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Prague center of industrial X-ray tomography: research and applications in NDT

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Abstract

X-ray reconstructive computer tomography (RCT) is a highly effective method of radiation NDT, combining advantages of physics and informatics. Traditional X-ray screening and computational mathematics together with digital technique solve introscopy problems. The basis of X-ray RCT is a detailed inner spatial structure reconstruction of the tested object. X-ray RCT is by two orders of magnitude more sensitive than traditional technical means of radiation NDT. Digital representation of NDT object obtained by X-ray RCT is advantage. Comparably to classical introscopy where testing objects are featured as intensity and color images. Non-contact testing and long-term storage of digital information about spatial structure through tested object life give new possibilities to NDT immediately in the process of manufacturing, using, testing, repairing or stocking. RCT images can be taken under various outer conditions as humidity, temperature, thermal or mechanical stress. We use VT 50 and VT 400 tomographs for aluminum casts, composite products testing and localizing. Our joint Prague Center of Industrial X-ray Tomography, reestablished in 2006, uses RCT in rather new research areas as geology, biology and paleontology together with education of students on master and postgraduate level. We shall inform about results of our research and teaching, about our experience of university and private company joined in research and educational center.

1. Introduction

Prague Center of Industrial X-ray Tomography is joint venture of Czech Technical University in Prague, Department of Physical Electronics and Industrial Tomography Services, Ltd., Czech branch of Russian manufacturer of X-ray tomographs. Joint venture of educational institution and industrial company serves as educational, research and development center to propagate exploitation of computed X-ray tomography in science and industry. In this paper we describe briefly our research and educational activities.

2. Principle of reconstructive computed tomography

The principle of computed tomography consists in measurement of attenuated X-rays passed through a tested object along the set of defined paths followed by the reconstruction of acquired dataset with the aid of mathematical reconstruction algorithms. The result is the distribution of attenuation coefficient μ (x, y) for individual pixels in each cross-section.
For simplicity, the classical tomograph configuration is considered where the tested object is moved in one direction and irradiated by the thin beam of rays. Then the object is rotated and the scanning process is repeated [1].
The measurement is carried out over successive rotations covering 180°. The logarithm of proportional path attenuation p(r, φ), referred to as X-ray absorption integral is:

$$\ln[I_0(r,\varphi)/I(r,\varphi)] = p(r,\varphi) = \int\int_{-\infty}^{\infty} \mu(x,y)\cdot a(r - x\cos\varphi - y\sin\varphi)dxdy \qquad (1)$$

where I(r,φ) is intensity of X-ray after the way through the object along the path with r and φ parameters. $I_0(r,\varphi)$ is intensity in front of the entering X-ray into mass with r and φ parameters. The function a(r,φ) respects the nonzero X-ray source dimension and the detector spatial resolution. The equation of X-ray beam is described in this form:

$$r = x\cos\varphi + y\sin\varphi \ . \qquad (2)$$

The coordination system and the passage through the object are defined in Figure 1.

Further it is necessary to consider carefully that the number of motions and rotations is not infinite. Therefore it requires switching from continuous to discrete coordinates. The discrete equidistant coordinate system with constant increments Δr and Δφ is introduced. Subsequently the path attenuation is expressed as:

$$p(m\Delta r, n\Delta\varphi) = \int\int_{-\infty}^{\infty} \mu(x,y)\cdot a(m\Delta r - x\cos n\Delta\varphi - y\sin n\Delta\varphi)dxdy \qquad (3)$$

where m and n are integral numbers. The task of RCT consists in the solution of integral equations of the first order otherwise the computation of μ(x, y) function from measured values p(r,φ).

