PHOTOGRAMMETRIC SURVEY OF ANCIENTS MUSICAL INSTRUMENTS

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ABSTRACT:

Today's violin makers try to replicate the characteristics of the best ancient instruments, such as Stradivari's. To this aim, they need templates to replicate the soundboard with as much accuracy as possible. Despite several attempts, surveys with laser scanning did not produce usable results, because the instrument's varnish coating gives rise to multi-path and reflections. Controlling illumination and using a projected pattern to get successful results from image correlation, a photogrammetric survey provided the requested accuracy, in the order of a tenth of a mm, although through careful survey planning and execution. The paper describes first of all the preliminary tests, focussed on trying to avoid spot reflections of the light sources and coping with the changes in the visual appearance of the violin texture from different standpoints by using a PC projector and random pattern. Method to assess the survey accuracy are also discussed. Finally, the results of a Garimberti violin surveyed in Cremona at the International Luthiery School "A. Stradivari" with a Nikon D70 are presented.

1. INTRODUCTION

Non-topographic, close range surveys quite often requires both high accuracy and non-contact techniques; think for instance of biomedical engineering, quality control in manufacturing, archaeology, restoration and preservation of cultural heritage. A rather special case is the survey of ancient musical instruments, with the purpose to produce templates of the soundboard shape. Using such templates, violin makers try to replicate the characteristics of the best ancient instruments, to get the same exceptional sound quality. In Cremona (Italy), where the famous luthier Antonio Stradivari sets up his workshop, production of violins and other string instruments still continues in the tradition of this great master. Old string instruments (especially violins and violas) are studied and their shape carefully reproduced by luthiers.

As far as instrument shape is concerned, the top plate and the back are thought to be the keys element in defining the sound quality, while the violin's ribs are rather the same in all instruments. The focus is therefore on reproducing the two plates of the soundboard. The top plate and the back are made by carefully shaping the wood with a thumb plane; reproducing old instruments therefore requires accurate comparison with templates shaped from the ancient instrument (Gatti, 1999). Several moulds are necessary, derived from longitudinal as well as cross sections of the plates. The accuracy requirements for the templates are generally at the sub-millimetre level; given the size of violins and violas, this translates in relative accuracies of the survey ranging from 1:3500 to 1:10000.

The goal of the luthiers is indeed to perform a sort of "Reverse Engineering" where a numerical model of a physical object is produced. Unlike industrial manufacturing, though, this numerical model is not input to a numerically controlled machine to directly produce the copy of the original. Rather, the numerical model is used to produce the templates needed by the luthiers to refine their work. Cross sections of the top and back plates can be extracted and used to build moulds or templates, either manually or by numerically controlled machine tools. This is obviously safer than the previous manual method used to produce the templates, where the valuable instruments had to be frequently manipulated to check for differences with the template.

Several measuring devices or techniques can be applied today to survey a violin: coordinate-measuring machines (CMMs), optical triangulation systems, laser scanning and photogrammetry. Luthiers would only allow non-contact measuring methods, since they would not let other personnel to handle the instruments nor would permit targeting of any sort directly attached to the instrument. Given the accuracy requirements and the limited size of the instruments, optical triangulation systems and laser scanning should be the ideal candidates to perform the survey: several short range instruments allow accuracies in the order of 0.1-0.05 mm or better.

The authors got in touch with the International Luthiery School "A. Stradivari" in Cremona; there, some experience with different measurement techniques has been gained in the past years. For some time, templates were obtained by profile measurement with analogue and analytical photogrammetry, although with mixed success. Lately, laser scanning systems were also tried. Despite several attempts with different types of scanning instruments, results turned out to be disappointing because of the varnish applied to violins, that gives multi-path and reflections. With too few echo's are actually being true returns from the surface, the acquired point cloud is too noisy to be of any use, although some parts might be correctly measured. As mentioned above, the problems for laser systems come from the combination of the ground and varnish applied to the wooden surface. While the ground is made of a mineral rich mixture, with large percentage of alumina and silica, the varnish is made of oils, oxidized resins and colouring matter. Colour comes also from the addition of lakes, fine coloured particles that remain suspended in the varnish layer, still maintaining the varnish translucid. The violin coated surface therefore is not Lambertian and the reflectance may vary with the incidence angle; not homogeneity in the varnish layer may also cause the absorbance to depend on incidence angle.

