Validation of a photogrammetric approach for the study of ancient bowed instruments

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Abstract

Some ancient violins have been reduced throughout their history. We propose an objective photogrammetric approach to differentiate between a reduced and an unreduced instrument, where a three-dimensional mesh is studied geometrically by examining 2D slices.

First, we validate the accuracy of the photogrammetric mesh by the way of a comparison with reference images obtained with medical imaging. Then, we show how contour lines and channels of minima can be automatically extracted from the photogrammetric meshes, allowing to successfully highlight differences between instruments.

1 Historical context and motivation

The morphology of today’s violin differs greatly from that of the instruments built between the late 16th and the mid 18th century. After 1750, in order to meet the standards suggested by famous orchestras and conservatories, many ancient violins have been reduced. Figure 1 shows on the left a reduced violin from the first half of the 18th century and an estimation of its original dimensions. Two types of reduction are also illustrated on the right: re-cutting the top and bottom parts of the sound box, and removing a slice of wood along the axis of the instrument to reduce its width. As historical testimonies about this process are imprecise, a common issue for today’s musicologists, organologists and luthiers is to determine whether an early violin has been reduced and, if so, to quantify the alterations it has undergone. It is therefore desirable to quantify violin geometry in a completely objective way, which is the problem we address. We study two violins¹, one of which was reduced. Our main tool are 3D photogrammetric meshes, described in Section 2. We validate their use

¹Strictly speaking, both of them are violas (the intermediary violin size), but we will use the common name of violin throughout this article.
by estimating how accurate they are with respect to CT scans obtained with medical imaging techniques. Then, in Section 3, we use those meshes to highlight the edges of the violins, their contour lines and minima channels, allowing us to illustrate differences between a reduced and an unreduced instrument.

2 Obtaining and validating photogrammetric meshes
The studied instruments will be referenced by their luthier’s name: Hofmans (which is reduced) and Cuypers (which is not). As the necks have been replaced over time, we focus exclusively on the upper surface of their body, called the “sound board”, which we acquire in the following two ways.

- **Photogrammetric mesh.** About 160 photos for each instrument were taken by a Nikon D850 camera with a 60 mm focal lens. Photogrammetry software Agisoft Metashape was used to create the meshes of the sound boards (sound holes were delineated and removed manually).

- **CT-scan mesh.** Both violins were scanned at University Hospital Saint-Luc (UCLouvain, Brussels-Woluwe), which produced 512 × 512 pixels slices with 50% overlap (around 2300 slices with 0.67 mm thickness for Hofmans, 1600 slices with 0.9 mm thickness for Cuypers). They were converted into meshes using ITK-SNAP software based on the contour segmentation algorithm detailed in (the part of the mesh corresponding to inner walls was removed manually).

**Similarity and alignment between both representations.** To quantify the similarity between a photogrammetric and a CT-scan mesh of the same instrument, we compare the corresponding point clouds, each made of 400k–500k nodes. The classical Hausdorff distance between two sets does not fit our purpose, as it does not quantify the overall similarity, but only focuses on the worst-case distance between corresponding points. Instead, following Agisoft Metashape 4, we compute the average distance between each point of the photogrammetric cloud and its nearest neighbour from the CT cloud. As the two point clouds are not aligned, we compute the optimal translation, rotation and scaling that produces the minimum average distance as defined above. We

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2 Hofmans Matthys IV, inv. no 2846, Antwerp, before 1679 (Musical Instruments Museum)
3 Cuypers Johannes Th., inv. no 2833, The Hague, 1761 (Musical Instruments Museum)
4 https://www.agisoft.com
5 http://www.itksnap.org/pmwiki/pmwiki.php
therefore optimise the seven parameters $X \in \mathbb{R}^3$, $\theta \in \mathbb{R}^3$ and $K \in \mathbb{R}$ describing the translation, rotation and scaling that the CT cloud has to undergo to best match the photogrammetric one, as in Figure 2 (left), and solve

