Dual-energy computed tomography of historical musical instruments made of multiple materials

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Abstract
During the last three years the MUSICES project was carried out with the purpose to develop guidelines for the computed tomography of historical musical instruments. One of the frequently occurring challenges posed by these objects is their composition of wood and metal. This causes artefacts in the reconstructed volume data sets, which are thus difficult to analyse and utilize. A significant reduction of the artefacts can be achieved by means of dual-energy computed tomography. This is shown exemplarily by applying this method to keyed woodwind instruments.

Keywords: X-ray computed tomography (CT), beam hardening, artefact correction, dual-energy CT, CT of cultural heritage, multi-material objects

1 Introduction
Recently the digitization of cultural heritage objects gained more and more importance \cite{1-5}. The techniques used for this purpose also include X-ray computed tomography (CT). Among many other objects, historical musical instruments are scanned. In some cases, medical CT is used because the facilities are available in many hospitals and the CT scans are fast \cite{6, 7}. However, medical systems are optimized for the examination of humans. They are not suited for objects containing large amounts of metal like brass instruments. Further, the manageable object size and the obtainable spatial resolution are limited. An alternative is provided by industrial CT \cite{8}. There is a multitude of scanners designed for specific purposes. They are built for handling certain materials or object sizes or to allow particularly high resolutions and provide more flexibility concerning the scan parameters. Thus, in comparison to medical CT there are more objects that can be scanned and more options, i.e. machines and parameters, from which to choose. During the last three years the Germanisches Nationalmuseum (GNM) in Nuremberg, Germany, and the Development Center for X-ray Technology (EZRT) of the Fraunhofer Institute for Integrated Circuits (IIS) in Fürth, Germany, have collaborated within the project MUSICES (Musical Instrument Computed Tomography Examination Standard) to develop a guideline for the industrial CT of historical musical instruments.

Musical instruments provide several challenges to CT. Their dimensions cover a wide range, from a few centimetres (ocarinas) up to 2 m (grand pianos). Their shapes can resemble rods (flutes), boards (zithers) or be generally complex (bagpipes). They consist of materials with considerably differing densities like wood, bone, glass or metal. Depending on the organological question calling for a CT-examination, the required spatial resolution of the volume data set can reach from more than 100 µm for computer animation of an instrument to well below 50 µm for dendrochronological dating of wooden parts. Thus, the used equipment as well as the technical parameters for a CT, like tube voltage or scan trajectory, have to be chosen specifically for each object. More than 100 specimens from the collection of GNM and further project partners were used as representative examples to explore the best way for obtaining a three dimensional volume data set using CT.

2 CT of multi-material musical instruments
One challenge for CT is posed by objects consisting of multiple materials with highly differing X-ray interaction properties. The combination of wood and metals like brass or German silver is quite common for musical instruments. Necks of lutes and other stringed instruments are often fixed to the corpus with nails. Woodwind instruments, such as oboes or bassoons, have a wooden corpus and metal keys. The metal parts often cause artefacts that impede the interpretation of the volume data sets. In some cases the perturbing pieces can be removed for the CT. However, this is not possible for all parts due to conservatory reasons or because these parts are needed to answer a specific organological question. Exploring ways to reduce the artefacts caused by metallic parts in the special case of musical instruments is one of the aims of the MUSICES project.

2.1 Beam hardening artefacts
Laboratory X-ray tubes emit a polychromatic spectrum. As the attenuation of X-rays by any material is depending on energy, the spectrum changes when matter is transmitted. This beam hardening effect is more pronounced for metal than for wood.

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Typical reconstruction algorithms, that could be recommended in a guideline, like filtered backprojection (FBP) do not take beam hardening into account. The reconstructed volume data set can thus contain artefacts like cupping and streaks [9]. Especially the streaks can obscure the wooden parts of an instrument or make them invisible. Thus, the reduction of beam hardening artefacts is of high importance.

2.2 Beam hardening correction

One approach to avoid beam hardening artefacts is to use a harder X-ray spectrum in the first place. Pre-hardening the spectrum by applying a filter leads to improvements, but might not be sufficient. It also decreases the detected intensity, which has to be compensated by longer scan times. This is unfavourable from a conservatory as well as an economic point of view. Applying a higher acceleration voltage seems desirable. However, tubes with high kV are not accessible everywhere and typically have focal spot diameters of some 100 µm to a few mm, which limits the achievable spatial resolution. Therefore, other solutions are needed.

