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Chapter 10

Applications of Metrotomography in Biomedical Engineering

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Additional information is available at the end of the chapter

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1. 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 in X-ray technologies and computed tomography have been focused on special medical applications. Eighty years later computer tomography (CT) was first tested, and it has since become a powerful tool well-accepted in industrial applications. Today industrial CT is central to innovations in material testing and geometry analysis, and to the development of high-tech quality-control devices and industrial and medical tools [13].

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

The result of a CT scan displays the sample or object 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 three dimensional (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 sub-pixel respectively sub voxel interpolation, the effective resolution can be increased. Using techniques derived from 2D image processing, 3D voxel images are evaluated to arrive at dimensional measurements for the scanned samples or objects. This approach is especially advantageous because the 3D image reproduces the complete sample or object, including both outer and inner measurement features. Ultimately the user needs to know whether the sample or object under inspection meets his tolerance requirements and whether or not his measurement device can answer this question. In addition, reproducibility and operator independence are important criteria for the shop-floor deployment of a measurement tool.

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Industrial CT uses a series of 2-dimensional (2D) projections 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. And there are now nano focus tubes available with a focal spot less than one micrometer in size for the very precise measurement needed mostly for material inspection.

In biomedical applications, micro-computed tomography scanners can function as scaled-down (i.e., mini) clinical CT scanners. They provide a 3D image of most, if not all, of the torso of a mouse scaled proportionally to a human CT image at a resolution of 50–100 μm. Micro-CT scanners, on the other hand, can image specimens the size of intact rodent organs at spatial resolutions from cellular (20 μm) down to subcellular dimensions (e.g. 1 μm). Micro-CT scanners 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 of an amorphous silicon flat panel area detector. They offer 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) or 3600 images (one image every 0.1 degree) depending on the desired final resolution. Each image is between three to 10 megapixels, averaged and filtered to reduce noise. The 2D digital images taken during this step are saved directly into a single folder 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 an object to inspect and look for defects, to take accurate measurements, to reconstruct a surface model, and so forth. Industrial CT technology is improving very quickly. Years ago a few single CT slices would take hours to generate. Now it is possible to reconstruct in just seconds complete 3D models with billions of voxels. 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 to get a complete model of an object, both external and internal surfaces, without destroying it.

One of the new systems available today is Metrotom (Carl Zeiss, Germany) which offers new applications in the area of biomedical engineering, in addition to its industrial applications

2. Materials and methods

Metrotomography presented by the Metrotom device (Fig. 1) uses X-ray technology based on a simple principle: an x-ray source illuminates an object with electro-magnetic beams – 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.

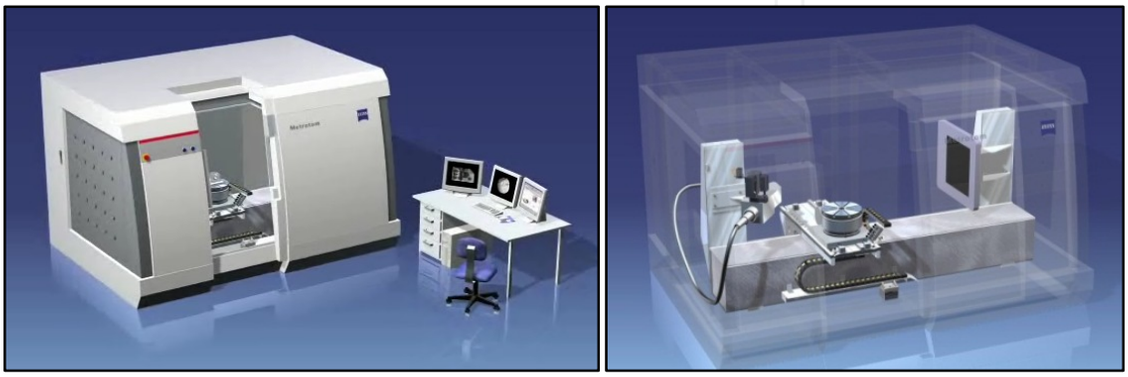


Figure 1. Metrotom (Carl Zeiss, Germany) and X-ray sensor.

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, producing a 3D image of the interior of the sample or object.

Metrotom has a measuring volume of 300 mm x 300 mm x 300 mm. The ability to perform a quantitative metrotomograph analysis of a material depends on the principle of cumulative material thicknesses. It is possible to metrotomograph plastics, for example, up to a thickness of 250 mm, and light metal alloys such as aluminum or magnesium up to a thickness of 120 mm. It is even possible to perform a tomograph on steel up to a thickness of 10 mm. This thickness is sufficient to provide a qualitative material analysis up to a resolution of 50 mm.

2.1. Mathematical model of X-ray CT transmission

The reconstruction of three-dimensional objects such as the simple key shown in Figure 2 by the metrotomography is based upon using X-ray computed tomography (x-ray CT) to acquire complete information on the distribution of material in each object. The underlying physics and mathematics of this process will be briefly described in this section. More information on these principles can be found in the technical literature (14, 15).

The X-ray photon density that emerges when a narrow bean of monochromatic X-rays with energy E (Joules) and intensity I_0 (Joules/sec-cm^2), passes through a homogeneous material of density η (g/cm^3) and atomic number Z can be expressed as:

$$I(x) = I_0 exp[-\beta(\eta, Z, E)x] = I_0 exp[-\beta_0 x] \quad (1)$$

where β_0 is the X-ray attenuation coefficient (1/cm). If we further assume for an inhomogeneous material that the attenuation coefficient is a space varying function, and the material can be represented by thin slabs, then adding up (or integrating the attenuation in each slab) we find that in one dimension the total attenuation by the material from x=0 to x=L is given by:

$$I(x = L) = I_0 exp\left[-\int_0^L \beta(x)\, dx\right] \quad (2)$$

Further, if we now scan the X-ray beam across the material in the y-direction we obtain an intensity profile for the object as:

$$I(y) = I_0 exp\left[-\int_0^L \beta(x, y) dx\right] \quad (3)$$

In X-ray CT imaging the X-ray source and detection equipment is designed to collect such intensity profiles over cross sections of three-dimensional objects. Each slice of the object presents a two-dimensional X-ray attenuation map –β(x,y) – to the beam with a thickness defined by the dimensions of the detector.

We need to keep track of the relationship between the fixed, laboratory frame of reference for the object (x,y) and the rotating frame of reference for the X-ray system (x',y'), which is a function of the rotation angle θ is given by the simple matrix equation:

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} x\cos\theta & y\sin\theta \\ -x\sin\theta & y\cos\theta \end{bmatrix} \quad (4)$$

Then, as illustrated in Figure 2, a simple plot of the X-ray intensity as the X-ray beam scans across the key as the angle θ can be written as:

$$I_\theta(x') = I_0 exp\left(-\int_{y'=A}^{y'=B} \beta(x, y) dy'\right) \quad (5)$$

The detected data then consists of many two-dimensional scans or projections, $P_\theta(x')$, each taken at a different angle (see Figure 2):

$$P_0(x' = p) = -ln\left\{\frac{I_0(x'=p)}{I_O}\right\} = \int_{Line\ AB} \beta(x, y)\, dy' \quad (6)$$

By rotating this projection through 180 degrees we collect information on the absorption of X-rays from all angles.

Finally, the overall relationship between the projection of the absorbed X-ray intensity is contained in the complete integration over the physical extent of the object. This representation has the mathematical form of the Radon transformation (16, 17):

$$P_\theta(x') = \iint_{Object} \beta(x, y)\delta(x' - p)dxdy \equiv R(p, \theta)[\beta(x, y)] \quad (7)$$

Inversion of the Radon transform, by simple back projection or some form of algebraic reconstruction gives the needed information, the cross section of the X-ray absorption β(x,y).