$$
\min_{X, \theta, K} D(X, \theta, K) = \frac{1}{N_p} \sum_{i=1}^{N_p} \| p_i - K(R_\theta s_{nn(i)} + X) \|
$$

where $\{p_i\}_{i=1, \ldots, N_p} \subset \mathbb{R}^3$ and $\{s_j\}_{j=1, \ldots, N_s} \subset \mathbb{R}^3$ are the $N_p$ points and $N_s$ points respectively from the photogrammetric and CT-scan clouds, and $R_\theta$ is the rotation operator

$$
R_\theta = \begin{pmatrix}
\cos \theta_3 & \sin \theta_3 & 0 \\
-\sin \theta_3 & \cos \theta_3 & 0 \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
\cos \theta_2 & 0 & -\sin \theta_2 \\
0 & 1 & 0 \\
\sin \theta_2 & 0 & \cos \theta_2
\end{pmatrix} \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_1 & \sin \theta_1 \\
0 & -\sin \theta_1 & \cos \theta_1
\end{pmatrix}.
$$

For each of the $N_p$ points $p_i$, we need to identify the nearest neighbour among the $N_s$ transformed $s_j$ points (the corresponding point is denoted $s_{nn(i)}$), which is computed efficiently by the Fast Library for Approximate Nearest Neighbours \cite{5}). The minimisation is performed with (scipy.optimize.fmin_powell), total computation time is around one hour on a standard laptop. Both clouds were first oriented using the principal axes from Principal Component Analysis (PCA), while their relative positions and scaling was adjusted manually. To speed up convergence, each parameter is first optimized separately to obtain starting values (Figure 2 (right) shows an initial value of $\theta_2$ around $-0.02$ rad $\approx 1.15^\circ$). Results of the fitting problem are presented in Table 1.

| Violins | Average distance $D$ | $\theta_1$ | $\theta_2$ | $\theta_3$ | K     |
|---------|---------------------|------------|------------|------------|-------|
| Hofmans | 0.45                | 0.267      | 0.793      | 0.500      | 0.98  |
| Cuypers | 0.29                | 0.034      | -0.082     | -0.016     | 0.97  |

Table 1: Average distance [mm] between the photogrammetric and CT sound board clouds, optimal angles [°] and scaling factor $K$ [/]

Angles in the optimal alignment range from 0.016° to 0.793°, indicating that the initial orientation obtained from PCA was relatively accurate.

**Error assessment and validation.** The average error lies in the submillimetre range for both instruments, which is rather small. The distribution of distances between nodes can be observed using heat maps and histograms on Figure 3 (left: Hofmans,
centre: Cuypers), showing very good agreement throughout the sound boards, and very few distances larger than 2.5 mm. To better interpret those average errors, we also computed the average distance from the photogrammetric Cuypers to the CT Hofmans, which is equal to 1.09 mm, a surprisingly small value despite the fact that one of them was actually reduced.

To explain this, we first observe that the heat maps and histograms clearly indicate that the fit is much poorer (see right of Figure 3). In addition, we realised that even if the photogrammetric mesh was perfectly describing the sound board, its nodes cannot be expected to be located exactly in the same locations as the nodes of the CT mesh. The average length of the edges in our CT mesh is equal to 0.59 mm (Hofmans) and 0.51 mm (Cuypers). Assuming that the average distance in an independent mesh can not be significantly smaller than half of that average edge length (0.25–0.30 mm), we conclude that the fit of both the Hofmans and the Cuypers violins is excellent, and that the average error in the mismatched Cuypers vs. Hofmans comparison is actually quite significant.

3 Geometric analysis of the sound boards

Results in this section are based on the geometric analysis of the photogrammetric meshes obtained and validated in the previous section. Further details can be found in [6] (including the technique used for general edge detection).