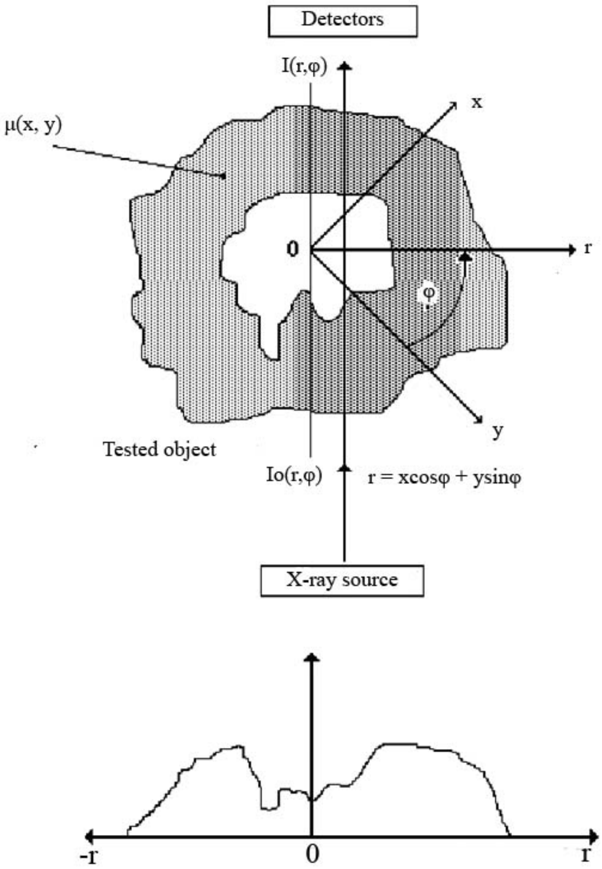

Figure 1. The X-ray passing through the object and definition of coordinates

3. Computed tomography in research and application

Our two tomographs, VT 50 and VT 400, resp. their characteristics are shown on fig.2 resp. table 1.

Figure 2. Industrial X-ray computed tomographs

Table 1. Technical data of industrial x-ray computed tomographs of the VT-series

VT-model	**VT-50**	**VT-400**
Test object maximum diameter[mm]	20	400
Effective thickness of a tested layer [mm]	0,1 ... 0,02	2 … 0,5
Spatial resolution limit [lp/cm]	500	50
Geometrical sensitivity [µm]	5	100
Sensitivity to local defects: pores [mm^3] metal inclusions [mm^3]	0,00003 0,000003	0,1 0,03
Scanning time [min]	10	5
The X-ray tube voltage range [kV]	40-120	50-420
Local tomography mode	not available	available
Number of pixels in the tomogram:	1024x1024 2 (512x512)	1024x1024 2 (512x512)

3.1 Applications in industry

Industrial X-ray computed tomography permits to make both nondestructive qualitative and quantitative evaluation of complex internal structure of the most important parts of modern machinery and electronics, as well as material itself.
The result of CT investigation is being visualized as layer-by-layer images with identification and quantitative estimation of defects such as geometric deflections, different densities, pores, cracks, inclusions etc., fig.3.