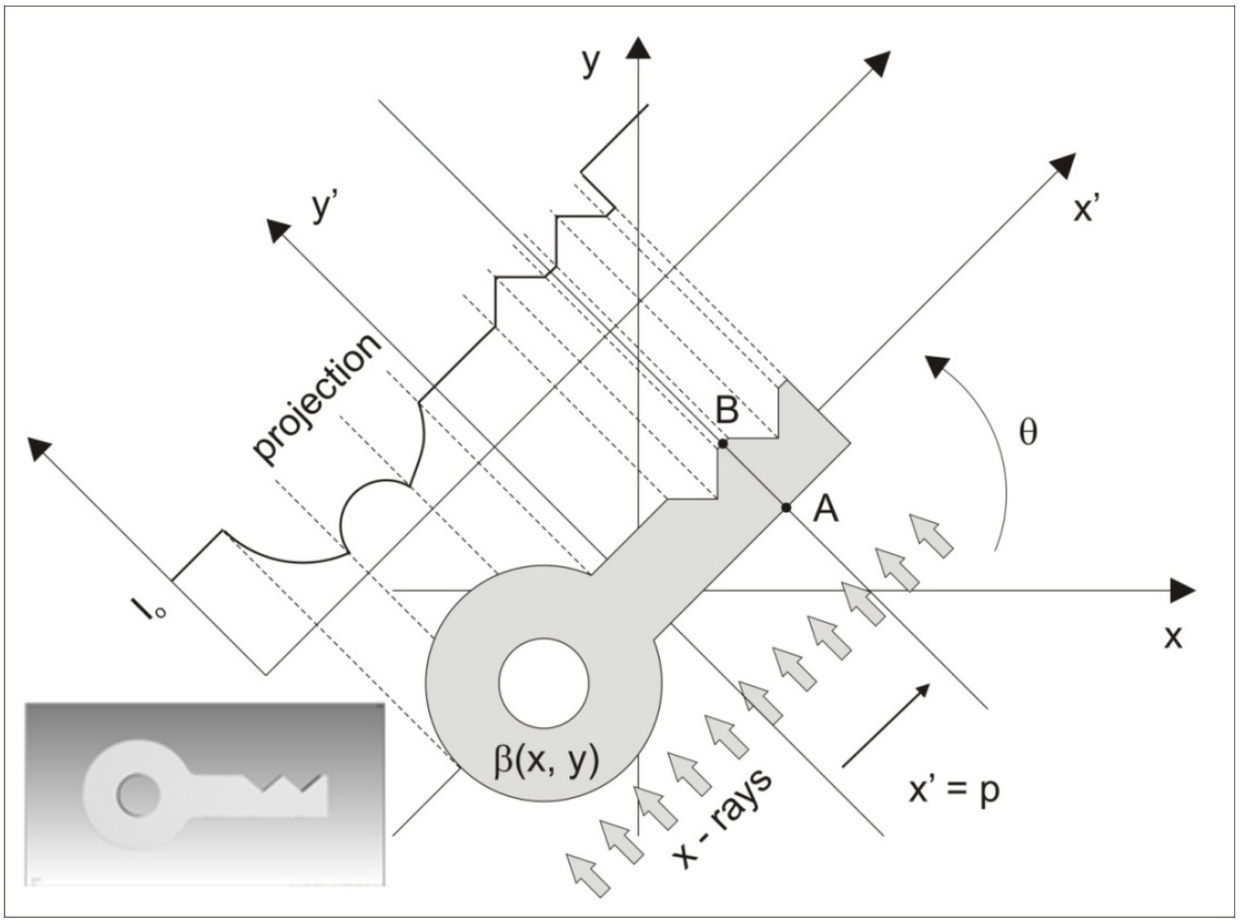


Figure 2. X-ray beam intensity profile of a key with X-ray attenuation β(x, y) along the x' axis for the viewing angle θ. From the profile the projection P_θ (x') can be constructed as a formal Radon transform.

The metrotomography procedure provides testing technology with a complete range of evaluation possibilities, from assembly inspection to damage analysis, including inspection of materials, porosity analyses and conventional defect checks, as well. At a glance, metrotomography now clearly shows the defects in areas where previously an inspection was not possible at all, or possible only using the time-consuming and costly cross section.

Workpiece data recorded using the metrotomography procedure can be applied to all areas of quality assurance and can be evaluated against the traditional metrology, as well as reverse engineering applications and comparison of geometrics.

Metrotomography uses a software environment called Calypso. Every metrotomographed component (whether a standard geometry or freeform surfaces) can be extensively evaluated using Calypso to perform the following steps: reading the features and orientation from the drawing and specifying 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 a new CNC measurement plan and evaluating the protocol.

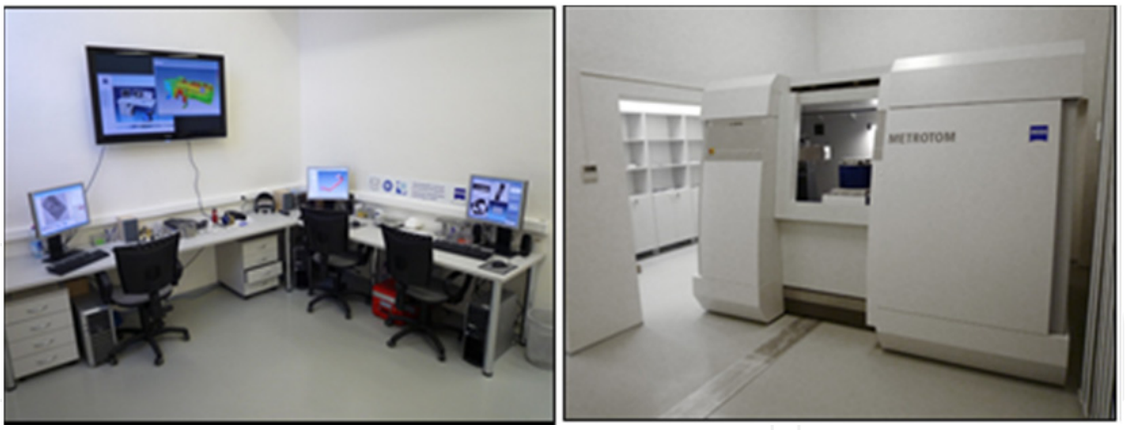


Figure 3. Technology Center of Computed Tomography, Department of Biomedical Engineering, and Measurement, Technical University in Kosice.

Industrial CT hardware and software at the Department of Biomedical Engineering and Measurement at the Technical University of Košice is shown above (Fig. 3.).

The industrial CT's reverse engineering capability is the quickest and the best solution, particularly when no CAD data exists for a component. When the evaluated workpiece (e.g. cube) is tomographed, 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. The 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) is described in the following steps: scanning the CAD design data of the bearing, entering the point cloud of the bearing from the metrotomograph, aligning the data sets with each other and displaying the measurement deviations in a color map. Fig. 4 shows Metrotom's measurement of the multidirectional valve, depicting the reverse engineering function of Metrotom, the material inspection, and the metrological possibilities of the scanner and software.

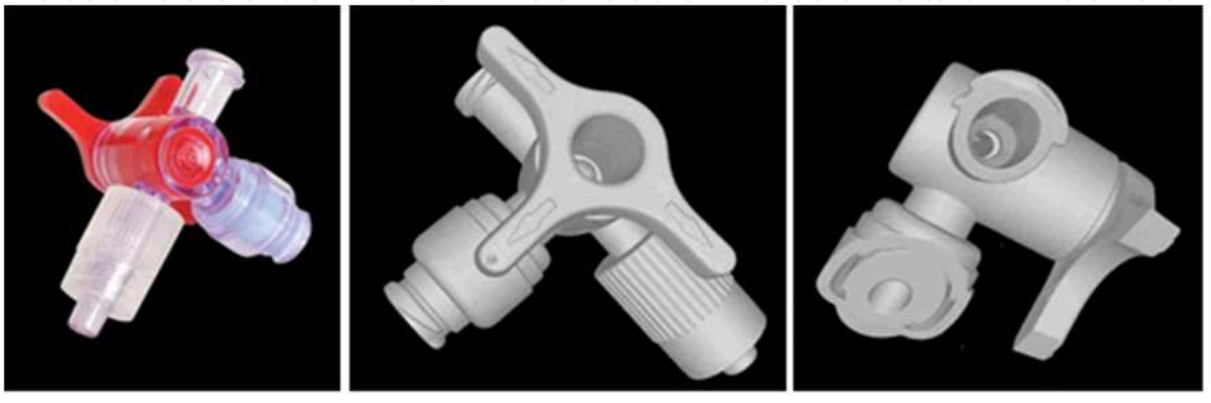


Figure 4. CAD models of the multidirectional valve – presentation of the reverse engineering.