Contour lines. As the PCA alignment was shown to be very accurate in the previous section, we use its orientation to compute horizontal sections of the sound boards every 2 mm. Figure 4 shows, especially in the zoomed area (red frame), that the contour lines are rounder on the unreduced Cuypers, and sharper on the width-reduced Hofmans (slice of wood removed along main axis).
Channel of minima. The sound board of a violin features a “channel of minima” running close to its outer edge. To identify this channel, we compute a large number of cross-sections through the mesh. These sections are orthogonal to the PCA horizontal plane (see above) and chosen to be perpendicular to tangents to the edge of the sound board, as shown in Figure 5. Those tangents are computed from a cubic spline approximation of the edge curve computed from extreme points. In each cross-section, minima are identified as the points with the lowest height among those close to the tangent point.

The channel of minima is shown in Figure 6, showing clear differences between the instruments. Indeed, we see that, in a reduced violin, the distance from the channel to the edge tends to decrease in some areas close to the top and the bottom of the sound board. Note however that the apparent recess in the channel at the bottom of the Hofmans sound board is due to the lower nut, and not to the actual channel, which has disappeared at this point (see [7] for a detailed explanation).
Figure 6: Channel of minima for Hofmans (left) and Cuypers (right) sound boards

4 Conclusion and future work

We proposed a photogrammetric approach for the study of ancient violins. We validated the accuracy of the acquired meshes using reference CT scans, and then showed how the computation of contour lines and channels of minima allows to characterise whether or not some instruments are reduced. In the future, we plan to apply our techniques to a larger corpus of approximately fifty instruments. We hope that this will allow us to detect features of reduced instruments automatically, using clustering or classification techniques applied to appropriate mathematical representations of the surface of the sound boards.

To the best of our knowledge this type of objective approach, based on the geometric analysis of three-dimensional meshes, does not seem to appear in the literature. The closest previous work seems to be found in [8], where the morphological evolution of the violin is studied, also in a purely objective way, albeit with an exclusively two-dimensional approach (contours are extracted from photographs and represented with elliptical Fourier descriptors).

Despite the fact that we start from three-dimensional data (meshes and point clouds), some parts of our geometric analysis rely on two-dimensional techniques (edge detection, use of cross-sections). We plan to develop an exclusively three-dimensional processing, allowing us to consider other features such as locating the inflection points, and identifying the true shape of the minima channel as a three-dimensional curve.

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References

[1] Karel Moens. Les voix médianes dans l’orchestre français sous le règne de Louis XIV: les instruments conservés comme source d’information. Duron, Jean; Gétreau, Florence. L’orchestre à cordes sous Louis XIV: Instruments, repertoires, singularités., pages 119–138, 2015.

[2] Robin Stowell. Violin technique and performance practice in the late eighteenth and early nineteenth centuries. Cambridge University Press, 1990.

[3] Paul A. Yushkevich, Joseph Piven, Heather Cody Hazlett, Rachel Gimpel Smith, Sean Ho, James C. Gee, and Guido Gerig. User-guided 3D active contour segmentation of anatomical structures: Significantly improved efficiency and reliability. Neuroimage, 31(3):1116–1128, 2006.
[4] Jie Tang, Gangshan Wu, Bo Xu, and Zhongliang Gong. Fast mesh similarity measuring based on CUDA. In 2010 IEEE International Conference on Progress in Informatics and Computing, volume 2, pages 911–915, 2010.

[5] Marius Muja and David G Lowe. Fast approximate nearest neighbors with automatic algorithm configuration. VISAPP (1), 2(331-340):2, 2009.

[6] Philémon Beghin. A digital tool at the service of organology: validation of a photogrammetric approach. Master’s thesis, Ecole polytechnique de Louvain, UCLouvain, 2021.

[7] Anne-Emmanuelle Ceulemans, Philémon Beghin, Paul Fisette, François Glineur, and Iona Thys. Baroque violas with reduced sound boxes: An evaluation method. In preparation.

[8] Daniel H. Chitwood. Imitation, genetic lineages, and time influenced the morphological evolution of the violin. PloS one, 9(10):e109229, 2014.