Application of biomedical metrotomography

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***Abstract*— Computed tomography scanners (or CT scanners) are very popular medical equipments for tens of years. Its invention initiated a revolution in diagnostic technology by allowing us to look inside a person and obtain a very clear anatomical image without violating the outer surface of his body, in other words, non-invasively [10]. Just few years ago this technology found way to the area of industrial applications and especially to geometrical metrology. Metrotomography is a term that consists of words metrology and tomography. Presented paper describes metrological possibilities of industrial tomography in the area of biomedical engineering in order to hardware limitations and software functions. Specific prosthetic and biomedical experiments were realized by Metrotom 1500 (Carl Zeiss, Germany) at the Technology center of computed tomography, Department of Biomedical Engineering, Automation and Measurement, Technical University in Kosice.**

I. 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 3 D imaging system is given in part by the number of voxels in the 3 D image, which in turn is given by the number of pixels in the detector. By using sub-pixel respectively sub voxel interpolation the effective resolution can be increased. Using techniques derived from 2 D image processing, 3 D voxel images can be evaluated to arrive at dimensional measurements for the scanned parts. This approach is especially advantageous because the 3 D 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 CT scan in the medical field. Today also nano focus tubes with focal spot under one micrometer are presented for very precision measurement and mostly for material inspection.

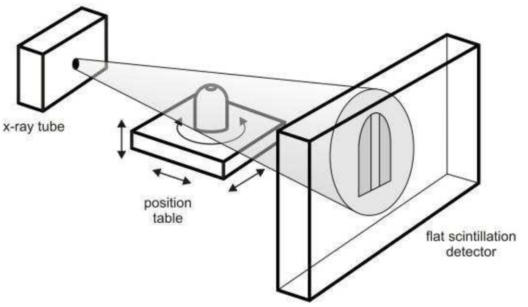

Figure 1. Principle of microtomography with flat panel detector

Figure 2. One of the first computed tomographs in medicine (left) and one of the first industrial computed tomographs (right)

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 quality and resolution. Each image is between 3 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.

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.

II. PRINCIPLE OF METROTOMOGRAPHY

Metrotomography presented by Metrotom 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.

Nowadays, the industrial tomographs are designed to scan with the high precision. Thanks to this, their use will be extended from the diagnosis area to the metrology area. In the metrology, they will improve the control of the shapely-complicated parts that could not have been measured until now. The main industrial tomography areas of the use are:

- testing:
  - quality of the connections in assemblies
  - analysis of the porosity
  - analysis of the defects
  - inspection of the material
- measuring the dimensions of the inner and outer elements
- reverse engineering (obtaining the CAD model from the real part)
- comparing the nominal with actual geometry

III. APPLICATION IN BIOMEDICINE

Technology center of computed tomography at Technical university of Kosice serves as support for many kind of researches. Biomedical research or research in prosthetics and orthotics are important supported areas. Tomography can be used for various evaluations. One of the most used is digitalization of very complicated shaped objects. In biomedical engineering there are many objects with so complex surfaces, that they are not measurable by any other methods of digitalization. Touching probes, lasers or optic scanners can not reach areas which are mostly hidden or unobtainable. With CT scanners we obtain 100% information about object shape. Because of that for example human teeth (fig. 3) or animal skulls (fig. 4) can be digitized. VGStudio Max is software which allow extract STL model from surface points. STL is universal triangular model which can be imported to every CAD/CAE/FEM/RP software for further processing.

With CAD software it is possible to do parameterization or design a supplement for scanned object. In FEM (Finite element method) software the stress/strain analysis can be performed. STL model is also ideal type of model for Rapid Prototyping. With 3D printer the plastic or even metal copy of real object can be done. On the figure 4 can be seen results from project of digitalization and printing of animal skulls. On the bottom picture there are the original monkey skull and printed copy of monkey skull. More about express creation of complex shaped object copy can be found in authors other publications [10].

In area of orthosis design there are also very complicated plastic parts, which are difficultly digitalized with any other scanning technology. Examples of digitalization of orthosis for hands made from low temperature thermoplastics (LTTP) are pictured on figure 5. With obtained data it is possible to do further analysis for example analysis of curvature, stress/strain analysis etc.