Step by step, an X-ray scan rotates around the object being measured. From the X-ray, the position of each voxel is calculated. According to the density of material, each voxel has a value from the gray scale in the range from 0 to 65535. This allows separation between the object itself and other low density materials, such as air or support materials. The 3D point cloud makes it possible to see the component from different directions, and to evaluate not only the surface of the model but also the inner environment in cross-sections.

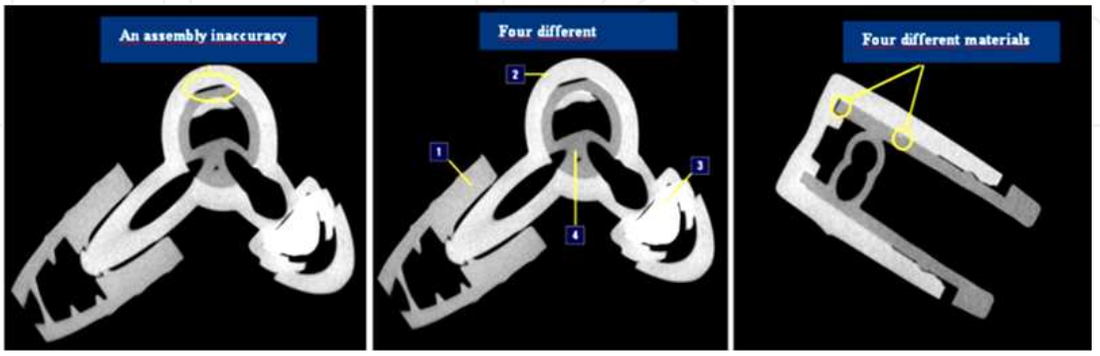


Figure 5. An analysis of the constructional junctions in multidirectional valve.

Figure 5 presents the inspection function of metrotomography. An advantage of this method is the possibility of inspecting constructed junctions in assembled work pieces for contact surfaces analysis, quality control, and detection of foreign materials or air spaces.

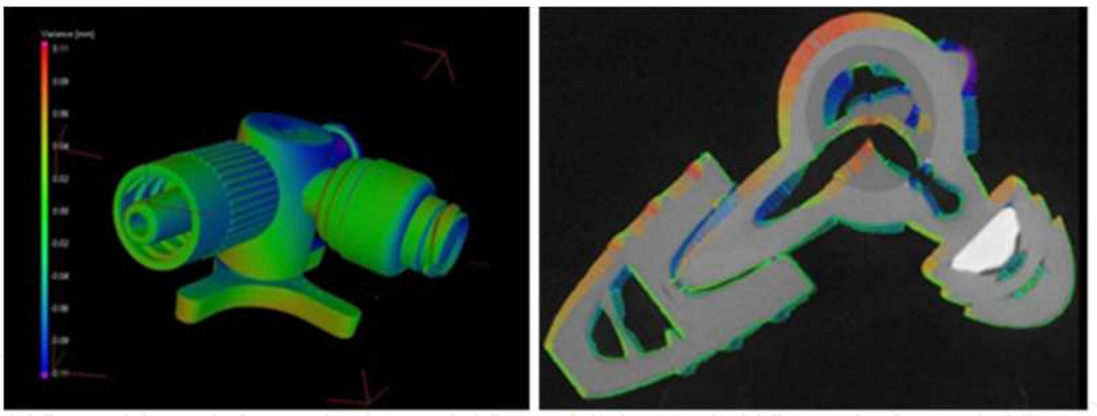


Figure 6. Geometry deviations analysis of the multidirectional valve.

The Metrotom measures with relatively high accuracy. Calypso software (Carl Zeiss, Germany) allows an evaluation of each obtained component. Comparing the CAD model (Fig. 6, 7), which is created with nominal geometry and dimensions, with metrotomograph's model, it is possible to generate a view of geometric deviations. Calypso also offers an evaluation of length parameters, angles and geometry, and position deviations.

Carl Zeiss used metrotomography to scan an epithetic hand, foot and plastic skull (Figure 8). These objects were selected to evaluate the kind of plastic materials frequently used in the practice of medicine and in biomedical engineering research. Wooden materials and the metallic parts of the skull were investigated to check the Metrotom's capabilities versus those of an industrial CT.

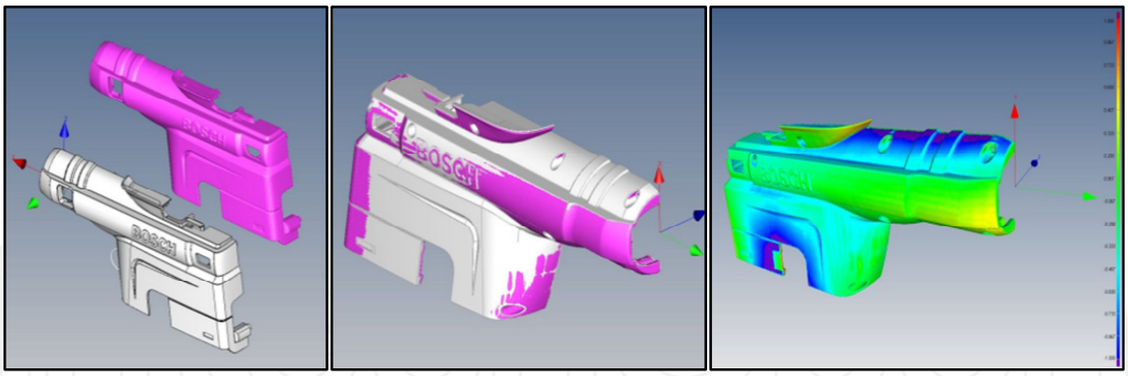


Figure 7. CAD model (left) with CT data and evaluation of geometry deviations with default toleration field (middle and right).



Figure 8. Samples from the field of biomedical engineering evaluated by metrotomography (epithesis and plastic human skull).

3. Results of measurement

The products of biomedical engineering research or research in prosthetics and orthotics (Fig.8) were scanned by an industrial CT machine and investigated using different software applications. This initial study shows the functions and possibilities of industrial CT and software applications (Calypso and VG Studio Max).

Software VG Studio Max (Volume Graphics, Germany) is a tool which accepts a visualization of obtained data and applies the following analysis: geometric analysis (2D & 3D dimensioning, actual/nominal comparison, actual/actual comparison, wall thickness analysis and extraction of STL surface from a point cloud), and material analysis (detection of defects, inclusions detection and possibility of material distribution and position in composite material).

VG Studio Max, as well as other related applications, offers useful tools and methods for data visualization. The point cloud makes it possible to separate, by grey color intensity, the different density of materials and resultant inner material detection (Fig. 9). Within the artificial foot are visible reinforcing materials and inner structures and holes for foot assembly.

