IMEKO International Conference on
Metrology for Archaeology and Cultural Heritage
Torino, Italy, October 19-21, 2016

Measuring Stradivari violin "Cremonese" (1715) by 3D modeling

Piercarlo Dondi[1,2*], Luca Lombardi[2], Marco Malagodi[1,3], Maurizio Licchelli[1,4]

[1]*University of Pavia, Arvedi Laboratory of non Invasive Diagnostics, via Bell'Aspa 3, 26100 Cremona, Italy, piercarlo.dondi@unipv.it*
[2]*University of Pavia, Department of Electrical, Computer and Biomedical Engineering, via Ferrata 5, 27100 Pavia, Italy, luca.lombardi@unipv.it*
[3]*University of Pavia, Department of Musicology and Cultural Heritage, Corso Garibaldi 178, 26100 Cremona, Italy, marco.malagodi@unipv.it*
[4]*University of Pavia, Department of Chemistry, via Taramelli 12, 27100 Pavia, Italy, maurizio.licchelli@unipv.it*

***Abstract* – Acquiring precise measurements of historical violins is an important task both for researchers and violin makers. Up to now, the measures are taken manually using a caliber, with limitations in the repeatability, since the access to these instruments is restricted and the contact with the caliber has to be limited to the bare essential for avoiding accidental damages to superficial varnishes. In this work we propose a new protocol for the acquisition and creation of high quality 3D models of violins suitable for taking precise measurements. The procedure was applied to Stradivari "Cremonese" (1715) kept in "Museo del Violino" in Cremona. The quality of the result was validated comparing the measures taken on the 3D mesh to those ones taken by the curator of the museum on the original instrument. As a test case the data are then used to confirm the use of the "G" mould for the construction of this violin.**

***Keywords* – 3D scan, measuring, historical violins**

I. INTRODUCTION

An important goal in the study of the morphology of an ancient relic involves the acquisition of precise measurements. This task is particularly valuable in the case of historical violins, not only for researchers, but also for violin makers, that can use these data as reference for the making of their instruments. Up to now, the classic way to measure a violin with precision is the manual use of a caliber. Even if this procedure is standard with modern instruments and can be repeated several times, it can be performed only occasionally on historical ones. This is not only due to the restricted access but also to the need to limit to the bare essential the direct contact with the caliber, in order to not ruin the ancient varnishes or even (in the worst scenario) chip the wood. The varnishes in particular could represent a limit in the application of mechanical measurments, because of their historical importance, brittleness and thickness [1]. Moreover, damages on the varnishes could be a key factor of the material degradations, especially biological ones, with a consequent requirement of a restoration work [2]. A faithful 3D model of a violin can be very helpful in this field. With a 3D model it is possible to repeat several times the measures without risks and also reach areas nearly inaccessible on the original instrument without opening it (e.g. the highness of the belly).

The digitalization of historical relics is becoming a standard practice in many museums and archaeological sites. Different Imaging technologies are available (laser scanner, photogrammetry, stereocams and so on), the final choice depends on the characteristics of the object to acquire [3]. These different techniques may be merged to improve the quality of the reconstructed models, as an example both photogrammetry and 3D scanning were used to create a model of the Donatello's "Maddalena" [4]. Mathys et al. presented a comparison among the different techniques, including also Computer Tomography; as a conclusion the authors suggest to use laser scanners when only external surfaces are needed and Computer Tomography if it is useful to acquire internal structures [5]. Also the possibility to use low cost devices, such as the Kinect, has been demonstrated for the reconstruction of excavation sites [6]. The acquisition of a historical violin is particularly critical, the complex morphology and the presence of a lot of small details require a very high precision in phase of scanning; moreover the presence of highly reflective varnishes made complex or nearly impossible the use of classic photogrammetry techniques. For these reasons, the digitalization of violins are generally obtained by CT-scan. This is surely the most precise existing scanning technology, it can acquire both external and internal surfaces of an instrument and provide important information, such as the thickness of the ribs, or the presence of internal damages and repairs [7]. More recently, the Smithsonian institution adopted the CT-scan for the study of seven Stradivari vio-

