New Applications of industrial Computed Tomography in Biomedical Engineering

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BIOGRAPHICAL NOTES

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KEY WORDS

tomography, X-radiation, public environment, CAT scan, CT image. high-end CT, 3D images, Workpiece data, Metrotomography, X-rays scan, visualize, reverse engineering, Applications

ABSTRACT

Computed tomography (CT) using X-radiation reconstructs an unknown object from X-ray projections and has long been used for qualitative investigation of internal structures in industrial applications. For everyday use in an industrial setting, the key specification of the system is the measurement accuracy/uncertainty. Presented paper describes

metrological possibilities of new metrotomography in the area of biomedical engineering in order to hardware limitations and software functions. Specific prosthetic and biomedical experiments were realized by Metrotom (Carl Zeiss, Germany) at the technology center of computed tomography, Department of Biomedical Engineering, Automation and Measurement, Technical University in Kosice.

INTRODUCTION

More than one hundred years ago X-ray technology started its triumphal procession when Wilhelm Conrad Roentgen discovered a new kind of radiation in his laboratory in Wuerzburg, Germany in the year 1895. Up to this moment most of the developments on X-ray technologies and computer tomography have been focused on special medical applications. Another twenty years later computer tomography (CT) has become a powerful, well accepted tool in industrial applications as well. Today industrial CT is on its way to become a major tool of industrial quality control in high-tech branches, not only for material testing but for geometry analysis as well.

Besides the challenge to further optimize the CT systems hardware, its performance and capabilities, the probably biggest challenge at this moment is to process the huge amounts of data resulting from today's CT scanners in reasonable amounts of time.

The result of a CT scan displays the part as a three-dimensional image composed of so called voxels [1]. Each voxel has a gray value that represents the local X-ray absorption density. The resolution of this 3D imaging system is given in part by the number of voxels in the 3D image, which in turn is given by the number of pixels in the detector. By using subpixel respectively sub voxel interpolation the effective resolution can be increased. Using techniques derived from 2D image processing, 3D voxel images can be evaluated to arrive at dimensional measurements for the scanned parts. This approach is especially advantageous because the 3D image reproduces the complete part including both outer and inner measurement features. Ultimately the user needs to know whether the part under inspection meets his tolerance requirements and whether his measurement device can answer this question or not. In addition, reproducibility and operator independence are important criteria for the shop-floor deployment of a measurement tool.

Industrial CT uses a series of 2-dimensional (2D) images taken at specific intervals around the entire sample. Basically any type of industrial CT system uses three principal components: an X-ray tube, an X-ray detector, and a rotational stage. Everything is enclosed within a radiation shielding steel/lead/steel cabinet that typically ranges between four and 10 feet cubed. This allows use of the system in a public environment without any additional safety concerns. Micro computed tomography (micro-CT) is primarily the same as standard CT except it uses a micro focus tube instead of a traditional tube. A micro-CT scan yields resolutions in microns because the focal spot of a micro focus tube is only a few microns in size.

For comparison, micro-CT resolution is about 100 times better than the best CAT scan in the medical field.

In biomedical applications, micro-computed tomography scanners can function as scaled-down (i.e., mini) clinical CT scanners that provide a 3D image of most, if not the entire, torso of a mouse at image resolution (50–100 μm) scaled proportional to that of a human CT image. Micro-CT scanners, on the other hand, image specimens the size of intact rodent organs at spatial resolutions from cellular (20 μm) down to subcellular dimensions (e.g. 1 μm) and fill the resolution-hiatus between microscope imaging, which resolves individual cells in thin sections of tissue, and mini-CT imaging of intact volumes.

High quality industrial X-ray detectors used for CT are typically a new generation amorphous silicon flat panel area detector. They offer a very high sensitivity, resolution and bit depth. The resulting 2D X-ray images are very clear and the contrast is unparalleled. A modern high-end CT scan consists of taking several 2D X ray images around the object, preferably covering 360 degrees (complete rotation). CT systems typically acquire between 360 images (one image every degree) and 3600 images (one image every 0.1 degree) depending on the final desired resolution. Each image is between three to 10 megapixels and is also averaged and filtered to reduce noise. The 2D digital images taken during this step are saved directly into a single folder, which will be used in the next step of the CT process [4].

Once the acquisition process of the CT scan is completed, CT calibration and CT reconstruction algorithms are used to reconstruct the 3D CT volume.