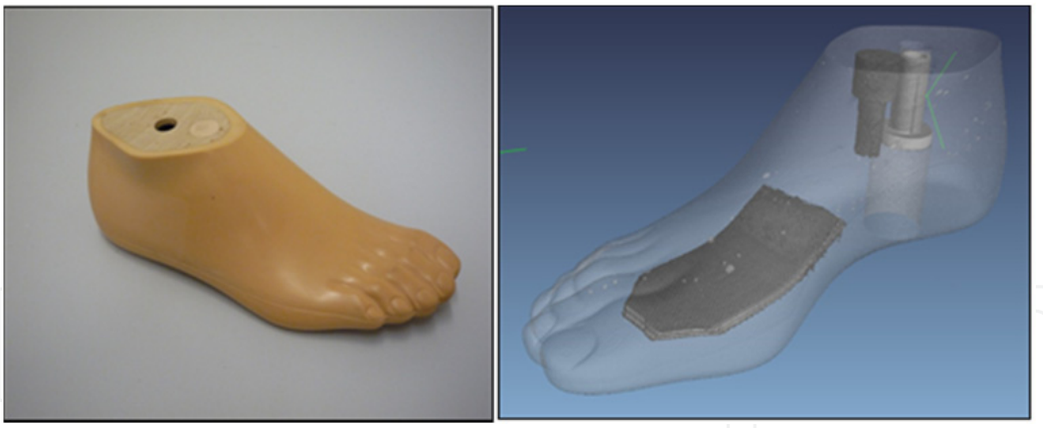


Figure 9. Epithetic foot and obtained 3D model (visible transparency of lower density material – soft surface plastic and wood).

With the greater translucency and the lower density of the foot's skin-colored plastic cover material, problematic air spaces (originating at the plastic casting) are getting more apparent. VG Studio Max enables detection of material inhomogeneity often presented by air cavities. By use of histogram function in the relation with an air cavity geometry it is possible to assess the exact position of the cavity.

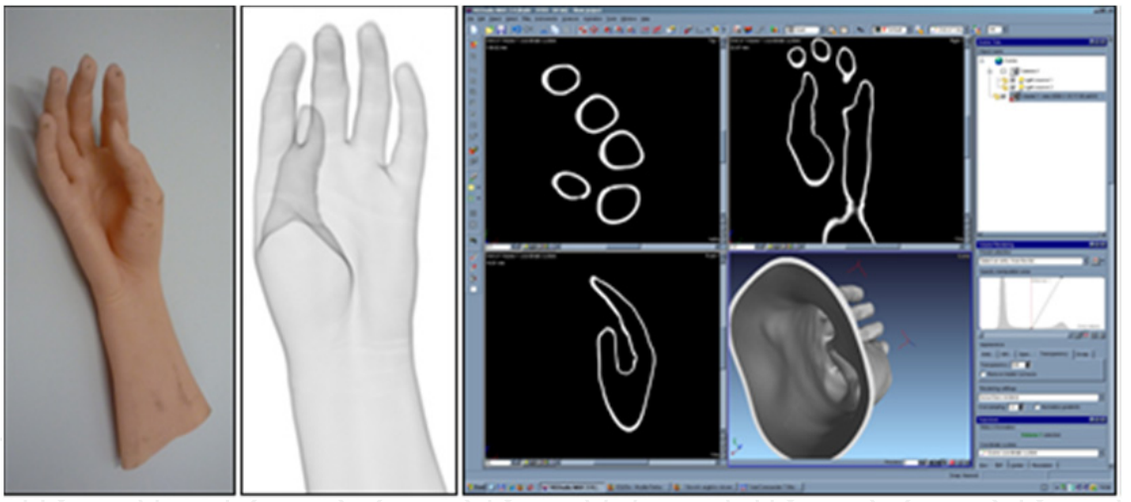


Figure 10. Epithetic hand glove (left), its X-ray scan (middle) and an environment of the VG-Studio Max software with three cross-sections and 3D view of rendered model of the glove.

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. 10, middle), which allows non-destructive cross-sectional analysis (Fig. 11). The right side of Figure 9 shows the window of VG Studio Max 2.0. In four windows, it is possible to visualize the 3D view of the rendered model and the epithetic glove cross-sections in perpendicular views.

The software enables easy use of 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, and the different densities in the observed object.

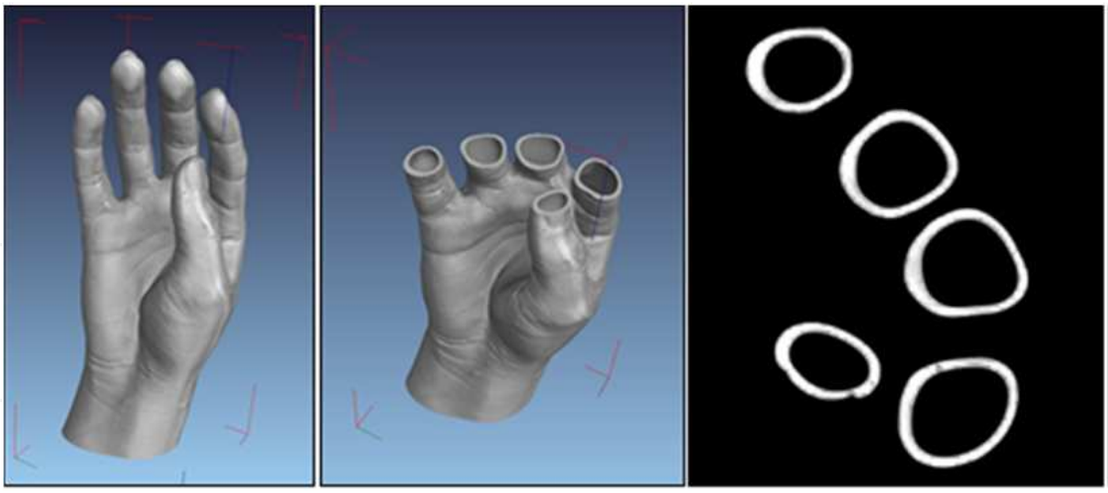


Figure 11. Rendered 3D model created by point cloud grid (left), cross-section of the 3D model in an arbitrary direction and cross-section of the glove model in one of the three views.

The VG Studio Max animation consists of multiple overflights around the object or crossing the object in an optional direction. Data can be loaded into the generally-supported STL format and further processed for reverse engineering or rapid prototyping/manufacturing.

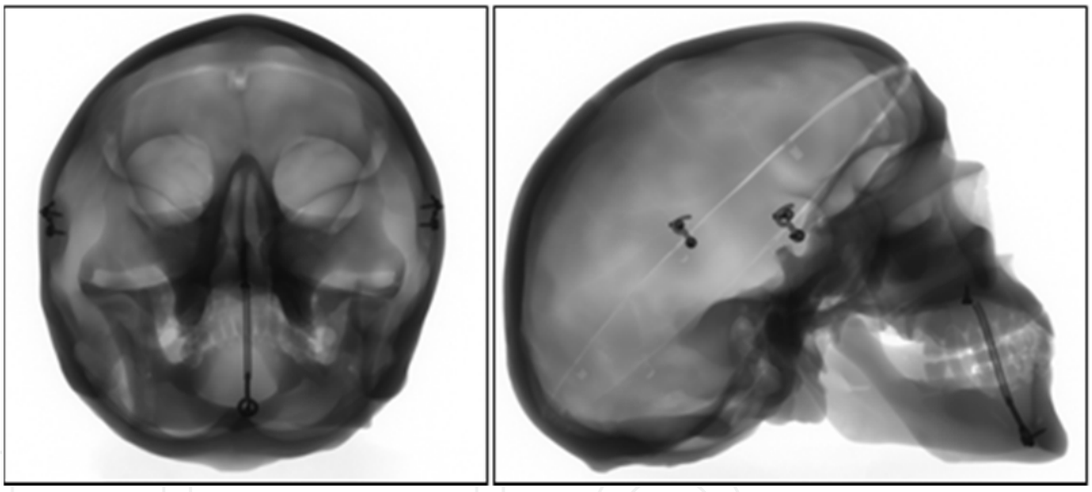


Figure 12. Two views of skull X-rays.

Different grey scales in the presented scans (Fig. 12) are caused by reduction of X-ray energy detected by an X-ray detector. This represents higher material thickness where the X-ray is passing through (skull borders) or higher material density (springs and clasps).