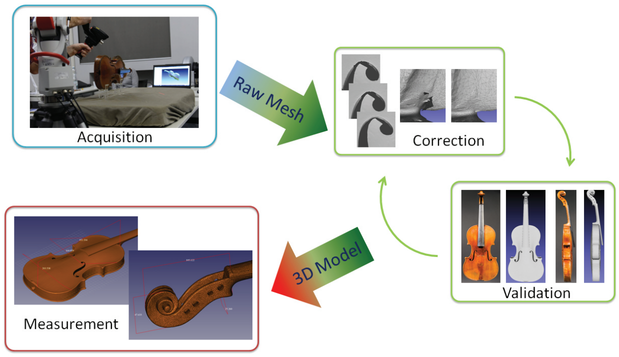

Fig. 1. Overall schema of the proposed procedure of acquisition, 3D modeling and measurement of a violin.

lins and proposed a detailed protocol for their acquisition and modeling. They also demonstrate the usability of such models for measurements tasks [8]. The use of laser scanners is instead very limited, since they can acquire only the external surfaces. Only some notable cases are described in litterature, such as the analysis of elastic deformation performed on Guarneri del Gesú "Cannone" (1734) [9]. However, some advantages of this technology with respect to CT-Scan must not be neglected: it is more affordable; it only needs one people to perform the acquisition instead of a team of experts; it can be used directly in the museum without the need to move the instrument. Moreover, in our field of interest the limitation to the external surface it is not critical, since the most of the important measures involve the outside of the violin.

In this work we propose a protocol for the creation of accurate 3D models of historical violins, suitable to take high precision measurements. The main steps of our workflow are summarized in Figure 1: the raw data were acquired using a high resolution laser scanner and then refined and validated in an iterative way. The procedure was applied to an important instrument held in "Museo del Violino" of Cremona (Italy), the "Cremonese" (1715) made by Antonio Stradivari. A comparison between measures taken with CAD software on the 3D mesh and measures taken with a caliber on the original violin was performed. As a test case, the data obtained are used to confirm what mould was used by Stradivari in the construction of this important instrument. A preliminary description of this last result was previously presented in the celebrative book for the 300° anniversary of the "Cremonese" [10]. In the current paper we provide a more in deep explanation of the procedure adopted.

The paper is organized as follow: section ii. describes the proposed acquisition and the modeling protocol underling the most critical parts and the solutions adopted; section iii. discusses the measurement problem and the comparative tests performed; section iv. describes the checking of the correct mould; finally the conclusions are drawn in section v..

II. Acquisition and 3D Modeling

As previously stated, the complex morphology of a violin and the high reflectivity of the varnishes make difficult the acquisition with a laser scanner. Even if a perfect solution does not exist some characteristics are crucial in the choice of the scanner to adopt: a high level of mobility, in order to reach all the surfaces of the instrument, and a high accuracy, in order to acquire as much details as possible. For these reasons we chose a "RS3 Integrated Scanner" (a linear laser scanner with a stated accuracy of $30 \mu m$) mounted on a mobile arm with 7 degrees of freedom (Romer Absolute Arm 7-Axis "SI") both produced by Hexagon Metrology. The suite Polyworks was used as scanning software and for cleaning the raw data.

Since wood instruments are sensible to abrupt variations in humidity and temperature, that can alter their morphology, the working laboratory was always maintained at the same climatic condition of the showcases of the museum, a temperature of $20°$ and a humidity of 50%. Before the scanning all the mobile parts of the violin that can interfere with the acquisition are removed: the tailpiece, the bridge and the chin rest because they hide part of the belly; the pegs because they partially hide the outer wall and the pegbox floor of the head; the strings because they can alter the light beam of the scanner. Their loss is acceptable, they are not strictly relevant for measurements and generally they are not the original ones (quite all the mobile parts of historical violins have been substituted during the centuries).

