X-ray CT analyses for paleontological subjects in the ICP system

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Abstract
A full-custom CT system for palaeontological purposes was developed in the Institut Català de Paleontologia Miquel Crusafont (Sabadell, Spain), based on a 450 kV X-ray source and an arc detector of 1.5 m length. Scan dimensions are up to 100 cm diameter, 120 cm height, with a spatial resolution of 0.27 mm/pixel for radiography and CT modes. The reconstruction is based on the filtered back-projection algorithm.

Multiple CT scans are continuously acquired in the ICP system. High-attenuation fossils cause noise artifacts in the images, and fossil-matrix separation is difficult for those pieces embedded in an stone matrix. These problems are a great challenge for CT of paleontological pieces; some solutions are explored in this article.

Data segmentation process is applied to CT images to obtain digital structures that are used to evaluate different characteristics and development of ancient animals. In conclusion, the specific developing of a CT scan has represented a step-ahead in the study of the archive subjects of the ICP facilities.

Keywords: X-ray, Computed tomography, palaeontology, artifacts, segmentation.

1. Introduction

Computed tomography (CT) is a non-destructive method with a growing relevance in palaeontology, as it can be found in bibliography [1-2]. CT imaging, as an X-ray inspection technique with no required contact, provides an useful method for 3D visualization of external and internal structures and further geometrical techniques can be applied for different analysis.

Therefore, X-ray CT imaging modalities offer interesting advantages for examination of fossils, as for example fragile specimens, internal structures or encased fossils in host rock. In this field, the interest of the Institut Català de Paleontologia Miquel Crusafont (ICP) for CT scans is straightforward, leading to a collaboration between the ICP, the Technological Center AIMEN and the Universidad de Santiago de Compostela (USC) to develop a full-custom CT system at the ICP dependencies in Sabadell [3].

In this paper we present a summary of the capabilities of the CT system and a detailed explanation of its implementation in the working environment for palaeontology studies.

1.1 Computed tomography system

The development of the CT system accomplished the integration of an X-ray source, an own-built X-ray detector and all the mechanical systems, controls and security switches. The X-ray source is a 450 kV dual focus (0.4 mm/ 1 mm) Y.TU 450-D09 from YXLON. Dual focus (0.4 - 1 mm size) varies the total power (900 - 1500 W) thus varying the acquisition parameters.

The mechanical elements are a vertical linear axis (1.2 m stroke) and a rotation axis with a 1 m diameter plate. Both the X-ray source and the detector were fixed once aligned. The pieces for inspect in this system can range up to 100 cm diameter, 120 cm height and 500 kg weight.

The detector development consisted on a 1D array with an arc geometry based on a photodiode matrix (from Sens-Tech Ltd). Each scintillator element (of CdWO₄ by Saint Gobain) was assembled in a 128 row of single crystals, separated by a plastic sheet and covered with epoxy. The implementation ends in a 3840 channel array of 0.4 mm pitch and 1.5 m length [3] for a fan beam CT configuration.

Control of the system was performed in LabVIEW integrating all the elements in a graphical user interface. Different parameters for acquisition can be chosen from the interface. Finally,
the reconstruction process (based in the filtered backprojection algorithm [4]) generates a file in Analyze SPM format which will be visualized in the software Avizo, maintaining geometrical data from the file header and a 16 bits data depth. This commercial solution allows generating CT data in different formats, as in DICONDE. Other visualization software solutions are also employed, as the ImageJ. Geometrical characteristics comprises a magnification of 1.4 for the 0.4 mm pitch detector, with an effective pixel size of 0.27 mm.

Figure 1: Photographs of the CT system with the arc detector (left) and the X-ray source (right).

2. Methods and materials

The working flow for CT data acquiring to generate a reliable fossil digital representation consists on several steps: from the acquisition process (calibration, selection of parameters), through the reconstruction method and final improvement of the image for further analyses.

2.1 Acquisition process

The acquisition process starts with the selection for the system parameters, divided as:

- **Source parameters**: energy (kV, mA), focus size, external filtering.
- **Geometrical parameters**: integration time (from 20 ms - 120 ms), number of readout channels and number of projections (360/720/900/1200/1440).