One possibility is the application of dual-energy CT [10]. An object is scanned twice with X-ray spectra having different effective energies. The proper combination of both scans reduces beam hardening artefacts. This combination can be realized in projection (pre-reconstruction) or in image domain (post-reconstruction). Several ways to implement the method have been published [10-12]. Within the project MUSICES a post-reconstruction approach was used, which was originally developed for use in medical CT [12]. It was chosen for its simplicity and because it is published and thus available to everyone, which is a necessary condition for the recommendation in a guideline.

For the work presented here, the tube voltage was limited to 225 kV. This is a typical limit of tubes available in X-ray laboratories. If higher voltages are available, the results of a single scan should be sufficient, making the two spectra approach unnecessary.

2.2.1 Simulation study and experiments with a contemporary clarinet

To support the experiments with historical musical instruments, a simulation study has been performed [13]. Its aim was to identify the optimal spectra for both scans. A virtual model of a part of a contemporary clarinet (see Figure 1(a)) was created from primitive geometries within ScorpiusXLab® [14]. Four different materials were assigned to parts of the model. The corpus consisted of earlywood and latewood, all metal parts were made of German silver and a felt seal below one of the keys was simulated as wool (Table 1). Several CT scans were simulated with different tube voltages and prefilters. The simulated projections were then reconstructed using an FBP algorithm. Hundreds of reconstruction pairs were combined. For each pair it was attempted to find the optimal combination parameter that globally minimizes the artefacts in the whole volume. Finally, the best combination was selected. The study showed that the effective energy of the two spectra should be as different as possible. There is, however, a restriction to this condition: the energy has to be high enough to transmit the object.

<table>
<thead>
<tr>
<th>material</th>
<th>composition</th>
<th>density</th>
</tr>
</thead>
<tbody>
<tr>
<td>earlywood</td>
<td>50 % C, 43 % O, 6 % H, 1 % N [15]</td>
<td>0.4 g·cm⁻³ [16]</td>
</tr>
<tr>
<td>latewood</td>
<td>50 % C, 43 % O, 6 % H, 1 % N [15]</td>
<td>0.62 g·cm⁻³ [16]</td>
</tr>
<tr>
<td>German silver</td>
<td>55 % Cu, 28 % Zn, 17 % Ni</td>
<td>8.4 g·cm⁻³</td>
</tr>
<tr>
<td>wool</td>
<td>50 % C, 23 % O, 16.5 % N, 7 % H, 3.5 % S inspired by [17]</td>
<td>1.32 g·cm⁻³</td>
</tr>
</tbody>
</table>

Table 1: Properties of the materials used for the simulative study.

Of the simulated spectra nine were chosen to experimentally verify the results of the simulation study. The spectrum with the lowest effective energy was obtained with 65 kV tube voltage, the one with the highest effective energy with 220 kV and an additional 2.5 mm Cu prefilter. Some of the reconstructed volume data sets are depicted in Figure 1(b, c, e, f). They show artefacts caused by the keys of the instrument. Their impact on the reconstruction decreases with increasing effective energy of the X-ray spectrum. However, they persist even for the highest energies used as shown in Figure 1 (f). Bright and dark streaks pass through the wooden corpus. Areas that are expected to appear dark as they contain air, like the inner bore of the clarinet and the space between the keys, are brightened. This complicates the interpretation of the data sets. Reconstructions with different effective energies were therefore combined pairwise.

Two different attempts for the combination were tested. One was a global minimization of the artefacts in the whole reconstructed volume similar to the simulation study. The second was the reduction of artefacts in a smaller region of interest. While in this region the results might be better than in the global optimization, this is compensated by more artefacts in other areas. Accordingly, the result depend on the chosen region (Figure 1(g) and (h)). This gives the opportunity to improve the reconstruction in the places interesting for answering a specific organological question. In the examples depicted in Figure 1,
the combination parameter for the global optimization was between those of the regions chosen in wood or in air. Overall, it differed by up to approximately 15% between the global and the different regional optimizations. When comparing experiments and simulation study, different combination parameters were found for each pair of spectra. The difference is due to simplifications in the simulation, like the lack of noise. However, the spectra that the simulation study predicted to give the best results were verified in the experiments.

2.2.2 Dual-energy CT of historical musical instruments

The simulations as well as the experiments with the contemporary clarinet showed that for the scans of the historical musical instruments, basically, one spectrum should be as hard as possible, i.e. the maximum tube voltage and as much prefiltration as possible, while still providing enough intensity to allow for a sensible scan time, should be used. The other spectrum should be as soft as possible while still transmitting the object. Therefore, the maximum available tube voltage of 225 kV was typically used also for the second spectrum as lower tube voltages typically did not allow transmission through the keys of the specimen under investigation. The two spectra thus differed only through the different prefilters. Usually these were 2.5 mm Cu for the hard spectrum and 0.89 mm Ti for the soft spectrum. The scan time for these two cases differed by a factor of four approximately. In the combination of both scans it was usually attempted to improve not the whole volume, but the wooden parts of an instrument because typical organological questions concern those.