We performed a series of tests on sample violins to tune the acquisition protocol. The morphology of the instruments and the limitations of the laser scanner were studied in deep. We identified the most critical areas, the best way to acquire them (or at least the most of them), the errors to avoid, and the typical corrections needed for obtaining a good final mesh. After this tuning phase we applied the procedure to Stradivari "Cremonese" (1715). The instrument was acquired in four steps, generating many partial scans that will be aligned and connected in post-production later: left side of the body, right side of the body, front side of the head, back side of the head. Two supports in Plexiglas, a vertical one (Fig. 2(a)) and a horizontal one (Fig. 2(b)), were designed to place the instrument in the optimal positions for reaching as much details as possible. In particular, the vertical support was used for the body (better for reaching with the laser the internal edges of the f-hole and the part of the top plate under the fingerboard); the horizontal one for the head (better for reaching the pegbox floor, the peg holes and the throat of the scroll).

The resulting cloud of points is cleaned, removing redundant or bad acquired scans. In this phase it must be payed particular attention to the head of the violin, because

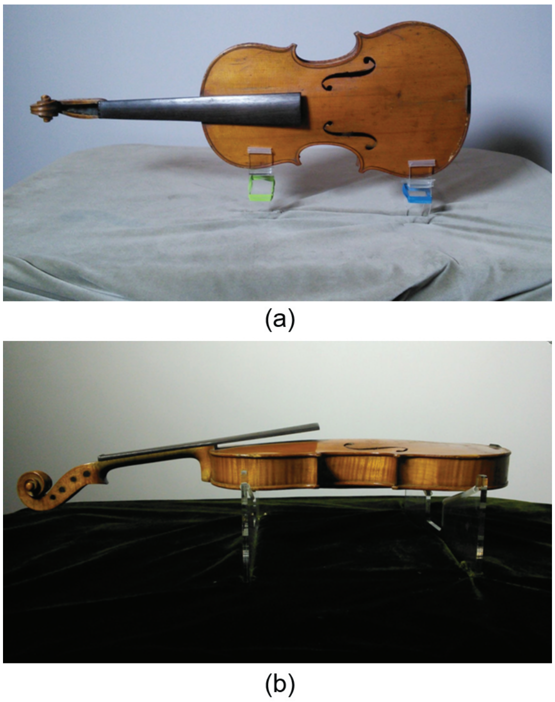

Fig. 2. Supports used during the scanning process: (a) vertical; (b) horizontal.

overlapping scans are very frequent due to its small dimension and to the presence of a lot of details that requires multiple runs. Then, the cleaned cloud of points are triangularized and converted in a raw 3D mesh.

The refinement of the raw 3D mesh was performed by two open source 3D modeling software, Meshlab and Blender. The number of corrections varies from instrument to instrument, it generally depends by the state of the surface in particular the presence of abrupt change in color or of very dark areas can interfere with the laser and produce errors or loss parts. Despite these considerations there are some areas of the instruments that are always problematic to reach with the scanner: the internal part of the head, the throat of the scroll, the internal edges of the f-holes. High resolution images of the instrument, previously acquired with a Nikon D4 camera equipped with a 50 mm objective, were used as reference for the reconstruction of these areas. The procedure is iterative, each correction is validated using the images and the supervision of the curator of the museum and repeated until the level of precision is considered acceptable.

III. MEASUREMENT

Taking measures on a violin is a complex task. The rounded shapes and the not perfect symmetry makes difficult to obtain precise and replicable values. Moreover, the definition of the areas to be measured is not always univocal and can depend by subjective choices. To assess the accuracy of the acquired 3D model, we asked the curator of the museum to take a series of reference measures with a digital caliber on the original instrument. The same measures were subsequently replied (always with the supervision of the curator) on the 3D model using FreeCAD, an open source CAD software. The 25 chosen measures characterize all the main parts of the instrument (sound table, back, ribs, f-holes, head).