Energy requirements or focus size choice will depend on the desired resolution for the piece to inspect. From this point, the selection of the integration time for the detector (in combination with the output intensity of the X-ray source) must be established. A simple rule of thumb is to visualize the detector signal with the piece to inspect (for fixing the working energy), and without it for choosing the integration time and intensity value according to the best SNR value (that will be the closest signal to 65535 ADC value related to detector noise value, of 3000 ADC approximately). Moreover, the election of the number of projections combined with the readout channels number is of primary importance in order to minimize the aliasing noise in the image. Typically, the number of projections must be similar to the channels number [4]. Other noise sources can be minimized by improving the SNR value, with the use of physical filters and a robust calibration of the detector.
2.1.1 Calibration of the detector

Linear X-ray detectors based on scintillator elements must be calibrated to account for dark noise (from detector electronics) and gain values (i.e. different response to X-ray of adjacent pixels). The complete calibration consists on the called *air scans* [5], acquiring data for a fixed energy without piece to inspect for increasing intensity values. A linear fit and its coefficients are obtained and will be lately implemented in the acquisition, with an automatic correction of the saved data. This calibration should be performed for every energy and preferably before a complete CT acquisition [6]. Variations with intensity/integration time are not relevant since the signal dependence is linear.

The mean of a series of measurements is acquired for each intensity value: fixing a large number for this mean's calculation and small intensity steps for the calibration procedure improves the linear fit and therefore reduces the basic noise in the image.

![Figure 2: Snapshot of the calibration screen and final channels fit (upper plot at the right).](image)

2.2. Reconstruction method

File data acquisition consists on raw data files with a header of geometrical data (for reconstruction and further information retrieve). Following the geometry of the system (fan beam for a third generation CT), CT data is organized in individual slices - sinograms - consisting on the detector signal for a complete rotation in a given vertical position. The acquisition software also acquires single slices and complete digital radiographies.
The reconstruction solution is the widespread filtered back-projection algorithm [4]. The output data format is the Analyze SPM format, which consists on a raw data file with the reconstructed slices and a data header file. Data header information comprises the following values: pixel size, number of slices, size (pixels) of each slice, data-type (unsigned integers of 16 bits in this case). These parameters are defined from the header parameters in the custom data header for the sinograms in the CT system (see Fehler! Verweisquelle konnte nicht gefunden werden. Fehler! Verweisquelle konnte nicht gefunden werden. for details), that can be retrieved for future acquisitions.

### Table 1: Header parameters for data files in the CT system.

<table>
<thead>
<tr>
<th>HEADER PARAMETERS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical</td>
<td>Number of channels, Projections, Total number of slices,</td>
</tr>
<tr>
<td></td>
<td>Actual slice, Pixel size, Vertical voxel size</td>
</tr>
<tr>
<td>Acquisition</td>
<td>Image origin (detector), Offset, kV, mA, Focus size,</td>
</tr>
<tr>
<td></td>
<td>Integration time, Source filtering.</td>
</tr>
</tbody>
</table>

The visualization software, as indicated previously, is Avizo (http://www.vsg3d.com/avizo) or the ImageJ package (http://imagej.nih.gov/ij/). This free software solution can read multiple data files and provides a large number of added tools, like digital filters, image edition, process and analyze tools, etc.

### 3. Improving image quality

#### 3.1 Physical constraints

CT inspection in palaeontology deals with two principal constraints to generate images with enough image quality while maintaining a good compromise with spatial resolution:

**3.1.1 Image separation between fossil - stone matrix**

Most fossil pieces of the ICP archive are embedded in a stone matrix and show different conservation states. In these pieces the image separation between the fossil and the stone matrix is difficult: the attenuation to X-ray is similar for both materials. Image contrast has to be increased for image enhancement, which requires lower X-ray energy. On the contrary, diminishing the scan energy can cause the enhancement of other image artifacts as beam hardening and edge noise.
3.1.2 Image noise for high-attenuation methods
Larger and denser fossils can produce artifacts becoming from a high-attenuated signal. In this way, artifacts arising from beam hardening, edge streaks, scatter radiation and statistical noise [7] can cause useless images.

3.2 Methods to improve image quality

Several approximations can be implemented for improving the image quality:

3.2.1 Physical filtration of the source.
Implementation of physical filters (of common materials as aluminium and copper) eliminates the low-energy contribution of the X-ray source spectrum. Filter choice must be accomplished for maintaining a reasonable SNR along with better image. In any case, the calibration procedure must be performed after placing the corresponding filters.

