The MUSICES Project: Simulative automated CT acquisition planning for historical brass instruments improves image quality

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Abstract:

Complex object shape implies difficulties in positioning for CT scanning. We developed an image metric based method to optimize the positioning of brass instruments for cultural heritage research. The optimization task is performed on simulated data. As figure of merit we used Shannon entropy. The positioning based image quality gain is shown via comparison of real CT scans of a historical instrument.

Keywords: X-Ray simulation, quantitative image characterization, computed tomography of cultural heritage

Introduction

The digitalization of cultural heritage as a field of research is gaining more and more importance in the last years.

In the MUSICES project, the GNM (Germanisches Nationalmuseum) and the EZRT (Development Center for X-ray Technology) of the Fraunhofer Institute for Integrated Circuits (IIS) are jointly developing a guideline for the three-dimensional X-ray computed tomography (CT) of musical instruments.

As part of this project we performed a positioning optimization for brass instruments. Brass instruments, such as double horns and cornets, have a complex shape and consist of both compact solid parts and large thin-walled parts. Thus, positioning is a crucial task since good positioning reduces artefacts, e.g. beam hardening artefacts, and makes elaborated artefact correction software dispensable.

Our approach uses the deterministic X-ray simulation tool Scorpius XLab\textsuperscript{®} and an image quality metric in order to perform a fully automated acquisition optimizing. We will show that the chosen image metric is able to optimize for positioning and imaging parameters such like source spectrum and exposure time. As image quality metric Shannon entropy was chosen.

Methods and results

For positioning optimization we have used a brute force simulation approach. Therefore we simulate for each relevant positioning the full CT imaging process. X-Ray projections are simulated with respect to the CT system that is intended for the measurements and reconstructed using a state of the art filtered backprojection algorithm. For the relevant positionings those are chosen which lead to appropriate projection of the instrument on the sensitive area of the detector. The secondary restriction to the number of possible positionings is that mechanically stable mounting of the historical instrument must is essential. For the brass instrument of this study those requirements are fullfilled for tilt angles from 0° to
45° (“standing upright” to “tilted by 45°”), while defining the tilt angle as the angle between the rotation axis of the CT scanner and the normal vector to the trumpet hole.

We define the Shannon Entropy (SE) for CT images, as follows. Being $p_i$ with $i = 1 \ldots N$ the normalized histogram values of a CT image with $N$ different grey values, the SE defines as

$$H := (−1) \sum_{i}^{N} p_i \log_2 p_i$$

Considering a CT image with equally distributed grey values we yield the maximum possible SE $H_{\text{max}} = \log_2 N$ [1, 4]. Thus, we define a normalization of SE $H_{\text{norm}} = \frac{H}{H_{\text{max}}} \leq 1$.

We will call $H_{\text{norm}}$ the Shannon Entropy in the context of this paper. Normalization is just for the sake of more comparable numbers.

All kind of CT artifacts can be identified through graylevels that differ from the correct graylevel in a certain voxel. Therefor a perfect CT image has a histogram with only sharp peaks. One peak for each material of the scanning object plus one for air. Consider especially the so called “cupping” artifact that results from the beam hardening effect. This artifact causes non-symmetric peak broadening in histograms.

Shannon entropy is considered as measure of the variety of values that occur in a particular signal. For a CT volume this means: the larger the amount of different graylevels the larger is Shannon entropy.

This leads to our central assumption: if the Shannon entropy of a realistic simulated CT volume is small the image quality of this particular volume is high. SE can be considered as figure of merit for CT image quality. Thus we reach the positioning optimum via minimizing the SE.

For a number of the above described positionings the simulated CT was evaluated in terms of SE. Fig. 1 shows the SE values for a simulated tilt scan of the Cervený cornett [MI826 inventory of GNM].

![Figure 1: Scatter plot of normalized Shannon entropy vs. different simulated positionings of the cornett. Lowest SE is considered to denote the best image quality. Therefore the instrument position was chosen to be 45° tilted, which is the maximum tilt possible with having the full instrument in a scan volume which can be achieved by the intended system.](image-url)
We examined our approach on several historical instruments, one of them is shown in Fig. 2. It has been modeled in detail, in order to simulate and evaluate for best positioning. SE evaluation of the relevant positionings predicts best image quality at 45° tilt angle.

![Figure 2: The Cervený cornett; about 1910 (left, Copyright: Germanisches Nationalmuseum, Photo: Günther Kühnel) with a sketch of the digital model (upper right) and a simulated projection (lower right).](image)

In order to proof the concept of the position optimization approach we did two CT scans of the Cervený cornett. One in the optimum positioning and one in the “upright” position (tilt of 0°) which should yield less image quality. The CT system for this task is equipped with a 500 keV X-Ray tube and a 2048x2048 pixels flatpanel detector with 200 µm pixelpitch.

Since the valves and the mechanics around them are the most dense parts of the brass instrument, we expect most beam hardening and related artifacts for those parts. In Fig. 3 we compare slice views of the cornett valves. From qualitative image analysis less cupping for the tilted measurement, especially for the valve shaft, becomes evident. Beam hardening artifacts and scattering artifacts that arise in the air volume around the valves have less intensity in the case of the tilted measurement. The cornett valves have some drill holes in the valve shaft. We use those holes to evaluate the contrast via investigation of a tracker line plot. In Fig. 3 the two line plots compare the graylevels of the two measurements. The contrast between the air volume in the holes and the surrounding brass from the shaft is about a factor of two higher in the case of the tilted measurement.

**Fazit**

We performed an approach to automatically improve specimen positioning for CT. The approach uses pre-scanning simulation of the target specimen. Via image quality investigation of a set simulated CT measures the best positioning was determined. In particular the focus was put on reducing beam hardening caused artifacts.

On the example of a historical music instrument, a Cervený cornett, the method was performed and verified experimentally. Comparison of image quality of a measurement in optimized positioning with a non-optimized measurement resulted in quantitatively measurable improved image quality.
Figure 3: Representative slices of two CT measurements of the Cervený cornett, the slices show the valves of the instrument. Red boxed images belong to a scan in upright position, green boxed images to 45° tilted positioning. The bottom plot contains two line plots which are drawn along the orange arrows of the CT slices. The line plots cut drill holes that occur in the valve mechanics. The increased contrast for the tilted measurement becomes evident in the comparison of the green and red line at the drill hole positions.

Acknowledges and project description

The project is funded by the German research association DFG (Deutsche Forschungsgemeinschaft). The project partners are drawing up examination standards that, independent of the deployed devices and operating staff, are set to produce useful results in the medium term beyond the field of musical instruments, not just for other cultural assets but for industry as well. Representative examples carried out during the project will ensure the applicability of the technical parameters.
References