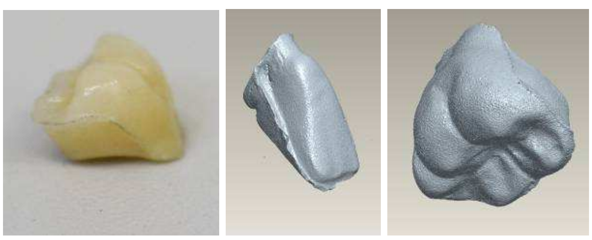

Figure 3. STL format of human teeth (middle and right)

Figure 4. Skulls of animals (top) and example of monkey’s skull printed with 3D printer (bottom left)

Metrotom 1500 with maximum power of x-ray source 250 W is ideal for plastic parts and light metal alloys. Also metals with higher density can be scanned with Metrotom 1500, but wall thickness of the part is limited. Nice example of digitalization for dental clinic is a STL model of metal dental bracket on figure 6. The maximum dimension of this bracket is 3 mm. With so small parts it is possible to achieve resolution of pointcloud around 9 μm. With subvoxeling process the resolution can be increased. Small objects can be magnified more then bigger parts, because they are placed closer to the x-ray source. The size of the projection is zoomed many times and because of that size of voxel (volume pixel) of final point-cloud is just a few micrometers.

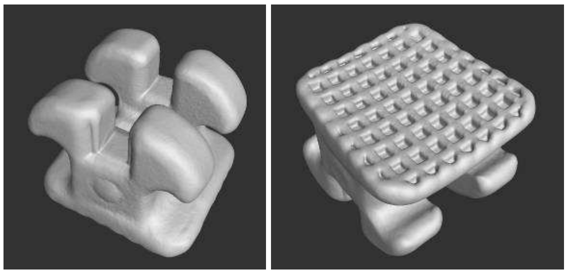

Figure 6. Pointcloud of mall metal dental bracket

X-ray is kind of radiation which can penetrate through objects. Because of that we have information not only about surface of object, but also about inner volume. After reconstruction of point cloud we can look inside the object by using virtual cross-sections without destroying of real object or separate materials with different density.

In the figure 7 the separation of different plastics, composite materials and wood is shown. Prosthesis contains components which are not visible because they are hidden in the inner volume. We can set transparency for polyurethane in reconstructed point-cloud and inner components appear in 3D rendered visualization. With this simple separation it is easy to evaluate, if the all components are at correct position and if they are not broken. These evaluations are made without cutting of real object.

Inspection of inner structure of pork femur is pictured on figure 8. The different gray-values depend on density of material. The air around the bone is black, because have a lower density. The outer structure of the bone has a higher density and the color of the pixels in this area is light gray. The density of bode is changing from outer surface to inner volume what is considerable from cross-section picture.

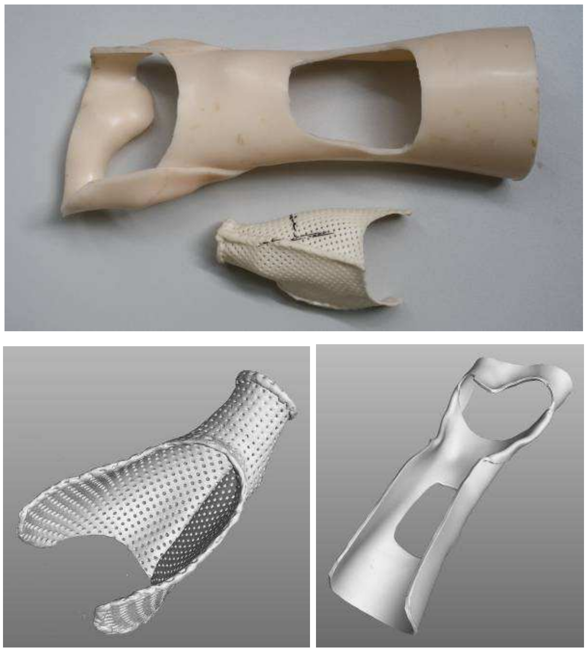

Figure 5. Plastic orthesis (top) and their pointclouds (bottom)

Figure 7. Prosthesis (left) and rendered point cloud with predetermined transparency of PUR material (right)

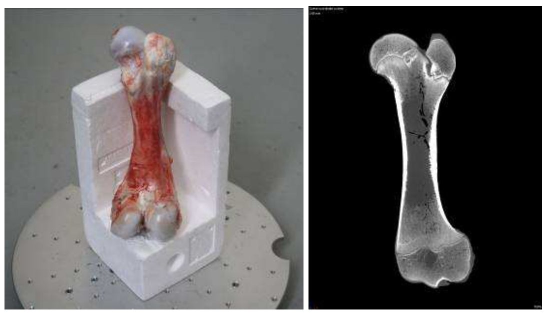

Figure 8. Pork femur (left) and its virtual cross-section (right)

Another research supported by CT technology at our laboratory was porosity analysis at two samples of human bones (fig. 9). The research was focused to compare amount of solid phase of two human demineralised bone matrices, where one of them was cultivated with mesenchymal stem cells (MSC) for two weeks.

After cultivation the amount of solid phase increased rapidly and the results can be seen also on figure 9. Porosity of selected regions of interests have been calculated and compared. Results of research can be found in authors' publication [6].