These 3D images are made of voxels (three-dimensional pixels), and with the use of visualization software the 3D volume can be manipulated in real time. Because of this it is possible to slice through anywhere inside the object, inspect and look for defects, take accurate measurements, reconstruct a surface model and so forth. Industrial CT technology is improving very quickly. While a few single CT slices would take hours to generate years ago, it is now possible to reconstruct complete 3D models with billions of voxels in just seconds. This opens the door for numerous new applications like 3D reverse engineering, rapid prototyping, 3D metrology and more. In that regard, industrial CT has become a very competitive technology for 3D scanning. The principal benefit of using 3D CT for scanning or digitization is that we obtain a complete model with both external and internal surfaces of an object without destroying it.
On of the new systems available today is Metrotom developed by Carl Zeiss Company. This system opens beside industrial applications also new applications in the area of biomedical engineering.

MATERIALS AND METHODS

Metrotomography presented by Metrotom (Fig. 1) device uses X-ray technology based on a simple principle: an x-ray source illuminates an object with an electro-magnetic beam – the x-ray beams. The beams meet on a detector surface and are recorded in varying degrees of intensity depending on the thickness of the material and its absorption characteristics. The result is a two-dimensional gray-scale image. However, this image is only meaningful for visual inspection when shown as a cross section. Metrotom rotates the component 360° around its own axis, thus producing a 3D image of the interior of the part.
Metrotom has a measuring volume of 300 mm x 300 mm. The ability to perform a metrotomograph of a material depends on the principle of cumulated material thicknesses. It is possible to metrotomograph plastics, for example, up to a thickness of 250 mm; light metal alloys such as aluminum or magnesium up to 120 mm. It is even possible to perform a tomograph on steel up to a thickness of 10 mm; the pure defect check also works up to a thickness of 50 mm.
The metrotomography procedure provides testing technology with a complete range of evaluation possibilities: from assembly inspection to damage analysis, inspection of materials, porosity analyses and conventional defect checks. At a glance, metrotomography now clearly shows the defects in areas where previously an inspection was not possible at all, or only using very timeconsuming and costly cross section.
Workpiece data recorded using the metrotomography procedure can be applied to all areas of quality assurance and evaluated to traditional metrology, reverse engineering applications and comparison of geometries. (Fig. 1)
Metrotomography uses software environment called Calypso. Every metrotomographed component (whether a standard geometry or freeform sufaces) can be extensively evaluated. By Calypso, the following steps can be performed for metrological purpose: reading the features and orientation from the drawing and specify a measurement strategy, generating a CNC measurement plan based on the computed STL or CAD data, entering and aligning the CAD model with the CT data, starting new CNC measurement plan and evaluate the protocol. (Fig. 2)
Metrotomography is the ideal and, primarily, fast solution, particularly when there is no CAD data on a component (reverse engineering). When evaluated workpiece (e.g. cube) is metrotomographed, a point cloud is computed from the resulting 3D model. Splines and knots are generated via reverse engineering. A complete CAD model, which can be displayed in all standard formats, is available at the end of the process. Duration of this process is approximately 1 hour.
For comparison of geometries, standard data formats such as IGES, STL, VIDA and STEP can be easily compared using a 3D model generated with the Metrotomography procedure. The plan/actual comparison work (e.g. a damper bearing evaluation) as it is described in following steps: scaning the CAD design data of the bearing, entering the point cloud of the bearing from the metrotomograph, aligning the data sets of each other, displaying of the deviations as measurement flags or extensive, colorful displays of the deviations.
The utilization of Metrotom is presented by measurement of the multidirectional valve (Fig. 3). Following pictures show description of reverse engineering function of Metrotom, material inspection and metrological possibilities of the scanner and software. (Fig. 3)

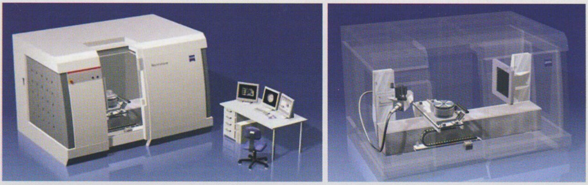

Fig. 1 Metrotom (Carl Zeiss, Germany) and X-ray sensor.

Fig. 2 Technology Center of Computed Tomography, Department of Biomedical Engineering, Automation and Measurement, Technical University in Kosice.

