Evaluating the Use of Industrial X-Ray CT for the Reverse Engineering of Bowed Stringed Instruments

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Abstract

For centuries, simple contact measuring instruments (e.g. callipers, profile and thickness gauges) have been used by violin makers for recording bi-dimensional information about their creations. Since its invention, film and digital photography have also been used to document shapes and colours. Traditionally, gypsum castings and RTM replicas are used to store information about the 3D shapes of back, bellies and scrolls.

During the last 30 years the applications of non-contact systems such as X-ray computed tomography (CT), and laser and structured light scanners (LS) have opened new horizons to the bowed stringed instruments metrology.

This work compares two state-of-the-art non-contact systems: an industrial X-ray computed tomography system and a Structured Light 3D scanner. Their results in terms of accuracy, repeatability and uncertainties are assessed and compared to reference tactile Coordinate Measuring Machine (CMM) measurements. Experimental results prove that, with the considered experimental set-up, CT provides better results than LS in terms of deviation from CMM reference measurements, and uncertainty.

1. Introduction

X-ray computed tomography (CT) has proved to be a useful diagnostic tool in musical instruments making and restoration [1]. It has also been used to document the bowed stringed instrument conditions [2, 3].

Non-contact systems like laser scanners and structured light scanners (LS) have positive features in terms of portability, device cost and fast acquisition time. However, they cannot be used with very dark and reflective surfaces, both common characteristics of violin surfaces. Therefore, this type of surfaces should be covered with optically cooperative coatings, which is not always desirable.

Medical CT has been already used for the reverse engineering of violins, as reported in “The Betts Project” [4]. This kind of application of medical CT is limited by its resolution.

Industrial CT may overcome the limitations of medical CT, thanks to higher resolution and better radiographic contrast.

This study focuses on the application of industrial CT to the reverse engineering of bowed stringed instruments. The aim of this work is the evaluation of CT as a tool for the dimensional analysis of a violin soundboard.

This part of the violin is chosen because it presents a wide range of common problems related to the dimensional analysis of wooden free-form objects like violins or other strings.

2. Materials and methods

We focused on the comparison of performances of CT and LS when measuring a violin soundboard.

In order to assess the accuracy of CT measurement results, a tactile Coordinate Measuring Machine (CMM) is used as the reference. Tactile CMMs usually provide the reference in coordinate metrology, due to their proven accuracy and to the availability of internationally accepted standards for performance verification and measurement uncertainty determination (ISO 10360-2 [5] and ISO 15530-3 [6]). However, when measuring free-form handmade components like violins, because of the extreme variability of surface curvatures, and the presence of non-accessible features, tactile CMMs show several limitations, including the risk of damaging the instruments.

We designed and manufactured a test sample (Figure 1, right), machined from red spruce (Fiemme Valley, Italy) with a CNC milling machine.

The test sample was conceived in order to include the typical features measured on a violin top plate, and to be tested by the three systems used in this research: CMM, SL and CT.

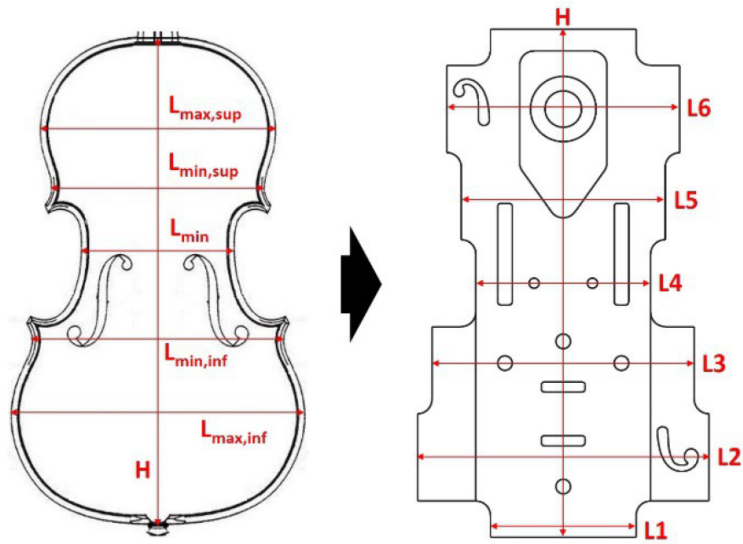

Figure 1: test sample (right) vs a violin top plate (left), with superposed measurands