Industrial tomography is a branch of technology which gives not only advantages of nondestructive testing and viewing of inner structure, but the reconstructed data are so accurate, that this technology can be used for very precise geometrical measurements. Also in biomedical applications it is necessary to measure characteristics, which are difficultly measurable by any other technology without destruction. Spherical form of used acetabular component was measured with Calypso software. This metrological software is used for almost all coordinate measuring machines from Carl Zeiss. With Calypso we can evaluate characteristics of objects and make a protocols or graphical presentations of results. Graphical interpretation of form deviations at acetabular component in magnification are presented on figure 10. Deviations have been filtered to eliminate scratches on the spherical surface.

Quality of reconstructed point cloud and accuracy of measured data markedly depends on density and cumulative wall thickness of scanned object. Because of that material with lower density are more suitable for scanning than denser materials. Titanium, in comparison with other metals (steel, copper, etc.), is a metal with relatively low density and because of that small components made from titanium are measurable without restrictions.

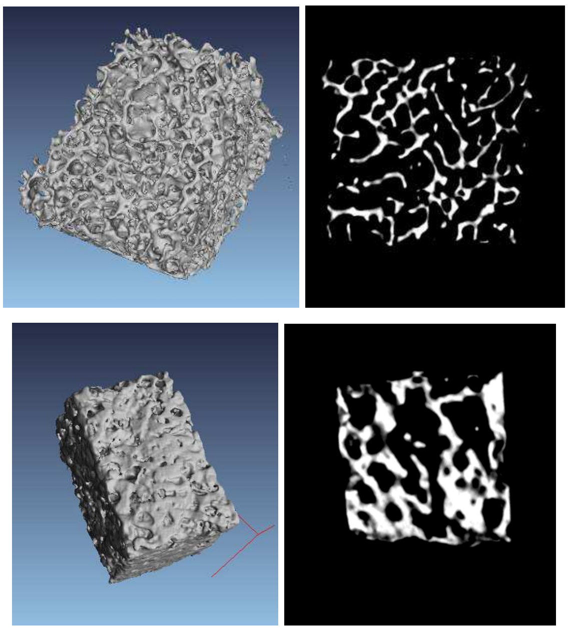

Figure 9. Demineralised human bone matrix without hMSCs (top) and demineralised human bone matrix with hMSCs after two weeks of cultivation (bottom)

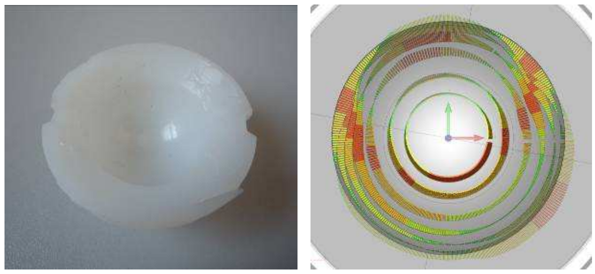

Figure 10. Used acetabular component (left) and form deviations on spherical surface (right)

One of the latest researches supported by our laboratory is digitalization of titanium dental implants. Analyses of material homogeneity, porosity, assembly quality and geometry have been performed on four different implants (fig. 11). With digitalized data we are able to do some modifications and print new modified dental implants with appropriate rapid prototyping technology.

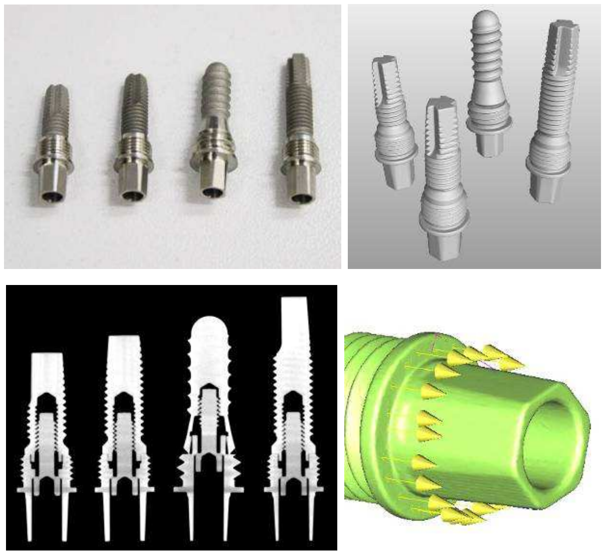

Figure 11. Four dental implants (top left), renderen point-cloud (top right), cross-section of point-cloud (bottom left) and detail to STL file imported to metrology software Calypso

ACKNOWLEDGEMENT

The paper deals with relatively new technology - industrial tomography - and application oriented to biomedical engineering. This technology with its advantages can increase 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 materials (monitoring of cavities, composities research, etc.), analysis of junction in medical devices, 3D modeling byreverse engineering and following rapid manufacturing are just few of applications.

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