The Luthiery school was interested in trying and possibly managing "in house" the survey of violins, given the background in photogrammetry of some of the teachers. It was therefore decided to find out whether digital photogrammetry could provide the 3D reconstruction of a violin soundboard, possibly with a simple procedure that could be managed also by non-professional photogrammetrists.

Of course, the interaction of the light with the varnish coating also affects optical imaging with natural or artificial lighting and therefore photogrammetry. Nevertheless, it was thought that setting up the survey in a properly structured environment could provide photogrammetry with an edge over laser scanning. Although the point density attainable by photogrammetry might be less than that achievable with triangulation systems, a point cloud dense enough to capture the curvature of the soundboard can be produced. The possibility to vary illumination, network geometry, block control and object texture gives photogrammetry more flexibility compare to laser. The violin texture coming from the wooden surface and the treatment with the ground and the varnish should provide enough details for digital image correlation algorithms to find conjugate points. Should this not the case, pattern projection could be used. Some preliminary tests were performed on a violin at the International School "A. Stradivari" as well as at the Politecnico lab in Cremona; finally, a Garimberti violin was surveyed at the Luthiery "A. Stradivari".

The paper is organized as follows: section 2 discusses the survey setup of the various preliminary tests, stressing the problems met and how they were dealt with; section 3 presents the algorithms used in surface reconstruction; section 4 discusses some results on the surveying quality (namely repeatability and completeness). In the last sections, results on the survey of a Garimberti violin are shown, before drawing conclusions and perspectives.

2. SURVEY SETUP

As pointed out above, rather than the whole violin 3D model, what is actually required is the shape and the curvatures of the two arched plates, to produce cross and longitudinal sections. The soundboard can be roughly enclosed in a box of about 35 x 20 x 5 cm in size. Besides planning the camera stations network and providing block control, the most important problems to face are controlling illumination, assessing whether the natural texture provides dense and reliable interest points or provide artificial texture, ensure quality assessment and completeness of the 3D reconstruction.

2.1 Camera stations network

The surface reconstruction being restricted to the top and back table, camera stations were set in two symmetric arrangements, one for the top plate, the other for the back plate, with the violin kept vertical. In each arrangement, stations were set along three vertical lines, one in front of the violin, the other two on the left and right side, with camera axes slightly convergent. A Nikon D70 camera with resolution of 3000x2000 pixels and pixelsize of 7.8 micrometers was used. In the first test, three images per vertical line were acquired with a 90 mm lens; the baselines was about 0.75 m and image scale about 1:17. This provided a strong network geometry and accuracy potential (see Table 1), but didn't lead to a successful 3D reconstruction: the matching algorithm found very few good conjugate points. It was thought at first that the reason was a too large viewpoint change for the l.s.m. to accommodate it: therefore, in a second test, the baselength along each vertical line was much reduced. Three image sequences, with 5 cm baselength at an average object-camera distance of 0.5 m were taken with a 20 mm lens. The idea was to perform the automatic image sequence orientation in each vertical row: again, despite the small baselength, very few matches were found between images 15 cm apart (three baselengths). The change in focal length and the different base-to-distance ratio make the theoretical accuracy worse than in the first test, but were necessary to include the targets on the wall and to gain depth of field.

In the final survey, four image pairs with a vertical base of about 10 cm were taken from four alignments (two for the top, two for the back plate) with slightly convergent images; a 20 mm lens at about 0.5 m distance was used. A random pattern was projected on the violin; this ensured an even distribution of good quality matches that, with a measurement accuracy around 1/5 of a pixel, is close enough to the accuracy requirements in object space.

Table 1 resumes the characteristics of the different survey setups; assuming an accuracy in image space of 1/5 of the pixel size (see §2.4) the theoretical accuracy in depth is computed from the normal case error propagation, neglecting the residual orientation errors.