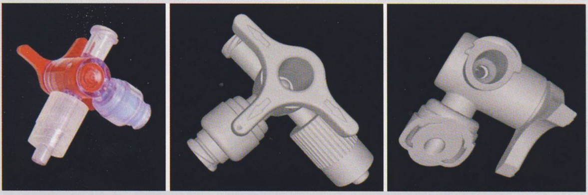

Fig. 3 CAD models of the multidirectional valve – presentation of the reverse engineering.

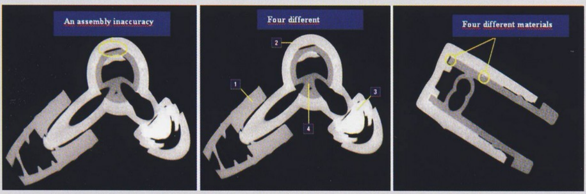

Fig. 4 An analysis of the constructional junctions in multidirectional valve.

In particular steps an X-rays scan rotated measured object. From X-rays the position of each voxel is calculated. According to density of material, each voxel has a value from the gray scale in the range from 0 to 65535. This allows to separate low density materials as an air and other support materials. The 3D point cloud gives a possibility to see the component from indifferent direction. Therefore, it is possible to evaluate not only the surface of the model but also the inner environment or cross-section.
Figure 4 presents inspection function of metrotomography. An advantage of this method is possibility of inspections of constructional junctions in assemblied work pieces (contact surfaces analysis, quality control, and detection of foreign materials or air spaces). (Fig. 5)
Metrotom measures with relatively high accuracy. Calypso software allows evaluating of each obtained component. By comparison of the CAD model (Fig. 6), which is created with nominal geometry and dimensions together with metrotomographs is possible to generate a view of geometry deviations. Calypso also offers an evaluation of length parameters, angles and geometry or position deviations.
Metrotomography by Carl Zeiss was used for scanning epithetic hand, foot and plastic skull (Fig. 7). Above mentioned products were selected to check plastic materials, which are frequently used in medical practice and biomedical engineering research.
Also wooden materials and metallic parts of skull were investigated in order to check the capability of Metrotom.

RESULTS

The products of biomedical engineering research or research in prosthetics and orthotics (Fig. 7) were scanned by Metrotom and investigated by different software applications. Presented initial study shows functions and possibilities of Metrotom and software aplications (Calypso and VG Studio Max).
Software VG Studio Max (Volume Graphics) is a tool, which except visualization of obtained data also allows to apply following analysis: geometric analysis (2D & 3D dimensioning, actual/nominal comparison, actual/actual comparison, wall thickness analysis and extraction of STL surface from point cloud) and material analysis (detection of defects, inclusions detection and possibility of material distribution and position in composite material). VG Studio Max offers many useful tools and methods for data visualization. The points cloud is possible to separate by grey color intensity which represents different density of materials and resultant inner material detection (Fig. 8). Within the artificial foot are visible reinforcing materials and inner structures and holes for foot assembly.
By the translucency of cover material (skin color plastic) with lower density and air spaces (originating at the plastic casting) are getting more apparent. VG Studio Max enables to detect material inhomogenity often presented by air cavities. By use of histogram function in the relation with an air cavity geometry there is possible to assess an exact position of the cavity.
An approximately 900 X-ray scans were captured by single steps during one revolution of the measured object around the vertical axis. Subsequently, the 3D model was processed (Fig. 9, middle), which allows non-destructive cross-sectional analysis. Figure 9 right shows the window of VG Studio Max 2.0. In four windows is possible to visualize the 3D view of rendered model and epithetic glove cross-sections in perpendicular views.
The software enables easily to use the measure features, e.g. a glove wall thickness. The histogram in the right lower corner of the window gives information about number and types of used materials (different density) in observed object. (Fig. 10)
VG Studio Max allows an animation consisting of multiple overflights around the object or crossing the object in optional direction. Data can be transported to generally supported STL format and further processed for reverse engineering or rapid prototyping/manufacturing.
Different grey scales in presented scans (Fig. 11) are caused by reduction of X-ray energy detected by X-ray detector. This is presented by higher material thickness in the place where X-ray is passing through (skull borders) or higher material density (springs and clasps).
The skull model as it is shown on Figure 12 consists of two types of materials, metallic springs and clasps and plastic skull. By separating of different materials density, there is possible to hide selected material (e.g. only metallic parts are visible).