The skull model as shown in Fig. 13 contains two types of material: metallic springs and clasps, and a plastic skull. When there is a large disparity between the density of different materials, other selected materials may remain hidden (e.g. only metallic parts are visible).

Technology center of computed tomography at Technical university of Kosice supports many kinds of research. Biomedical research and research in prosthetics and orthotics are important supported areas. Tomography can be used for various evaluations, most commonly, for the digitalization of objects with very complicated shapes. In biomedical

engineering, many objects have surfaces so complex, that they are not measurable by any other methods of digitalization. Touching probes, lasers or optic scanners cannot reach areas which are mostly hidden. With CT scanners, 100% of the information about an object's shape can be accessed. For example human teeth (Fig. 14) or animal skulls (Fig. 15) can be digitized. VGStudio Max software can extract from surface points via the STL model. STL is universal triangular model which can be imported to every CAD/CAE/FEM/RP software for further processing.

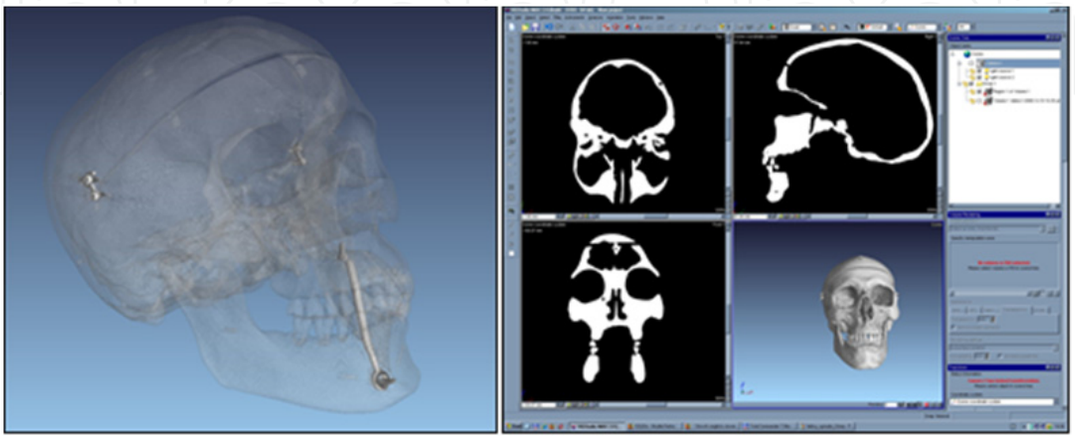


Figure 13. Skull translucency shows the metallic components of the assembly (left); **a** window with control tools of the VG-Studio Max software (right).

With CAD software, parameterization is possible, or perhaps the design of a supplement for a scanned object. In FEM (Finite element method) software, the stress/strain analysis can be performed. The STL model is ideal for Rapid Prototyping. With a 3D printer, a plastic or even metal copy of a real object can be made. Fig. 15 presents the results of the digitalization and printing of animal skulls. The bottom picture shows the original monkey skull and the printed copy of the monkey skull. More can be found about the rapid creation of copies of complex-shaped objects in other publication from several authors [10].

Orthosis design also requires very complicated plastic objects, difficult to digitalize with any other scanning technology. Examples of the digitalization of orthosis for hands made from low temperature thermoplastics (LTTP) are pictured in Fig. 16. With the obtained data it is possible to do further analysis of curvature, for example, or a stress/strain analysis, etc.

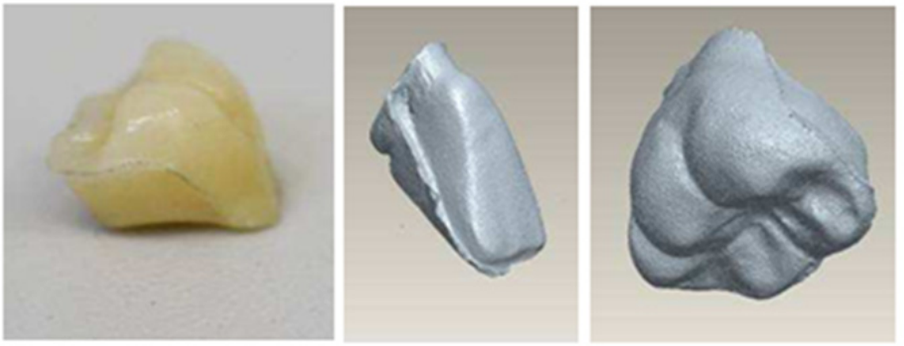


Figure 14. STL format of human teeth (middle and right).



Figure 15. Skulls of animals (top) and of monkey's skull printed with 3D printer (bottom left).

X-ray is kind of radiation that penetrates through objects, providing information not only about the surface of object, but also about its inner volume. After reconstruction of the point cloud, the inside of the object is visible using virtual cross-sections without destroying real object, or separating materials with different density.

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 sample or object is limited. An STL model of metal dental bracket provides a nice example of digitalization for dental clinic (Fig. 17). The maximum dimension of this bracket is 3 mm. With so small an object, a point cloud makes it possible to achieve resolution of around 9μm. However, the resolution of sub-voxeling process can be increased. Small objects can be magnified more than bigger ones, because they are placed closer to the x-ray source. The size of the projection is zoomed many times, and so the size of the voxel (volume pixel) of the final point cloud is just a few micrometers.

An inspection of the inner structure of a pork femur is shown in Figure 18. The difference in gray-values depends on the density of the material. The air around the bone is black because of its lower density. The outer structure of the bone has a higher density, so the color of the

pixels in this area is light gray. The density of the bone can be seen to change considerably from the outer surface to the inner volume in the cross- section picture.

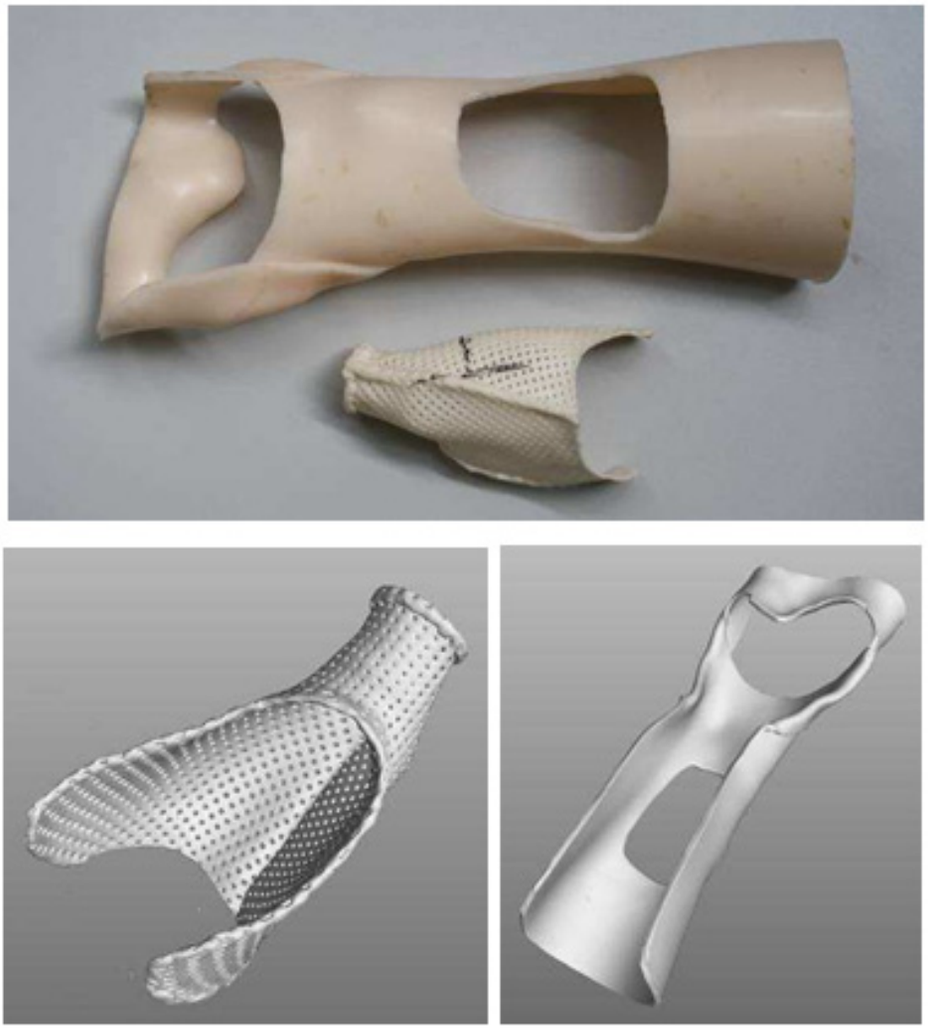


Figure 16. Plastic orthesis (top) and their point clouds (bottom).