Table 1 shows the comparison between the two types of values. The percentage difference (Diff) between measures taken with caliber (M_c) and measures taken on 3D model (M_{3D}) is defined as follow:

$$Diff = |M_c - M_{3D}| / M_c \tag{1}$$

Table 1. Comparison between measurements (in mm) taken on Stradivari "Cremonese" (1715) with caliber and with CAD software on the correspondent 3D model.

Metric	Caliber	3D	Diff %
back length	357.0	357.2	0.06
back max higher width	168.0	167.6	0.24
back min width C-Bouts	112.0	111.8	0.18
back max lower width	207.5	207.6	0.05
table length	355.0	355.1	0.03
table max higher length	167.2	167.2	0.00
table min width C-Bouts	110.0	109.7	0.27
table max lower width	205.5	205.7	0.10
ribs height lower bouts	31.8	31.8	0.00
ribs height lower corners	32.4	32.4	0.00
ribs height upper corners	31.9	32.0	0.31
ribs height upper bouts	30.0	30.1	0.33
diapason	197.0	197.0	0.00
f-holes upper lobes dist.	43.1	42.9	0.46
f-hole notches distance	75.2	75.5	0.40
f-holes lower lobes dist.	112.7	112.4	0.27
f-hole DX length	73.8	73.9	0.14
f-hole SX length	74.8	74.8	0.00
scroll length	104.6	104.6	0.00
scroll eyes width	42.3	42.1	0.47
scroll neck heel	26.0	25.9	0.38
scroll volute height	49.0	48.7	0.61
scroll first turn height	38.4	38.6	0.52
scroll volute top width	11.8	11.7	0.85
scroll max length over nut	25.3	25.4	0.40

As can be seen the quality of the 3D model is high, the percentage difference is generally very low, with a average value of 0.24% and a maximum value of 0.85% in correspondence of the scroll volute top width. Analyzing the data in function of areas of the instrument some discrepancies are evident: on the belly (the combination of back table, sound table and ribs) the average percentage difference is only 0.12% , on f-holes areas it increases to 0.25%

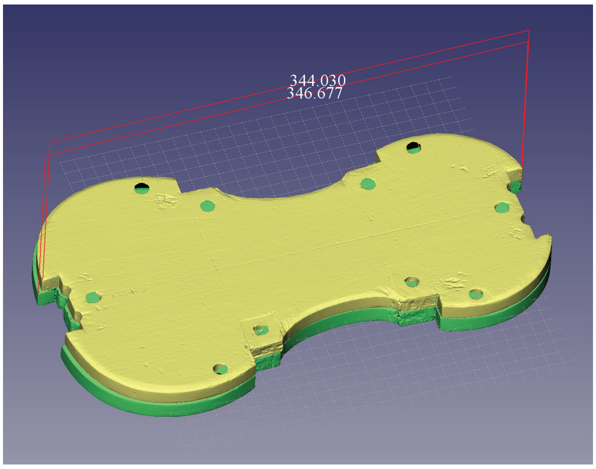

Fig. 3. Comparison between the 3D models of PG (yellow) and G (green) moulds

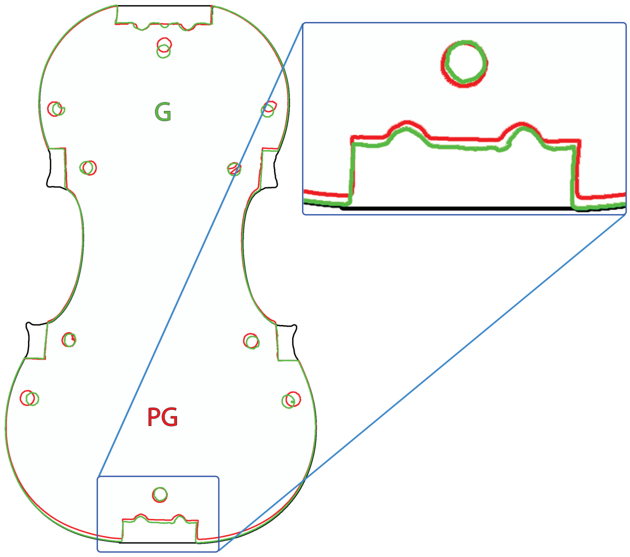

Fig. 4. Comparison among the profiles of the 3D models of "G" (green) and "PG" (red) moulds and the internal edges of the back plate of "Cremonese" (1715) (black).