Survey	**c** [mm]	**Z** [mm]	**B** [mm]	**mb**	**σ_pix** [μm]	**σZ** [mm]	**Site**
Test1	90	1500	750	16.7	1.56	0.05	Luthiery
Test2	21	500	100	23.8	1.56	0.19	PolitecnicoLab
Final	21	510	126	24.3	1.56	0.15	Luthiery

Table 1 – Theoretical accuracy in depth with three different survey setups (normal case)

2.2 Testfields: targets, block control and block orientation

Since the camera network is in fact made of two separate blocks, unless it is accepted that the top and back plates are reconstructed in different reference systems, there is clearly need for targets outside the violin body, to connect the front and rear blocks. To design and place such targets some constraints must be considered. Due to the large image scale, the target size should be small; since targets must be visible from nearly opposite directions, they must be either of spherical shape or of negligible thickness. Putting some targets in the foreground would disturb the later stage of surface reconstruction by dense matching; therefore their location is to be confined to the sides only, providing little depth information and uneven coverage of the image format.

Conjugate points are also necessary on the violin surface, to improve relative orientation of image pairs used in the surface reconstruction and to provide the seed points for the dense matching (see §3.2)

As far as block control is concerned, theodolite measurements may provide relative accuracies of the same order or better than photogrammetry in this scale range, but unless rather special targets are devised, it is far from ensured that this potential can be exploited. Besides, since the survey of the most valuable violins is to be performed at the Luthiery, a sort of "portable" testfield is necessary. Two different setups for block control were therefore tested: one at the Politecnico lab, the other at the School of Luthiery.

At the Politecnico lab, a camera calibration testfield is available; it consists of about 150 theodolite-surveyed targets attached to a wall and to several wires, tensed between the rods of a metallic frame. Small spheres (2 mm in diameter) are attached to the wires to add depth to the testfield. Targets and spheres were surveyed with theodolites to an inner precision of a few hundreds of mm; since the measurement of distances could not be better than 1 mm, this affects the scale factor accuracy.

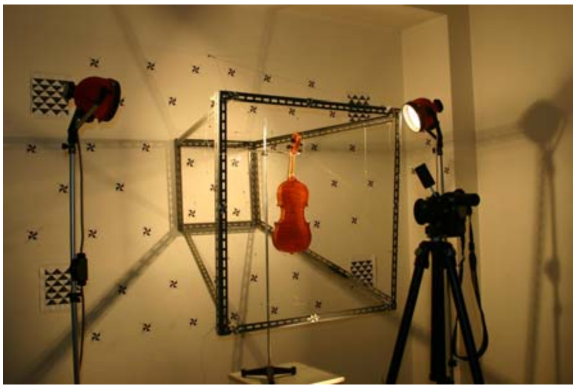


Figure 1. The Politecnico lab testfield

At the Luthiery "A. Stradivari", as already mentioned, no permanent set up of a testfield was possible. Therefore, just four wires, each carrying several small flags, could be used to provide tie points and connect the front and rear block. The wires were put in place at the sides of the violin, in such a way that were non-coplanar. A ruler was suspended nearby, to provide for the object scale.

Figure 2. The Garimberti violin with pattern projection at the International Luthiery School "A. Stradivari"

2.3 Image orientation

Image orientation was performed manually, with Photomodeler™, in all tests and in the final survey, as far as targets were concerned. The number and spatial distribution of the targets were enough to ensure a stable block orientation for the images taken in the Politecnico lab (on average, each point was surveyed in 18 images); additional points on the violin body had to be measured on the images taken at Luthiery "A. Stradivari". In both cases the RMS of the residuals was in the range 0.4-0.6 pixels, i.e. 3-4 micrometers.

2.4 Illumination

Illumination, as expected, is the main problem affecting the survey. Three different setups were tried: indirect illumination from neon lamps; direct illumination with halogen lamps; projection of a pattern with a PC-projector and neon illumination for the surrounding (i.e. the targets and the ruler). With convergent images, bright spot reflections are almost unavoidable in some of the images, due to the specular component of the violin surface reflectivity; changing the lamps position during image acquisition gets rid of such spots, but makes on the other hand more difficult to get a good match between homologous regions, because of the different illumination.