CONCLUSION

The paper deals with modern metrotomography presented by Metrotom device (Carl Zeiss, Germany) and application oriented to biomedical engineer-

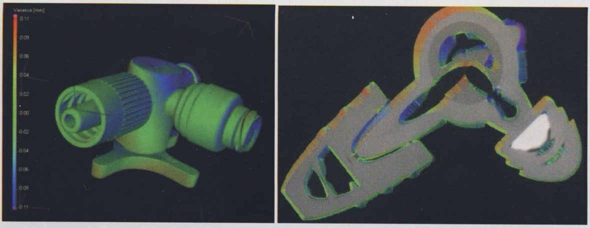

Fig. 5 Geometry deviations analysis of the multidirectional valve.

Fig. 6 CAD model (left) with CT data and evaluation of geometry deviations with default toleration field (middle and right).

Fig. 7 Samples from the field of biomedical engineering evaluated by metrotomography (epithesis and plastic human skull).

Fig. 8 Epithetic foot and obtained 3D model (visible transparency of lower density material – soft surface plastic and wood).

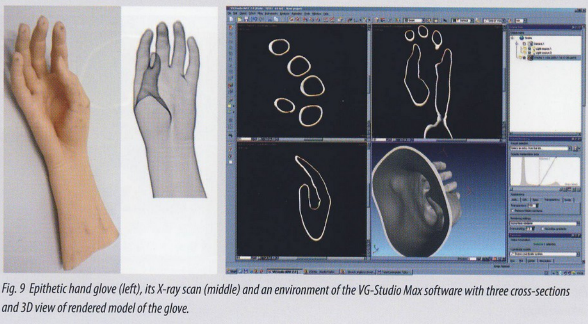

Fig. 9 Epithetic hand glove (left), its X-ray scan (middle) and an environment of the VG-Studio Max software with three cross-sections and 3D view of rendered model of the glove.

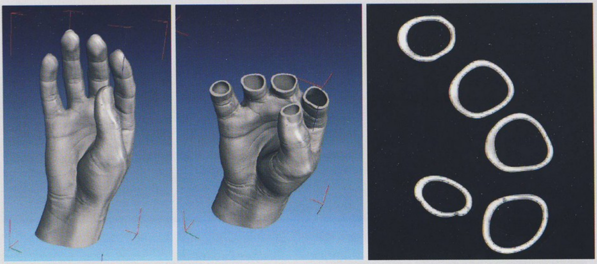

Fig. 10 Rendered 3D model created by point cloud grid (left), cross-section of the 3D model in indifferent direction and cross-section of the glove model in one of the three views.

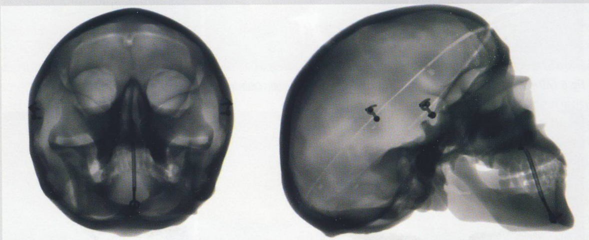

Fig. 11 Two views of skull X-rays.

Fig. 12 By skull translucency is possible to see metallic components of the assembly (left); window with control tools of the VG-Studio Max software (right).

ing. Analysis and obtained results showed in order to initial measurements of selected products the potential of Metrotom together with its restrictions (maximal dimensions of scanned object, material restriction, etc.) which on the other hand allows considering applicability of planned measurements.

An advantage of metrotomography is non-destructive testing of materials, detection of inner defects and inhomogenity, the use of Metrotom for reverse engineering, metrology, rapid prototyping and manufacturing etc.

Applications in the area of biomedical engineering rest mostly in biomaterials research (implants and other invasively or non-invasively applied materials) where by the geometry analysis is possible to assure a quality of biomedical products.

A possibility of analysis of osteosynthetic junctions, analysis of total replacements in order to endoprosthesis release and analysis of biomechanical properties of biomaterials (monitoring of cavities, composites research, etc.) are not less important.

The specific applications in biomedical engineering research include analysis of junction in medical devices, 3D modeling by reverse engineering and the following rapid manufacturing (production of orthosi and epithesis, casing and covers, adjuvatics and its modules or elements).

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