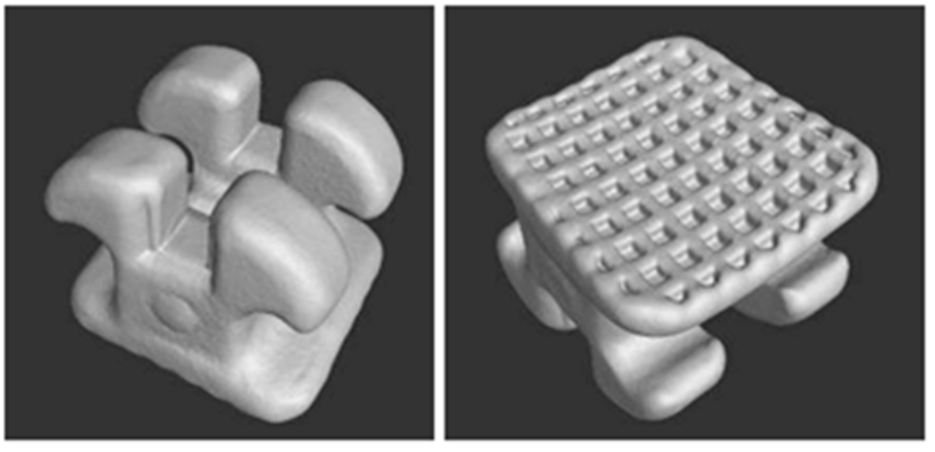


Figure 17. Point cloud of mall metal dental bracket.

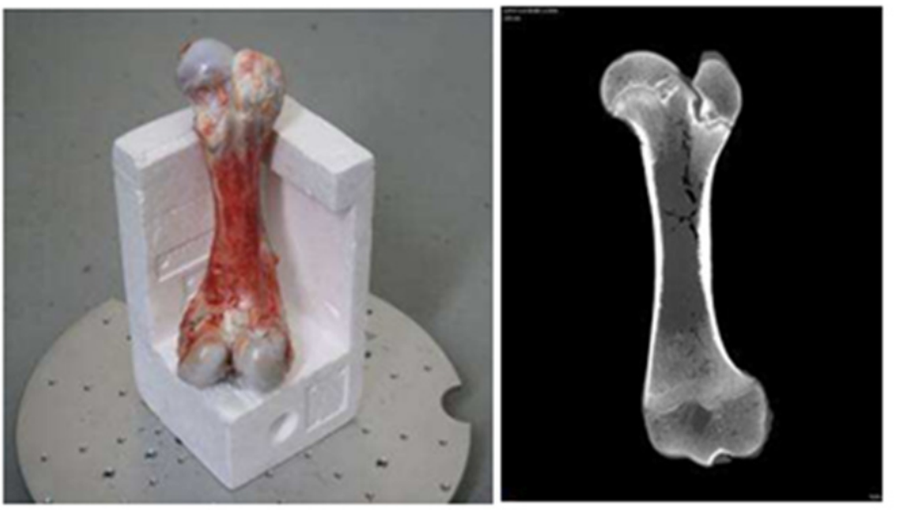


Figure 18. Pork femur (left) and its virtual cross-section (right).

Other research at our laboratory used CT technology in a porosity analysis of human bone (Fig. 19). The research measured the amount of solid material in two human demineralised bone matrices, before and after one of them was cultivated with mesenchymal stem cells (MSC) for two weeks. After this cultivation, the amount of solid material in the cultivated bone increased dramatically. The porosity of selected regions in each sample was calculated and compared. Results of research can be found in the authors' publication [6].

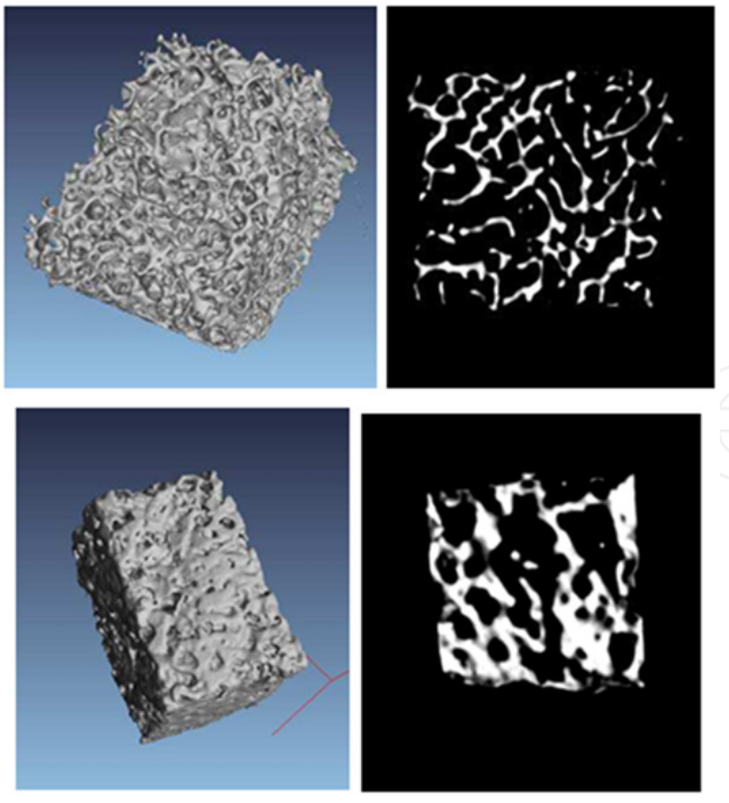


Figure 19. Demineralised human bone matrix without hMSCs (top) and demineralised human bone matrix with hMSCs after two weeks of cultivation (bottom).

Industrial tomography offers biomedical researchers the advantages of nondestructive testing and a precise view of inner structure. But it is also a tool capable of sharply accurate data reconstruction and very precise geometrical measurements. For example, Figure 20 presents a spherical form of a used acetabular component that was measured with Calypso software. With Calypso, researchers can evaluate characteristics of objects and make a protocols or graphical presentations of results. Graphical interpretation of form deviations in a magnified, used acetabular component are presented in Figure 19. Deviations have been filtered to eliminate scratches on the spherical surface.

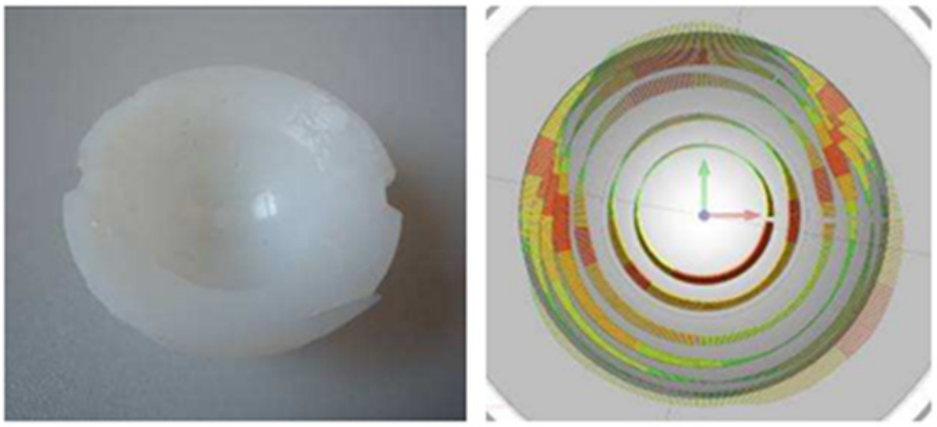


Figure 20. Used acetabular component (left) and form deviations on spherical surface (right).