and on the scroll it reaches 0.46%. This result is expected since the f-holes and the scroll are difficult to acquire completely due to the large amount of small details, thus they need a more in deep reconstruction during post processing phase that can introduces some errors. Moreover, the measures taken on the scroll are in correspondence of the most rounded parts of the instrument, that are difficult to measure precisely even with a manual caliber.

IV. CHECKING OF THE CORRECT MOULD

The comparative tests proved the quality of the 3D model, and in particular of the belly. Starting from this consideration we decided to use the data obtained for verifing what mould was used by Stradivari in the creation of "Cremonese" violin. A mould is a particular wood artifact created by a violin maker and used for the creation of the belly of his instruments. With the same mould it is possible to create many different violins, thus it is important for historians and violin makers try to attribute the correct mould to a historical violin. In the case of "Cremonese" there are two possible candidates, the "G" and "PG" [10], both part of the collection of Stradivari's relics preserved at "Museo del Violino".

The two moulds were scanned with the procedure previously described for the violin; then the resulting 3D models were measured and compared with precision. It can be noticed (Fig. 3) that the two moulds are very closed in width but not in length, the "G" is around 2.6 mm longer than the "PG". Unfortunately, the comparison with the 3D model of the violin is problematic. Since the laser scanner is unable to acquire the internal surface of the violin, we cannot know the thickness of the ribs, thus we need a valid approximation. During the mounting of the violin, the purflings on the back plate tend to overlay to the internal edge of the ribs. This overlaying is not perfect but it is a reasonable approximation in our case, because the two moulds differs among each other more than 2 mm, while the ribs are generally very thin (around 1 mm). However, even with this approximation, we cannot directly use the 3D model. In fact, the purflings are dark areas, thus they are not always perfectly acquired, due to the technical limitations of the laser scanner previoulsy stated. To overcome this issue we used a high resolution image of the back plate of instrument in which the purlings are very evident. The image was acquired with a Nikon D4 equipped with a 50mm lens, following the procedure described in our previous works [11, 12] and then rescaled with precision using the measures previously taken on the 3D model. The profile of the purflings was extracted using a standard image processing filter (Canny's edge detector [13]), and compared with the external profiles of the moulds extracted with Polyworks by the respective 3D models. The overlapping of these three edges are shown in Fig. 4). Both "G" and "PG" fit well to the upper half of the back plate; on the contrary, on the lower half the "PG" is too short (up to 2.0 mm), while the "G" better follows the profile. This result is in accordance with the hypothesis previously made by violin makers on the basis of historical sources [14] and can reasonably confirm the use of the "G" mould for the creation of "Cremonese".

V. CONCLUSIONS

In this work we described a new protocol for the acquisition of faithful 3D models of historical violins, suitable for taking high precision measurements. The proposed approach was used to digitalize the Stradivari "Cremonese"

(1715) violin. The comparison between measures taken with a caliber on the original instrument and on the 3D mesh proved the quality of the proposed method. The measurements taken on the 3D models are then used to confirm the historical hypothesis that Antonio Stradivari used the “G” mould in the creation of this instrument.

The scanning of other precious violins held in “Museo del Violino” in Cremona is currently undergoing. At growing of the data set, comparisons among violins of different ages and violin makers will be possible.

ACKNOWLEDGEMENTS

We would like to thank “Fondazione Museo del Violino Antonio Stradivari”, association “Friends of Stradivari” and “Distretto Culturale di Cremona” for collaboration. A particular acknowledgment to the curator of the museum Fausto Cacciatori. This work was supported by Fondazione Cariplo [Research project “Opificio del Suono”], Regione Lombardia [POR Ob. 2 - FSE 2007/2013 research project No. 61385772 “VIVA MUSICA”] and Fondazione Arvedi Buschini of Cremona.