Strong illumination with halogen lamps placed at the sides of the violin (see Figure 1) did not gave rise to reflection spots, but the heat coming from the lamps may damage the violin.

Apart from the bright spots, the interaction of varnish with illumination gives raise to a more serious problem, causing changes from image to image that cannot be explained by just the different perspective. As pointed out above, this is presumably due to the light path in the varnish layers, that cause the same violin patch to vary from image to image depending on the viewing angle. As can be seen in Figure 3, some patches look rather different under different viewing angles.

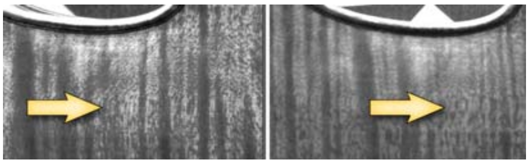


Figure 3. Images of two homologous regions may look quite different, despite surface smoothness

The problem showed up when, after a preliminary manual image orientation, a dense matching algorithm was applied to a pair of images: few points were successfully matched with large areas with any matches at all; varying the template size brought little improvement. It was thought that perhaps the natural texture of the violin might be inappropriate or insufficient for the matching. To find it out while checking the feasibility of the photogrammetric reconstruction and assessing its expected accuracy, a simulation was performed.

2.5 Tests with synthetic images and pattern projection

To evaluate the quality of the survey, especially in terms of accuracy, is not trivial. A theoretical accuracy estimate, useful also in survey planning, can be obtained by variance propagation from the photogrammetric measurements to the object coordinates; this value linearly depends on the measurement accuracy of image coordinates, i.e. the accuracy of least squares matching. The accuracy estimates from the l.s.m itself are very often quite optimistic, so an alternative evaluation method was sought. The idea was to generate a synthetic version of the violin, with photorealistic texture, with the same imaging geometry as the real survey. By performing the photogrammetric 3D reconstruction of the object from the images, a true error in object space can be computed and, by inversion, the actual accuracy of the image measurement error (i.e. the accuracy of l.s.m.) can be inferred.

To this aim, the 3D model of a violin was obtained and draped with the image texture from the images taken in the preliminary survey. From this photorealistic model, a sequence of synthetic images was generated, setting the surface reflectance properties as lambertian and the illumination as neutral; the relative geometry of the simulated camera stations was slightly different from the final one adopted in the real survey, but this does not affect very much the estimate of the matching accuracy.

Using a parallel dense matching algorithm, about 840.000 points were matched and triangulated to get object coordinates from the known exterior parameters; their distance from the known object mesh was computed to assess the accuracy of the point determination. The reconstructed surface matched the model with an average error of a few hundreds of mm; therefore, the accuracy in image space of the l.s.m. was estimated to be around 0.2 pixel, a value rather good for natural surfaces.

This result showed from one hand that the information content of the violin natural texture is fine for surface reconstruction; on the other hand, it also implied that the light path in the varnish may cause it to vary from image to image in a way that the matching algorithm cannot model. To proof that, a new series of images was taken, with better lighting control and with the projection of a random pattern on the violin using a PC-projector. While the matching was successful on the images with projected pattern, significantly fewer points could be matched on the images with natural texture only. As it can be seen from Figure 4, the superimposition of the random pattern effectively overlays the natural texture and homologous regions actually look similar.

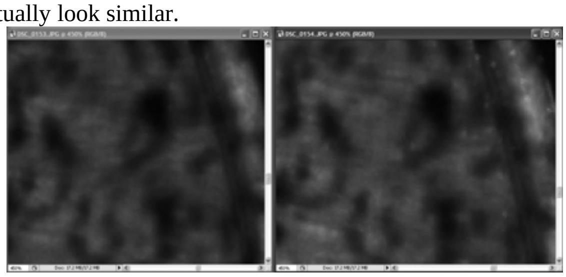


Figure 4. Two homologous regions with pattern projection

3. SURFACE RECONSTRUCTION

The top and back surface of the violin are obtained by combining a point cloud from dense stereo matching, conveniently smoothed using bicubic patch-wise functions, with the edges contour.