A set of measurands were defined, each of them representing a feature of the real violin soundboard, such as the overall dimensions, f-holes positions, plate thickness and elevation maps. In compliance with the similarity requirements stated in [6], the sample can be used to assess the measurement uncertainty for real violin top plates.

CT and structured light analysis of the test object were performed in the same conditions and with the same measuring procedure adopted for the analysis of the original violin component.

The sample was measured with a ZEISS PRISMO 7.9.5 tactile CMM at TEC EUROLAB, and then scanned with an NSI X5000 CT system at SIDEIUS. Finally, a set of surfaces was acquired by means of the structured light scanner Open Technologies Cronos 3D. For each measuring technique, three repeated scans were performed.

All the results (corresponding to the measurands) acquired with the different techniques were put in comparison, together with their relative standard deviations.
Deviations of CT and SL from the reference (CMM) were evaluated. Furthermore, the corresponding measurands of a Nicola Amati (Cremona, 1652) violin belly inside surface were measured using CT and SL. The outside surface was too dark and shiny to be scanned with structured light.

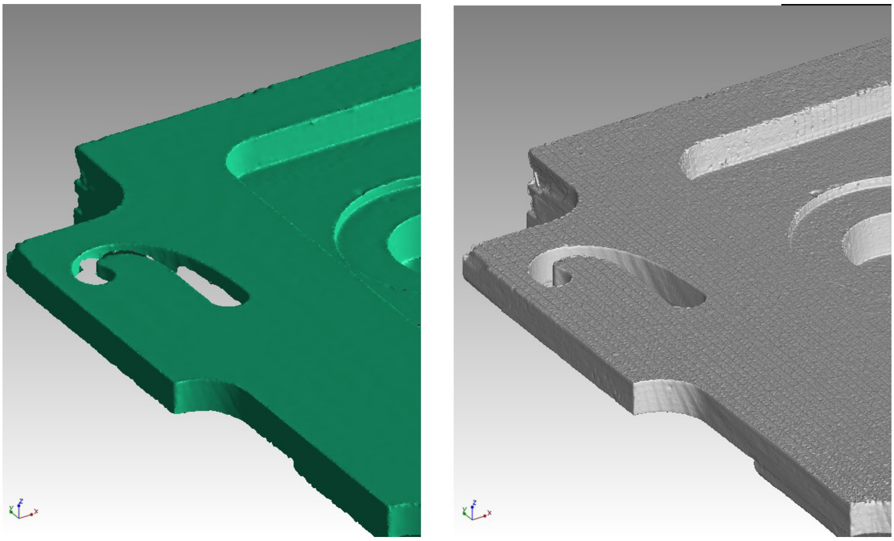

Figure 2: a comparison between SL polygon surface (left) and CT extracted surface (right) of the "soundboard" sample.

3. Results and discussion

Results obtained for measurands L_1, L_3-L_6 (see Fig.1) are reported in Table 1. Temperature and Relative humidity were monitored during all the measuring sessions. The comparison of the results obtained with CMM, CT and SL provides several indications.

Values from CT has an absolute deviation |Δ| from CMM values ranging from 92 to 102 µm. LS constantly overestimates measures, with a positive Δ deviation ranging from 350 to 560 µm.