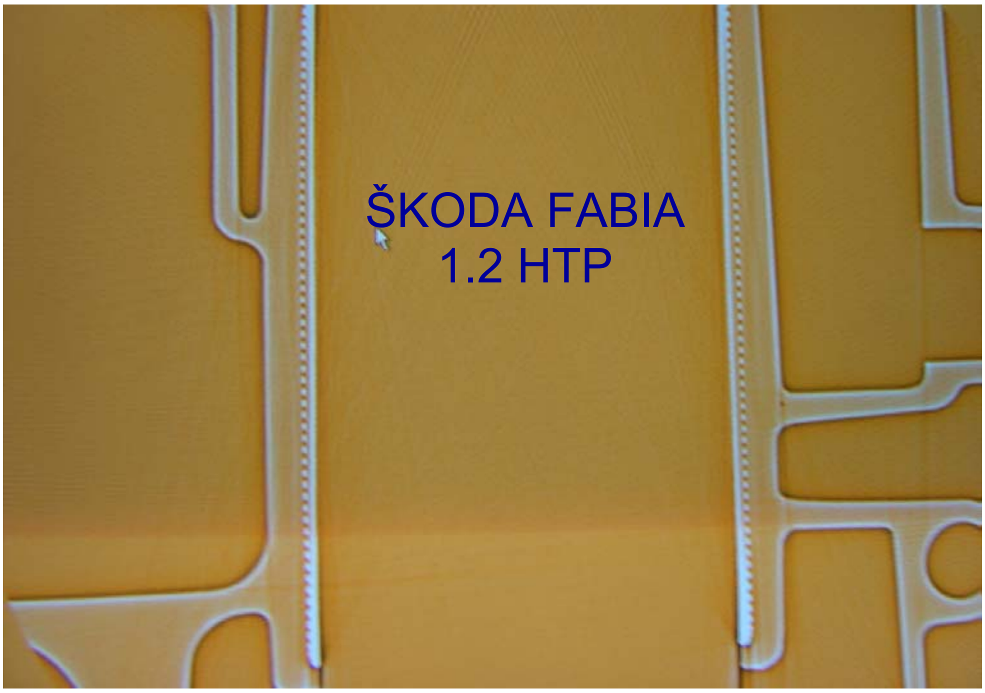

Figure 3. The aluminum cast of car engine with steel cylinder

Computed tomographs are efficient tools in working out technology, diagnostics and certification of products e.g. in airspace industry (nozzles, thermal protection, binder joints), important aircraft assemblies and units (turbine blades, vanes), complicated car industry products (heads of cylinder block, casting of light alloys, pistons, ceramic units.
Other applications have expanded in electronics, geology, medicine etc. Computed tomography exceeds other non-destructive evaluation methods by two orders in sensitivity.
In our short period of examination we are aimed at calculation the porosity in aluminum casts. In contrast to metallographical method the acquired tomograms require post-processing in order to get correct values of the quantity of pores in medium. The simplest methods are based on the adjustment the threshold value for the air/material interface. Apparently it includes the subjective intervention to assessment. Hence our aim is to avoid these human errors and to set up generally true method.
At present the porosity distribution method calculated against CT number is in research studies(2). The porosity is calculated directly from the CT numbers without using segmentation techniques and without using any user-defined parameters. From a novel distribution we can indicate the properties of the studied materials, the minimum of the curve gives the value of the estimated porosity.

3.2 Research in geology, biology and paleontology

Prague center of industrial X-ray tomography has broadened its activity towards the applications in science. The cooperation at the interorganizational level was started up between the Czech Technical University, Faculty of Nuclear Sciences and Physical Engineering and the National museum in Prague. The collection funds of the National museum represent several million items of material evidence about the inanimate and living nature and about the man and his activities in worldwide scale.
The exhibits in mineralogy, paleontology, zoology, anthropology, archeology have become the subject for the research and development. The scientists in museum try to preserve the rare collections without any damages. The nondestructive testing method by RCT matches all these requirements in entirety.
Moreover, the digital character of a CT dataset makes possible to visualize and animate features hidden from external view. Thus the structure and internal parts of exhibits are revealed and the determination of precise forms and dimensions has achieved the promotion for the latest scientific investigations.
In addition, many science investigations require examination of the internal structure of specimens in three dimensions, tasks to which RCT is well-suited.

The scale of the specimens to be studied is limited by the maximum acceptable object diameter applicable to different X-ray computed tomographs.
The experiments were carried out on both industrial tomographs with specimens' sizes from a few millimeters up to several decimeters in diameter. The maximum diameter along with the spatial resolution for each tomograph is shown in the table 1.
Since our research in natural sciences is found at the beginning the purpose of our study was to examine different kinds of objects, which should give us an acquisition to further examination.

The objects, which were examined, come from various departments in the National museum. Firstly we kept at disposition the exhibits from the Department of paleontology.
The first application of VT 400 tomograph to paleontology was the scanning of a 90 million-year-old (age of Late Cretaceous) fossilized vertebra of a marine reptile from the group of Pliosauria. In older publications it was described as a Reptile species "Hunosaurus fasseli". This is an original (syntype) described by A. Frič in 1905 [3]. Such a rare exhibit was found in a few pieces in Hudcov at Teplice, Czech Republic.
The rock-forming mineral was composed of marlstone (a rock containing clay materials and calcium and magnesium carbonates, with approximately the same composition as marl) – limestone rock type. The goal of this examination was to extract the bone part from the surrounded background of rock. However, as pointed at other applications this method based on absorption characteristics has its limitation. The contrast on two-dimensional projections arises from the difference of attenuation coefficients of each phase present in material.
The linear attenuation coefficient is a function of both the bulk density, ρ, and effective atomic number, Z in the following form:

$$\mu = \rho\left(a + bZ^{3.8} / E^{3.2}\right) \qquad (4)$$

where 'a' is the Klein-Nishina coefficient and 'b' is a constant. For energies above 100 keV, X-rays interact with matter mainly by Compton scattering depending on density whereas for energies less than 100 keV, the interaction is dominated by photoelectric absorption, which depends on atomic number.
In the case of the fossilized reptile vertebrate the set up parameters of X-ray tube 250kV of voltage are and 3mA of current fully conform to the conditions in which the vertebra was distinguishable from the surroundings.
The medium in which the bones are hidden makes difficult to easily determine the compact borders of bone. The chemical processes in such old specimen cause the diffusion of some small parts at the edge of bone into the surroundings. Thus the supplementary adjustments regarding software filtration and visualization are required to improve the image in the term of clearness. To cover the whole object the series of 98 slices were carried out with 1 mm thickness of each slice. Figure 4 shows the cross sections through the specimen, the composition of all slices represents a 3D model of vertebra. Non-destructive examination led to answering issues concerning the new information about the form and the size of the vertebra.

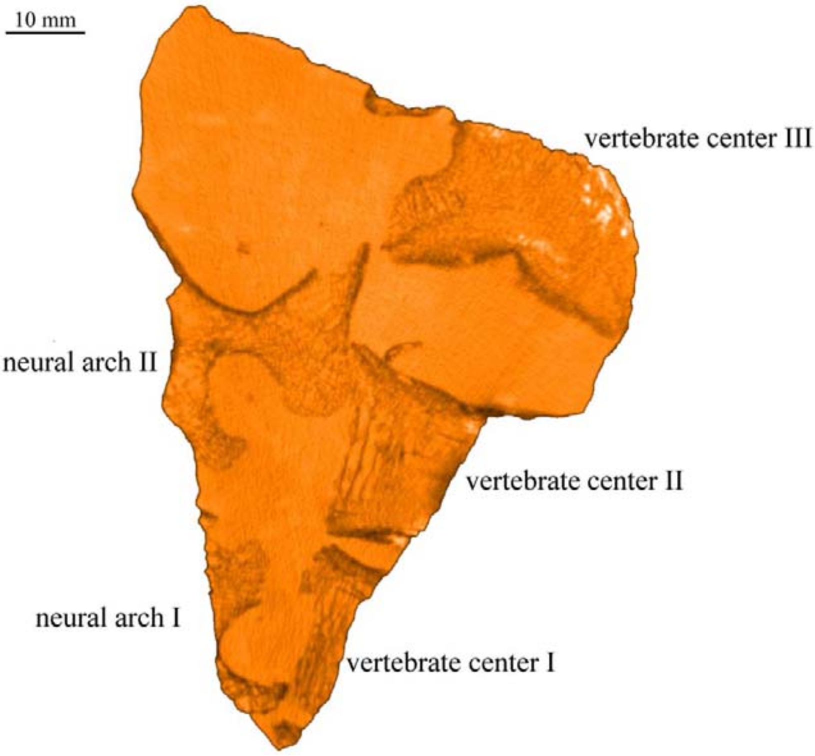

Figure 4. The composition of separated parts of fossilized reptile vertebrate

The nature of skulls makes them ideal candidate for research within the industrial tomograph. The skull of a bear from the genus Ursus found at the age of quaternary in Romania in the concrete.
The primary focus was aimed at the region of ears. Several series of slices depict the internal structure. The precise size in conjunction with spongy filling provides invaluable help for description the collection of bears. Another cross section as shown in Figure 5 was carried out trough the tooth in the palatine plane.