3.1 Dense matching

The violin surface is reconstructed from a point cloud generated by a dense stereo matching algorithm with the software program DenseMatcher developed at the University of Parma. The algorithm (Roncella, 2006; D'Apuzzo, 2003) is based on a parallel method, where each new matched point does not depend on the previous ones. Images are resampled to remove lens distortion and epipolar images are generated. The process can be executed along several levels of an image pyramid, if necessary.

A grid of seed points is required to start the process; with smooth objects, normally the tie points determined from the bundle block adjustment are enough if they roughly define the object shape. This was also the case with the violin, discarding the targets and measuring conjugate points along the table contours.

In DenseMatcher the seed points are first back-projected in the images; their position in the slave image is refined by least squares matching and their object coordinates computed again by triangulation with a direct algorithm (Cooper and Robson, 1996). From the seed point coordinates, a Delaunay triangulation is built to approximately describe the object surface and compute a disparity field to start the match; if necessary, also approximations for the l.s.m. shaping parameters can be computed.

3.2 Smoothing by multi-patch surface approximation

The actual violin surface being rather smooth, the sections taken by the 3D model should enjoy the same property, i.e. a certain amount of smoothing is necessary to remove noise from the point cloud. Moreover, despite the epipolar constraint, the point cloud from the dense matching still contains some gross errors and shows patches with higher noise level than the average. To get a smooth surface and to make up for these inconsistencies, an interpolation surface is generated importing the point cloud in a 3D modelling environment and, after triangulation, a grid of nodes is manually set over the violin surface by picking mesh vertices. From this grid, surface patches with bicubic functions can be estimated, to better approximate the violin surface. The choice of the grid parameters and their effect on the computed surface should also be considered, to balance between forcing a larger than desirable smoothing and not removing enough noise. In the following, this aspect has not been considered.

3.3 Contouring the outer edges of the plates

Both the top and the back tables of the violin end with a rather smooth curvature, shaped in a way unique to the violin maker; the tables outer edges on the contrary are highly curved, with a radius of curvature of a few mm only. Few points are successfully matched on these edges; this, combined with some matching errors, makes it difficult to define the border of the two surfaces to complete the 3D reconstruction with the bicubic functions approximation. To make up for this, the edges were traced manually measuring a series of points, both on the belly and on the back. The point sequence was interpolated within Photomodeler, also enforcing the planarity of the curve.

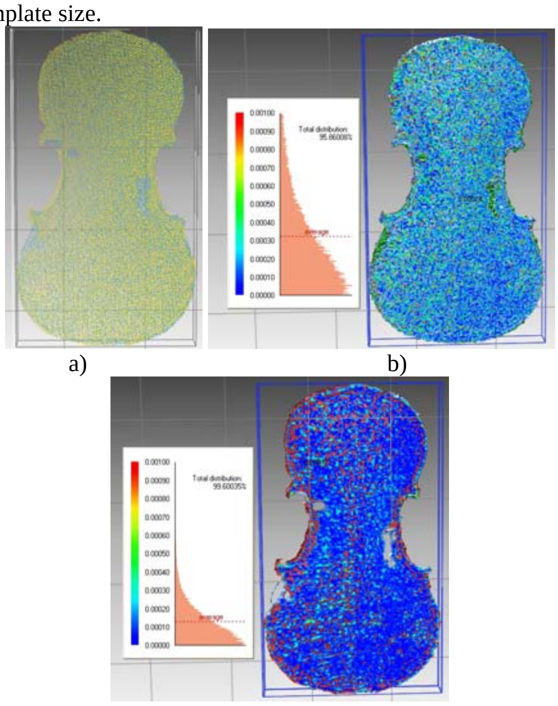
Besides, points of the point cloud were selected in buffer 1 cm wide along the plates border. This set of points was selected to estimate in a l.s. adjustment a plane, that is (hopefully) a good approximation of the table outermost contour.

