. Nonetheless the installation can be used for examination of objects with a weight of up to 80 kg, 600 mm diameter and 1,5 m length. Thanks to optimized 3D-CT-technology the result of a volume scan is available already at the end of the data acquisition, usually after 5 - 25 minutes.

Fig. 7: RayScan 200 at Zeiss 3D

Basic System RayScan 200

Experience of decades of CT-development has duly been absorbed in order to also operate the installation without expert knowledge of the user in the best possible way, and to fully utilize the multifarious possibilities of 3D-CT for quality assurance, dimensional measurement and reverse engineering.

Related Processes

The most widely used is the 2D and 3D-CT with X-ray tubes (160 kV minifocus, 225 kV microfocus or 450 kV). Depending on the object, also radio isotopes (Ir-192, Cs-137, Co-60) or linear accelerators (2MeV, 9MeV, 15 MeV) come into action.

A complementary technology is represented by the neutron CT, for whose development the Technical University Munich has dedicated a lot of pioneering work [10]. Whilst the X-ray absorption mostly depends on the atomic shell and increases with the nuclear number of the testing object, the neutron absorption is subject to the structure of the atomic nucleus. Therefore, penetration of some metals by photon radiation is difficult, for neutrons, however, fairly easy. On the contrary, some plastics show only faint contrast on the X-ray image, however, due to their hydrogen content they show distinctly in neutron CT. Thus, neutron CT is a valuable complement, but can by no means replace the X-ray CT. Neutron-CT installations are used in the research reactor at Munich and at the PSI at Villigen (CH).

All processes described so far are based on the comparison of the unattenuated radiation of an external source with the absorption generated by an object. This is also called transmission tomography, in order to make the distinction between the latter and emission tomography. Emission tomography makes use of the spatial distribution of the characteristic radiation of an object containing radioactive elements, in order to calculate back on the location of the emitting substance and its intensity. There, it can be helpful to use the results of a transmission tomography for emission tomography, in order to take into account the absorption due to externally located substances for intensity analysis of the radiation sources.

Some examples for this process are the combined installation for transmission and emission tomography of waste drums, installed by Sauerwein at the Institute of radiochemistry at the Technical University Munich [3] and investigations carried out at the CANDU Fuel Reactor in Romania [11]. The processes dealt with the analysis of the Cs-content and Cs-distribution in core fuel rods by emission tomography in order to determine the burn-up state of the fissionable material.

Conclusion

Due to their higher local and contrast resolution CT-installations for industrial applications are well established beside pure medical CT-systems. In the course of the last 25 years immense quality improvement was achieved, and a multitude of different applications was implemented in most different fields of technology.

Today CT is recognized as a powerful investigation tool which also in future will be widely used.

References

1) Oster, Computed Tomography as a Non-destructive Test Method for Fiber Main Rotor Blades in Development, Series and Maintenance, presented at Int. Symposium on CT for Ind. Applications, Berlin, 1999

2) Goebbels, BAM, Berlin, private communication

3) C. Sauerwein et al., „Tomographic Inspection of Nuclear Waste Containers“ Proceedings of ECNDT, Nizza, 1994

4) Habermehl and Ridder, „Ein neues Verfahren zum Nachweis der Rotfäule“ Proc. Fifth Intern. Conf. on Probl. of Root a. Butt Rot in Conifers: Hannoversch-München, Hess. Forstl. Versuchsanstalt, 340-347, 1978

5) Simon and Tiseanu, „High Resolution Cone-Beam Tomography for Two-Phase Flow Diagnostics“ 2nd Int. Symposium on Two-Phase Flow Modelling and Experimentation, Pisa, Italy, 23-26 May, 1999

6) Maier and Jakobi, „Computer-Tomographie im Automobilbau“ Journal „Materialprüfung“ No. 38, 1996

7) A. Flisch et al., „Industrielle Computertomographie für Reverse Engineering Anwendungen“, Berlin, 1999

8) Sauerwein et al., „3D-Tomography: Exciting Possibilities Exceeding Conventional NDT“, ECNDT, Barcelona, 2002

9) Simon et al., “Multi-Purpose 3D-Computed Tomograhy System”, ECNDT, Barcelona 2002

10) Schillinger, „3D Computer Tomography with Thermal Neutrons at FRM Garching“, Journal Neutron Research, Vol. 4, pp. 57-63, 1996

11) Tiseanu et al., ”High-Resolution X-Ray Tomography for Nuclear Applications and Research”, Annual Meeting on Nuclear Technology, Stuttgart 2002