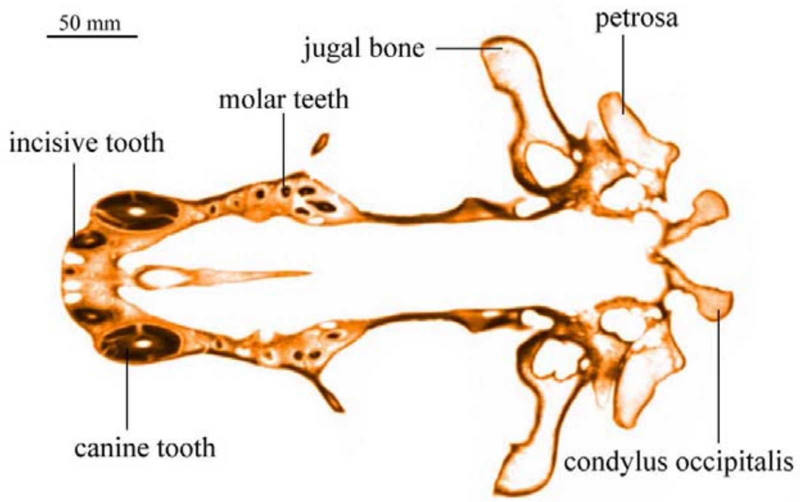

Figure 5. Palatine plane of a bear skull with the detail description

Fossilized fish of genus Paramblypterus from the primitive group Chondrostei presented next specimen. The age of this specimen is dated back 270 million years, age of Late Permian. The discovery site is located at Otovice at Broumov, Czech Republic.
The carbonized fish was covered by the thin rock layer, concretely bituminous thin layered limestone. According to formula (4) we are conscious that low Z material is slightly attenuated by the X-ray, moreover, if such low Z object is covered by a rock with higher Z. Because the X-ray source delivers a spectrum of X-ray energies, the lower energy portions are absorbed preferentially at the air-sample interface and in the sample itself. Besides this the continuous spectrum introduces beam hardening, the carbonized fossil is radiated by higher energy portions which have a negative effect on the fossil detection.
Nevertheless, the rough outline of the fish form was revealed (see Figure 6). In practice, it is maybe negligible for detailed research but on the other hand for the handy extraction is enough satisfactory.

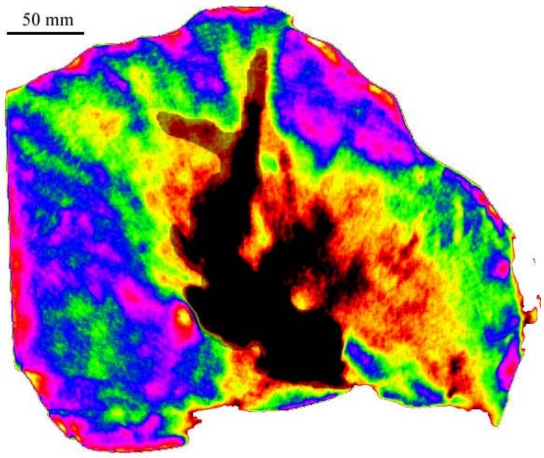

Figure 6. Fossilized fish hidden in rock

The preserved inanimate objects from the department of zoology belong among the other candidates for scanning by X-ray tomography. The lizard (4 cm in length) scanned in VT 500 and the fish named ground-gudgeon in VT 50 are studied for determination the number of vertebrate or for differentiation the gender.
The frontal section of the lizard of genus Lacerta at the level of vertebral column is shown in Figure 7.

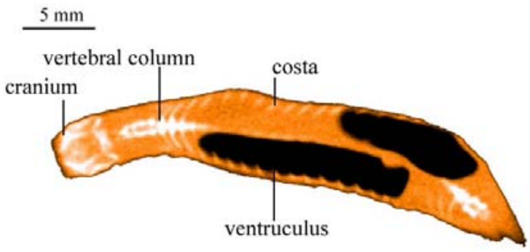

Figure 7. The cross-section through the lizard's body

As other examples we examined the human skull from the department of anthropology. More than 130 scans were acquired in order to describe in detail its whole structure.

3. Education centre

The purpose of our workplace is primarily to offer the support to students in a broad spectrum of applications. Students have possibilities to exploit the facilities as interactive aid for better lecture understanding. Some of them devote to this method more in detail in their theses and to a certain degree they acquire valuable experience, even if we take into account that the laboratory equipped with these types of tomographs is unique in the Czech Republic.

3. Conclusions

To conclude the paper, X-ray computed tomographs used in Prague Center of Industrial Tomography are able to fulfill modern educational and research requirements setting by users of our center. We hope to contact people from community to collaborate together.

Acknowledgements

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