Since the points of the manually measured curve may not actually belong to that plane, they were projected on the estimated plane.

4. RESULTS OF PRELIMINARY SURVEYS

Some tests were performed, with and without random pattern projection, to assess the influence of the template size on the results as well as the repeatability of the survey. To this aim, the template size was increased from 7x7 to 35x35 pixel and the point cloud was triangulated in a 3D modelling environment, comparing the number of successfully matched points, their distribution and the average distance between pairs of triangulated surfaces. As template size grows larger, the differences tend to be smaller both on average and dispersion.

As a general remark, the number of points successfully matched does not vary too much. Using small templates yields as expected a more noisy surface but on the other hand, less or smaller holes open in problem areas. Larger templates yield a triangulated surface that looks smoother but, without the random pattern projection, large areas do not get acceptable matches. Figure 5 and table 6 summarize the effect of changing template size.



a) b) c)

Figure 5 – Dependence on template size. Figure 5a: posting of 7x7 template size points (blue) against that of 35x35 template size (gold); Figure 5b: discrepancies between the meshes obtained by 7x7 and the 19x19 templates; Figure 5c: discrepancies between the meshes obtained by 19x19 and 35x35 templates.

	mean [mm]	st.dev [mm]
7x7-19x19 - Figure 5b	0.32	0.35
19x19-35x35 - Figure 5c	0.12	0.14

Table 6 – Statistics of the comparison between meshes obtained from dense matching with different template size

5. THE SURVEY OF A GARIMBERTI VIOLIN

Ferdinando Garimberti (1894-1982) taught at the International Luthiery School of Cremona from 1963 to 1966; his instruments, meticulously crafted, won important awards at the exhibitions for their style. He clearly preferred to fashion the backs out of one piece of carefully selected wood. He applied the varnish with great skill; this varies in consistency and colour, from a beautiful red-orange which sometimes becomes lighter towards the centre but is sometimes a darker red. He also did much repair work and was considered an expert in old Italian violins.

As anticipated, the survey of the Garimberti violin was performed at the Luthiery, under the supervision of the School staff. Orientation was performed manually, using both targets and natural points on the violin. Figure 7 shows the camera stations and the tie points used in the orientation. Only the left and right pairs with largest baselength have been used for surface reconstruction. The position of the projector was changed between the left and right images, in such a way that the surface reconstruction the front and back table can be executed independent of the other. This is obvious as far as dense matching is concerned, but also to a large extent for the orientation, since tie points on the violin are not the same for left and right images. A 35x35 template has been used in the reconstruction; although less noisy, large templates lead to errors close to the table edges.

The accuracy of surface reconstruction cannot be determined, because of the lack of reference data. To provide at least an indication of the reconstruction quality as well as of the effect of the smoothing by bicubic interpolation, the point clouds from the left and right image pair of the violin back table were compared. The comparison left-to-right is meant to provide an indication of the repeatability of the survey (and so, to some extent, of the inner accuracy). The comparison mesh-to-surface, on the other hand, will highlight the amount of smoothing introduced by patch-wise approximation.