REFERENCES

[1] C. Invernizzi, A. Daveri, T. Rovetta, M. Vagnini, M. Licchelli, F. Cacciatori, M. Malagodi, “A multi-analytical non-invasive approach to violin materials: The case of Antonio Stradivari 'Hellier' (1679)”, Microchem. J., vol.124, 2016, pp.743 - 750.

[2] M. Clausi, G. M. Crisci, M. F. L. Russa, M. Malagodi, A. Palermo, S. A. Ruffolo, “Protective action against fungal growth of two consolidating products applied to wood”, J. Cult. Herit., vol.12, No.1, 2011, pp.28 - 33.

[3] M. Hess, S. Robson, M. Serpico, G. Amati, I. Pridden, T. Nelson, “Developing 3D Imaging Programmes-Workflow and Quality Control”, J. Comput. Cult. Herit., Vol 9, No.1, 2015, pp.1:1-1:11.

[4] G. Guidi, J. A. Beraldin, C. Atzeni, “High-accuracy 3D modeling of cultural heritage: the digitizing of Donatello’s "Maddalena"”, IEEE T. Image Process., Vol.13, No.3, 2004, pp.370-380.

[5] A. Mathys, J. Brecko, P. Semal, “Comparing 3D digitizing technologies: What are the differences?”, in: Digital Heritage International Congress (DigitalHeritage), 2013, Vol. 1, 2013, pp.201-204.

[6] M. Zollhöfer, C. Siegl, M. Vetter, B. Dreyer, M. Stamminger, S. Aybek, F. Bauer, “Low-Cost Real-Time 3D Reconstruction of Large-Scale Excavation Sites”, J. Comput. Cult. Herit., Vol.9, No.1, 2015, pp.2:1-2:20.

[7] S. A. Sirr, J. R. Waddle, “Use of CT in Detection of Internal Damage and Repair and Determination of Authenticity in High-Quality Bowed Stringed Instruments”, RadioGraphics, Vol.19, No.3, 1999, pp.639-646.

[8] B. Frohlich, G. Sturm, J. Hinton, E. Frohlich, “The Secrets of The Stradivari String Instruments. A Non-Destructive Study of Music Instruments from The Smithsonian Institution, The Library of Congress, and Private Collections. A Pilot Study of Seven Violins made by Antonio Stradivari in Cremona, Italy, Between 1677 and 1709.”, The Materialise Group, Leuven, Belgium and Materialise, USA, Ann Arbor, MI, USA, Washington, DC, March 2009.

[9] M. Fioravanti, G. Goli, B. Carlson, “Structural assessment and measurement of the elastic deformation of historical violins: The case study of the Guarneri ‘del Gesú’ violin (1743) known as the ‘Cannone’ ”, J. Cult. Herit., Vol.13, No.2, 2012, pp.145-153.

[10] F. Cacciatori, M. Malagodi, A. Sarti, “Il Cremonese 1715-2015 - 300° Anniversario”, Fondazione Museo del Violino Antonio Stradivari Cremona, 2015.

[11] P. Dondi, C. Invernizzi, M. Licchelli, L. Lombardi, M. Malagodi, T. Rovetta, “Semi-automatic system for UV images analysis of historical musical instruments”, Proc of. SPIE, Vol. 9527, 2015, pp. 95270H–95270H–9.

[12] P. Dondi, L. Lombardi, M. Malagodi, M. Licchelli, “Automatic identification of varnish wear on historical instruments: The case of antonio stradivari violins”, J. Cult. Herit., 2016, in press.

[13] J. Canny, “A Computational Approach to Edge Detection”, IEEE T. Pattern. Anal., Vol.PAMI-8, No.6, Nov. 1986, pp.679-698.

[14] S. F. Sacconi, “I ‘segreti’ di Stradivari”, Libreria del Convegno, Cremona, 1972.