An example is shown in Figure 1. The cor anglais from the GNM (inventory number MIR396) depicted in Figure 2(a) has been scanned with two different X-ray spectra. The reconstructions of the two scans show considerable artefacts caused by the metal keys (see parts (b1), (b2), (c1), (c2) of Figure 2). Black streaks render parts of the wood completely invisible. Typical organological questions cannot be answered under these circumstances: a measurement of the diameter of the tube’s inner bore is not possible, the construction of the instrument cannot be investigated, tool marks remain hidden. Combining both reconstructions reduces the artefacts significantly (parts (b3) and (c3) of Figure 2). Also the metallic keys appear more homogeneous in the combination of both scans. Similar results were achieved with other instruments consisting of wood and metal.
While the combination of wood and metal is common for keyed woodwind instruments, also the case of a transverse flute with a corpus made of crystal glass was investigated. Figure 3 shows reconstructions of a piece of this flute, which consists of a glass tube with silver rings at both ends and one silver key. When examining the CTs performed with one spectrum only, it is impossible to distinguish the inner surface of the bore underneath the rings. In this area, the grey values indicate that the tube is filled with solid material with an attenuation coefficient similar to the one of glass (Figure 4). The dual-energy approach simplifies the interpretation considerably (Figure 3(c)). It can be recognized that the glass tube extends into the lower third of the upper ring and is hollow. The upper two thirds of the ring do not seem to contain glass but only air although there still remain artefacts at the inner surface.

Apart from the presented examples, dual-energy CT has been used for the investigation of several more historical woodwind instruments. As is revealed by the figures, not all artefacts are removed. With increasing transmitted lengths through metal, more artefacts remain, especially if X-rays are blocked completely by some parts. Nevertheless, this method was shown to improve the usability of the reconstructions.

Still, there are drawbacks to consider. Dual-energy CT requires two scans. There are only a few industrial facilities with two sources and two detectors or with energy sensitive detectors, which can thus record CTs with two spectra simultaneously [18]. Therefore, a typical dual-energy CT increases the time a valuable historical object has to spend in a place where climate is not as well controlled as in a museum. Also the absorbed dose is increased. For sensitive objects both could be critical. In this case it is recommended to perform dual energy-CT not for the whole instrument generally, but only for those parts of it, for which it is needed. Further, the combination of both scans requires the object to remain in the same shape during both scans. Dual-energy CT might therefore not be suitable for fragile objects that could deform during a measurement.

For cases, where only one scan is passable, there are specialized reconstruction algorithms that take beam hardening into account. For instance, the effect can be approximated, requiring the optimization of the parameters needed for this, and be considered iteratively during the reconstruction of the volume [19]. However, these algorithms are computationally demanding and not easily available everywhere.
Figure 3: Cross sections through different reconstructed volumes of a piece of the transverse flute MI410 from the GNM collection in two perpendicular vertical directions. (a) CT with tube voltage of 220 kV and 0.89 mm Ti prefilter. Especially at the upper end it is not possible to determine the inner surface of the corpus. (b) CT with 220 kV and 2.5 mm Cu prefilter. The artefacts are reduced slightly. (c) Combination of both scans. The cross sections suggest that the glass tube ends within the upper ring, which thus is hollow in the uppermost part. The red lines indicate the position of the line profile depicted in Figure 4.

Figure 4: Line profiles through the reconstruction of the transverse flute at the position indicated in Figure 3. Vertical lines show approximately the boundary between materials. The attenuation coefficient of air is $\mu = 0 \text{ cm}^{-1}$. However, for the single spectra scans this is not reproduced by the reconstruction especially inside the glass tube. This is corrected in the combination of both scans. Also the cupping artefact in the key is improved. Note that for the combination of the two reconstructions the value of the attenuation coefficient has no physical meaning.

3 Summary and Outlook

The MUSICES project developed guidelines for the X-ray computed tomography (CT) of historical musical instruments. Among other challenges, beam hardening artefacts in instruments consisting of multiple materials had to be reduced. This was achieved by using dual-energy CT. Due to the same involved physical mechanisms, material combinations frequently pose challenges also concerning other objects from cultural heritage, like clocks or furniture, and from industry, such as electrical connectors or carbon fibre reinforced plastics with metal inserts. The experiences made with musical instruments can thus be transferred to other items.
Acknowledgements

Financial support from the German research association (Deutsche Forschungsgemeinschaft, Wissenschaftliche Literaturversorgungs- und Informationssysteme LIS, Grant No. HA 2904/4-1) is gratefully acknowledged.

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