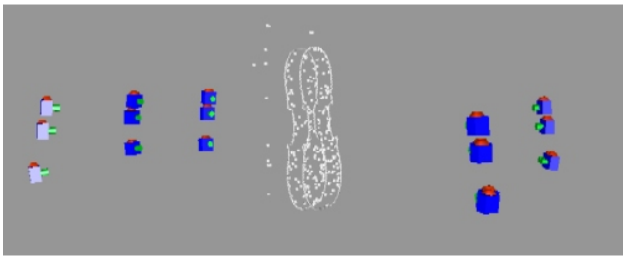


Figure 7 – Camera stations and tie points in the survey of the Garimberti violin

Figure 9, 10 and 11 show the results of the surface reconstruction for the back table and Table 8 resumes the main statistics. The colour map of the signed differences between the meshes and the surface coming from the triangulation of the left point cloud is pictured in Figure 9. It shows the smoothing operated by the bicubic approximation. As it can be seen, the largest discrepancies occur at or close the edge; the average distance between the two surfaces, as measured by the RMS of the discrepancies, is rather high compare to the expected noise level. Figure 10 and 11 show the comparison of the 3D models from the left and right point clouds, after mesh alignment with an ICP algorithm. Alignment was performed because, as pointed out, no tie points on the violin surface are common to the two photogrammetric models and the outside targets are not enough for an accurate orientation. As can be seen, general trend of the discrepancy looks similar, but the pattern is smoother in Figure 11; the average magnitude of the distance between the surfaces (i.e. the measure of repeatability) improves from 0.43 to 0.25 mm.

	RMS[mm]
Leftmesh-to-Leftsurface	0.32
Leftmesh-to-Rightmesh	0.43
Rightsurface-to-Leftsurface	0.25

Table 8 – Statistics of the comparison between meshes and surfaces obtained from different image pairs

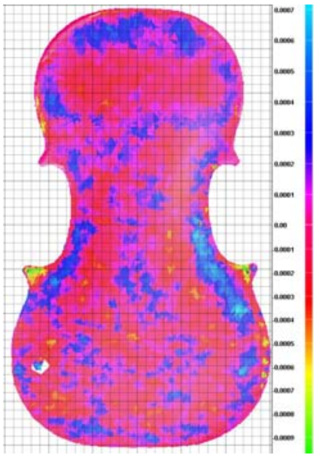


Figure 9 – Discrepancies between the surface and mesh coming from the dense matching with right images.

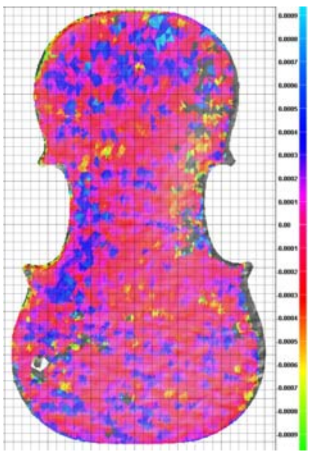


Figure 10 – Discrepancies between the meshes coming from the dense matching with left and right images.

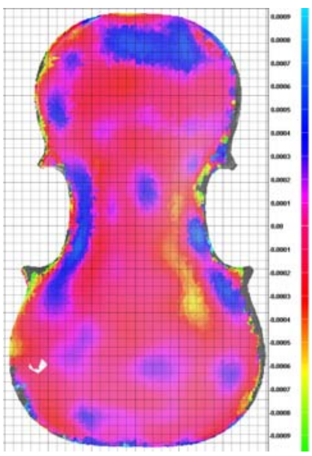


Figure 11 – Discrepancies between the interpolated surface coming from the dense matching with left and right images.

As far as the completeness of the reconstruction is concerned, the violin edge could not be reconstructed by the l.s.m. results; this is partly due to the large template size and to the different background of template and patch on the very edge pixels. Despite including the manually measured curve on the mesh, matching errors remain and are not effectively smoothed. Moreover, some reflections from the projector lamp still hinder a correct convergence of the l.s.m., leading to gross errors or to data holes.

6. CONCLUSIONS AND PERSPECTIVES

As for laser scanning, the main problem in the photogrammetric surface reconstruction of musical instruments is the varnish coating. Despite several attempts to vary illumination, only the projection of an artificial pattern allowed the l.s.m. to successfully find conjugate points. As far as survey quality is concerned, the repeatability of the surface reconstruction from independent surveys, as expressed by the average distance between two surfaces, is in the order of 0.2 mm. The completeness of the survey, on the contrary, has not yet been achieved in a satisfactory manner. The main problem here is how to track the top and back edges of the violin table. Although an empirical solution has been proposed, it is far from ideal, since there is no way to check its reliability and accuracy. Further work is still necessary either at the modelling level, to improve the choice of the functions and reduce noise and gross errors enforcing the regularity of the surface. Constraints should also be introduced in the l.s.m. for edge pixel, to reduce measurement bias.

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