The quality of the reconstructed point cloud and accuracy of measured data depends markedly on the density and the cumulative wall thickness of a scanned object. Because of that, materials with lower density are more suitable for scanning. Titanium, in comparison with other metals like steel or copper, has a relatively low density, and so small components made from titanium are measurable without restrictions.

One of the latest projects supported here is the digitalization of titanium dental implants. Analyses of material homogeneity, porosity, assembly quality and geometry were performed on four different implants (Figure 21). With digitalized data, appropriate modifications are made to the implants and the new modified dental implants are printed with the rapid prototyping technology.

4. Example of the use of tomography in biomedicine

A CT scan of the patient's head was obtained via medical CT in a clinical environment. For further reconstruction and implant design, the optimal density of the imaging is less than 1 mm. Medical screenings are stored in normalized format DICOM (Digital Imaging and Communication in Medicine). Because nowadays there are several generations of DICOM format, adapted software applications, such as MIMICS and 3MATIC (from Materialise, Belgium), are available.

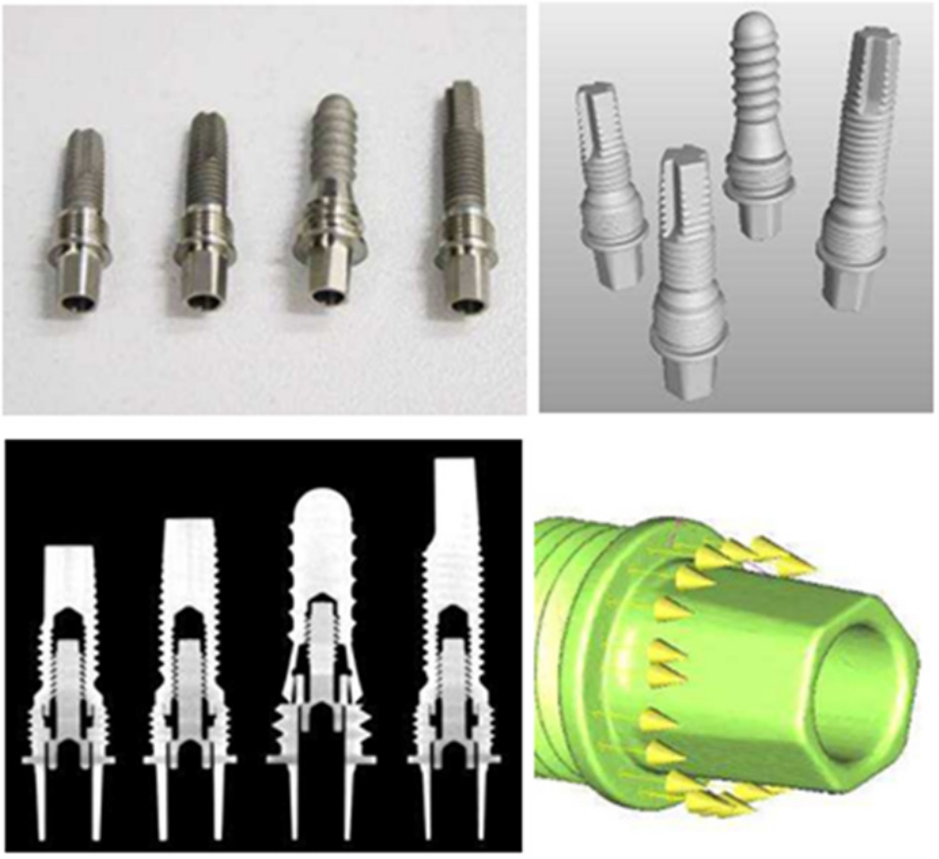


Figure 21. Four dental implants (top left), rendered point cloud (top right), cross-section of point cloud (bottom left) and detail to STL file imported to metrology software Calypso.

MIMICS software is used for transformation of the DICOM format into the 3D model. In general, the DICOM format is a series of slices – screens located one above the other – representing the complete model. A single shade of grayscale represents tissues with several different densities (Fig. 22).

It is necessary to separate soft and hard tissues to distinguish bone tissue from other human tissues. The MIMICS software contains a "mask tool", that the operator can use to achieve this effect. For the final model to represent only the requested areas, colors are modified by contrast and brightness level. In some cases, it is more effective to convert soft tissues to 3D, as well. For instance, in cranial implants the design of the implant has to follow brain tissue precisely to avoid creating pressure. After the mask is released, software creates the 3D model.

The 3D model is created as a point cloud that has its own surface structure. Often, the point cloud uses software tools to clean the surface of noise and other tissue burrs. For this cleaning the user's knowledge of anatomy is important, to avoid omitting significant areas that can affect final implant design. With the surface cleaned, the model is prepared for further processing. It is saved in MCS format. The software can also read bitmap pictures or jpegs, as well as the DICOM format. For those using older formats of DICOM, it is necessary to perform manual setup of the resolution (Fig. 23).

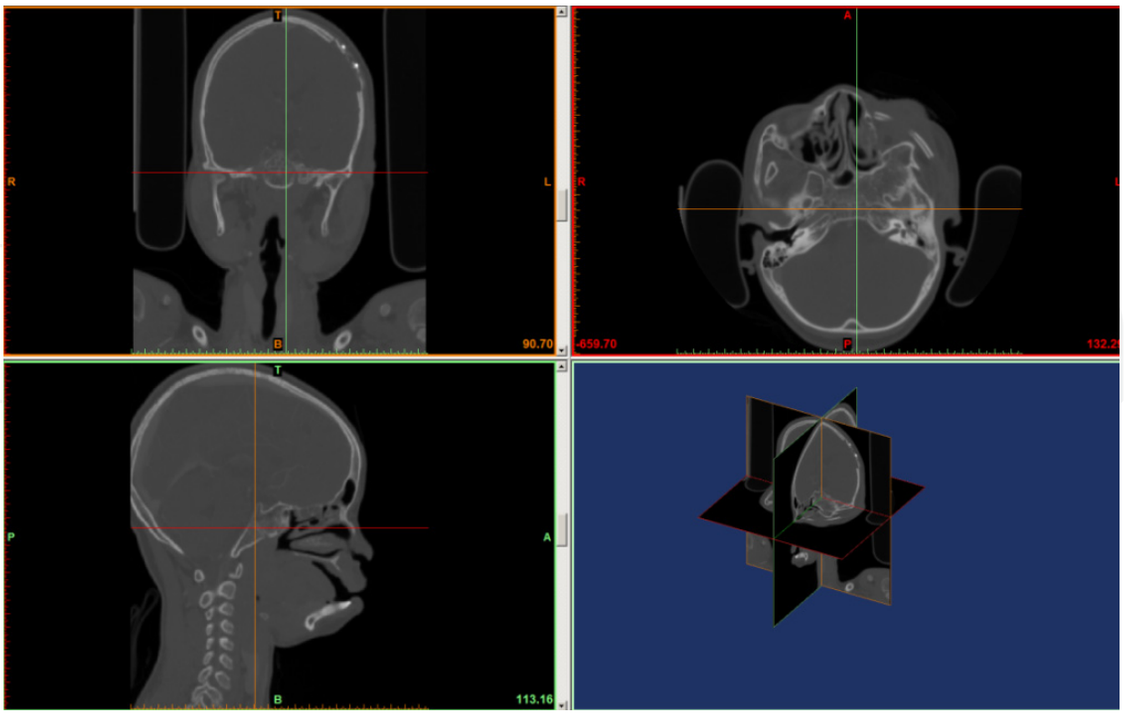


Figure 22. Mimics software environment.