Table 1 – Comparison of results for the soundboard sample L1-L6 measurands

	Average value [mm]			σ [µm]		Δ [µm]	
Measurand	CMM	CT	SL	CT	SL	CT-CMM	CT-SL
L1	99.794	99.819	100.144	14	129	26	350
L3	179.654	179.561	180.12	16	75	-92	466
L4	119.782	119.749	120.123	11	77	-33	341
L5	139.755	139.732	140.127	11	47	-23	372
L6	159.54	159.642	160.102	10	33	102	562

Moreover, CT results have a significantly lower standard deviation with respect to SL: CT standard deviations range from 10 to 16 µm, while the SL ones from 33 to 129 µm.

This confirms the good repeatability of CT measurements, and the stability of the environmental conditions during the scanning process.

Uncertainties according to (ISO 10360-2 [5] and ISO 15530-3 [6]). were calculated for all the measurands.

After the uncertainty evaluation, a similar set of measurands was evaluated in a real violin belly: a Nicola Amati (Cremona, 1652), results are reported in Table 2. It is to notice that for each of the measurands of Table 2 the uncertainty U_{CT} is higher when calculated according to the ISO 10360-2. This is because the deviation Δ between CT and CMM measured with the soundboard sample is taken into account into the calculation. On the last columns, uncertainty was calculated using an adapted approach of ISO 15530-3 as suggested in [7,8].

Table 2 – Examples of uncertainty evaluation for f-hole measurands on a real violin

Measurands	Value [mm]	U_{CT} 10360-2 [μm]	U_{CT} ISO 15530-3[μm]
Dinf	9.574	197	28
Dinf	9.824	197	28
Dsup	5.976	163	33
Dsup	5.837	163	33
E	69.286	261	70
E	67.564	260	69
L	4.445	275	22
L	4.655	275	22

4. Conclusions

In this work industrial X-ray CT and LS were investigated as a tool for the dimensional analysis of a violin soundboard. A test sample was conceived in order to include the typical features measured on a violin top plate, and to be tested by the three systems used in this research: CMM, SL and CT.

X-ray CT and LS have proved to be a valid alternative to traditional tactile CMMs for the reverse engineering of bowed stringed instruments.

Experimental results demonstrate that CT provides better results, in terms of measurement repeatability and uncertainty, compared to LS. A major advantage provided by CT is the possibility to extract information on the inner geometries of bowed stringed instruments and to deal with dark and shiny surfaces. This kind of measurement tasks, indeed, are not possible with traditional optical scanners without opening the instrument or altering its optical surface behaviour.

5. Future research

This work represents the first step in the dimensional analysis of stringed instruments by means of industrial X-ray computed tomography. Future development will address the evaluation of different geometrical characteristics of top plates, such as thickness mapping, free form profiles and surface roughness.

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References

[1] Borman T, Stoel B, J. Violin Soc. Am: VSA Papers, Vol. XXII, 2009

[2] Arnoldi, M. J., Smithsonian Institution Scholarly Press. 2016.

[3] Piasentini F., Scanavini A., "Multidisciplinary Approach to Wooden Musical Instruments Identification", Cremona 30/9- 01/10 2014.

[4] S A Sirr, MD, Golden Valley, MN; J Waddle; Radiologic Society of North America. Nov.2011.

[5] ISO 10360-2 (2010). Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) – Part 2: CMMs used for measuring linear dimensions. International Organization for Standardization, Geneva.

[6] ISO 15530-3 (2011). Geometrical product specifications (GPS) – Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement - Part 3: Use of calibrated work pieces or measurement standards. International Organization for Standardization, Geneva.

[7] P. Müller, J. Hiller, Y. Dai, J.L. Andreasen, H.N. Hansen, L. De Chiffre, CIRP Journal of Manufacturing Science and Technology, Vol. 7, pp. 222-232, 2014.

[8] J.P. Kruth, M. Bartscher, S. Carmignato, R. Schmitt, L. De Chiffre, A. Weckenmann, CIRP Annals – Manufacturing technology, Vol. 60, pp. 821-842, 2011.