3.2.2 Truncated calibration
When adjusting the mA intensity and the integration time for a high-attenuating piece, these parameters can result minimized for avoiding the saturation of the detector signal in the calibration step (air-scans). A direct possibility is to truncate the maximum intensity value during the calibration process and change it for a larger value during acquisition. This approximation causes saturation in air areas surrounding the piece to inspect, and some edge artifacts can arise after reconstruction. Nevertheless, SNR inside the piece is improved and therefore the image quality of the reconstructed piece in its interior part.

Figure 4: Example of reconstructed image acquired with truncated calibration. Edge artifacts arise in the image but the internal facts can be distinguished.

3.2.3 Post-processing

Post-processing is a simple approximation to improve image quality in a reconstructed image when no limit is required for spatial resolution. For the ICP facility this post-processing is achieved through different processing software tools: Matlab (Image Processing Toolbox, www.mathworks.com) and ImageJ (http://imagej.nih.gov/ij/).
Specific filters from ImageJ were tested in different images following a sequential process for obtaining an overall-corrected image:

- **Minimization of ring artifacts** coming from calibration misadjustments: by using the *Remove Outliers* plug-in.
- **Mean / Sharpen**: This filter minimize generic image noise
- **Transformation of the resolution of the CT image**: The 16-bit original image is reduced to a 8-bit image, to speed further calculations and measurements, in those cases where 8-bit data has enough data depth for further applications. 8-bit images maintain a good image quality for paleontological applications while maximizing the contrast.

![Figure 5: CT image without filtration (left), corresponding digital filtered image (right).](image)

### 4. Image analysis

The final step to analyze the biological characteristics of a digitized fossil is to process the CT images through a data segmentation process for obtaining a digital structure. Several software solutions can be used: Avizo (www.vsg3d.com/avizo), Rhinoceros (www.rhino3d.com), Ansys (www.ansys.com), Meshlab (meshlab.sourceforge.net/).

The software package Avizo allows to separate the fossilized bone from the stone matrix. When the fossil is well-preserved, its density value will be different from the matrix value, and the segmentation process is automatic. Unfortunately, in most cases, the grey levels between the fossil and matrix are very similar, what implies that the segmentation process must be manually performed.

Other fossils are found in broken and separated elements. In this case, the CT image is obtained separately for every part and the final segmented structures can be assembled together in a single digital structure following their actual relative position (as in Figure 6).
Digitalized structures are of great interest in for example morphometrics analyses. These analyses provide information of the animal as developmental changes in form, relations between ecological factors and shape. Quantification from digital structures can be obtained for evolutionary traits or detecting changes in animal shape, ontogeny, function or evolutionary relationships.

From these digital structures, it is possible to obtain biomechanical parameters from the fossil-corresponding living animal by applying finite element analyses (FEA, [8]). FEA allows obtaining different characteristics as stress and deformation in bones or bite strength, for example. The interest of these characteristics relies on the information for knowing the animal's behaviour, its relation with the environment and other animals and further comparison with living animals.

![Figure 6: Rests of a prehistoric crocodile. The different elements have been digitally repositioned to their original position.](image)

![Figure 7: Skull stress from a living salamander (from a previous CT study in the ICP).](image)
5. Results and discussion

Following the working flow described in this article, it is possible to obtain reliable and complete digital images from fossils. Thus, up to now multiple CT scans have been acquired and processed in the ICP facility.

The most interesting pieces range from prehistoric bears, hyenas and turtle skulls, together with primate femurs or dinosaurs vertebrae. The CT scans allow performing different biomechanical approaches for study.

As a specific example, brain and cerebellum data were obtained from endocranial cavity of different mammal skulls. Digital structures are here used to evaluate the animal's most developed senses and even to know their sociability degree by comparison with living animals (if they were solitary animals or lived in groups with hierarchy). Other example is the determination of bone illnesses from prehistorical crocodire vertebral from the ICP collections.

The implementation and use of the CT system built at the ICP will evolve continuously. Subjects digitization for archiving purposes and broadening fossils studies will fit the strategy plans of the ICP. Moreover, the development of specific software and hardware solutions for the paleontological characteristics for computed tomography will be of highest interest.

References