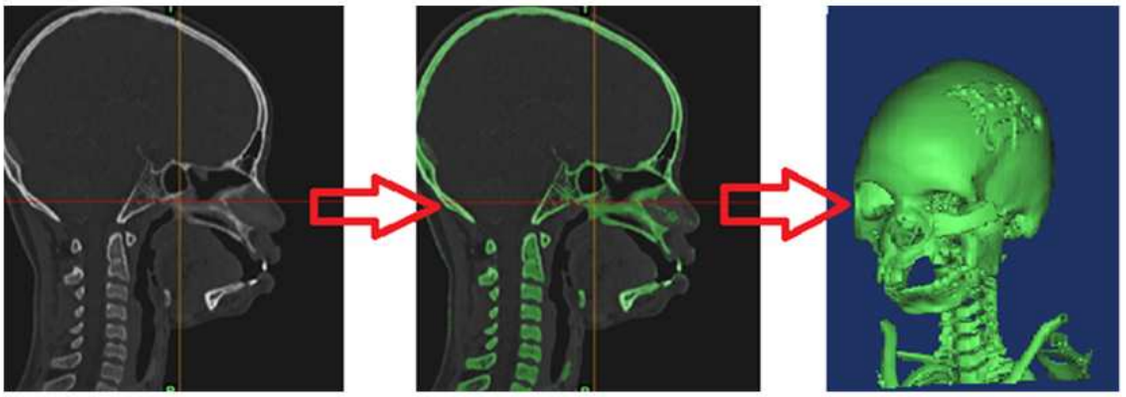


Figure 23. Steps of creation of 3D model form DICOM format (CT).

4.1. Adaptation of 3D model and implant design

The 3MATIC (Materialise, Belgium) application software allows the transformation of an uncounted 3D model into a series of polygons.

The size of the triangles represents the precision and the quality of the model – the more triangles, the smoother the surface of the model (Fig. 24). At the start of the process, the steps to optimize the triangles are performed. Next, the steps necessary to link the chosen type of implant and its localization are performed. In the case of a damaged jawbone, over-material was surgically removed to prevent it from interfering with the implant. At this step, consulting the surgery is required to verify the contact points/areas for the final application of the implant.

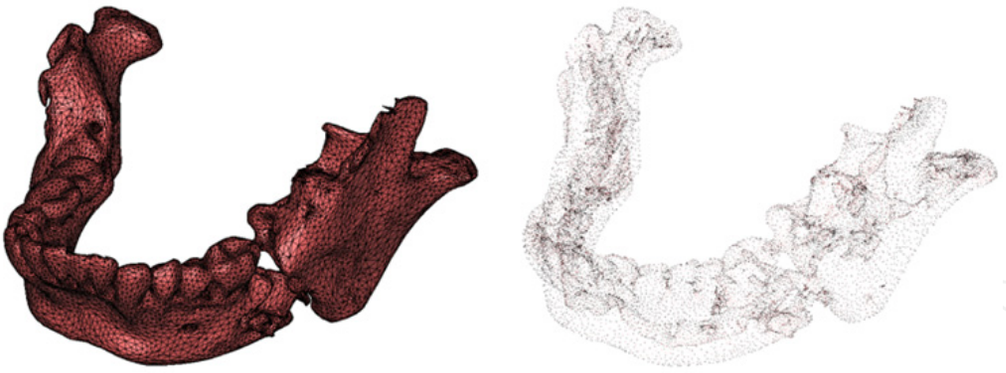


Figure 24. Model represented by mesh.

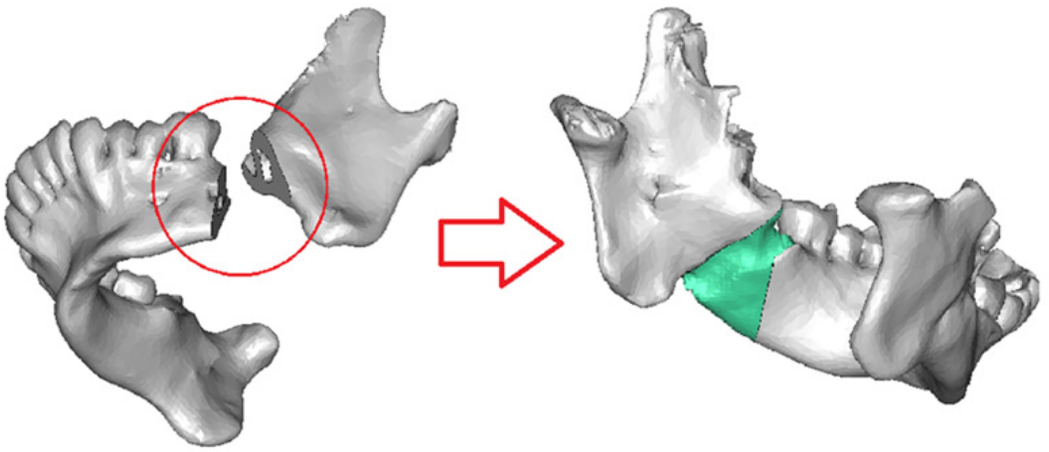


Figure 25. Damaged area and implant replacement.

The missing part of the model is reconstructed based on the present quality of the bone tissue. Here, the bone-like geometry was obtained by industrial CT (Metrotom 1500, Carl Zeiss, Germany). It is important that the complex geometry of the surface does not affect the physiological function of the jaw. Of course, the replacement must by morphologically similar to the missing part: differences in the size of the implant can completely change the ratios of the jawbone, leading to abnormal changes in the joint. Such changes affect other parameters in maxillofacial area, potentially causing a pathologic effect on the complete system. After modeling the replacement, analysis of the bone wall structure thickness must be performed. This step is important to create holes and interfaces needed to fix the implant to the bone (Fig. 25). Openings are designed individually and must be positioned so that they cannot affect important anatomic points, like vessels or nerves. The number of the openings should be limited to the minimum number required to fix the implant robustly to the bone. For better interface contact between the implant and the bone, the structure of the implant is made with predefined porosity (Fig. 26). That allows healthy bone to grow through the implant and stabilize it in position. Such stabilization is expected because the jawbone, as part of a live human articular system, is routinely exposed to mechanical stresses.

Afterwards, it is important to repair texture errors, like overhanging triangles, unwanted holes, etc. These errors can affect the surface relief of the final design. At this point, the implant is ready for production.

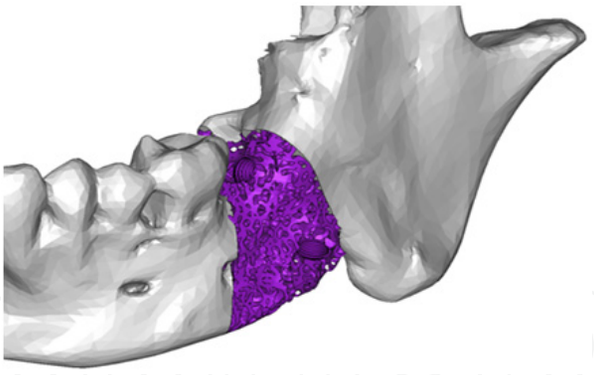


Figure 26. Creation of porous implant.

5. Conclusions

This study shows the possibilities and the limits of industrial CT when it is used for different biomedical applications. Wherever better resolution of output data is required, wherever the size of an analyzed object is problematic, there is a place for micro CT technology. Data obtained by metrotomography are usable in many biomedical applications, including material structure and homogeneity analysis, the inspection of the assembly of medical aids or devices, the evaluation of geometry deviations, quality control in medical production and reverse engineering. After acquisition of a digital point cloud, there are software tools that can enable different metrological or material analyses, and provide added value in biomedical research and development.

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