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Digital Cultural Heritage

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Editor
Horst Kremers
CODATA-Germany
Berlin, Germany

ISBN 978-3-030-15198-0 ISBN 978-3-030-15200-0 (eBook)
https://doi.org/10.1007/978-3-030-15200-0

Library of Congress Control Number: 2019935838

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

The Integrated Survey of the Pergamum by Nicola Pisano in the Cathedral of Pisa

Giovanni Pancani and Matteo Bigongiari

Abstract (M.B.) The paper deals with the methodologies and development of digital survey protocols and uses the Pulpit of the Cathedral of Pisa as the case study. The documentation project of the pergamum has forced to face the morphological complexity of this sculptured architecture: the wealth of decorations, sculptures, panels, columns and caryatids, which make the monument unique, likewise increase the complexity of reproducing a 3D model that describes its morphological and material characteristics. A first database of point clouds had already been made in the past years Pancani (Piazza dei Miracoli a Pisa: il Battistero. Metodologie di rappresentazione e documentazione digitale 3D, 2016 [1]); these measurements were made using a terrestrial laser scanner Z + F 5010C with integrated camera: these measurements were made with a Z + F 5010C terrestrial laser scanner with an integrated camera, performing 15 high-resolution scans around the pergamum. The result obtained however was not excellent: the limit of this model is the lack of shooting points at different altitudes, which led to have the pulpit described in its main dimensions; however the static nature of the instrument has created a cloud of points with numerous areas of shade, especially in the portions at the top of the monument, which do not allow to appreciate its sculptural qualities. Recently, the problem of the documentation of the Pergamum has been tackled a second time, trying to analyze the errors of the past experience in order to obtain a reliable and complete 3D model. For the purposes of the research the problem was divided into two different points of view: the morphological and metrically more reliable survey with laser scanner instruments; the realization of a three-dimensional textured model obtained with SfM technologies; since both methodologies work with point clouds it is understandable that it is possible to dialogue between the two databases; in fact the laser data can be used to check the error of the photographic one. A new laser scanner measurement campaign was carried out to follow the methodological protocols developed in recent years of scientific activities by the research group

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H. Kremers (ed.), *Digital Cultural Heritage*,
https://doi.org/10.1007/978-3-030-15200-0_25

coordinated by the writer Pancani (La Città dei Guidi: Poppi. Il costruito del centro storico, rilievi e indagini diagostiche, 2017 [2]). In addition to controlling the quality of the data collected during the acquisition phase, particular attention was focused on the recording phase of the obtained points clouds. In the attempt to define procedures to guarantee the reliability of the general point cloud, the certification phase of the survey was carried out. The database constitutes the metric and morphological basis on which to base all the following phase of realization of the photographic model: the use of SfM technologies today allows to create 3D point cloud from the alignment of the various photographs, not creating a model in metric scale, but based on the size of the acquired pixels; this procedure allows in the acquisition phase to take frames from different points of view, easily and quickly succeeding in integrating the shaded parts otherwise present in the laser scanner survey; the development of the calculation algorithms of the programs has led today to have clouds of increasingly reliable points and comparable to laser instruments Gaiani (I portici di Bologna Architettura, Modelli 3D e ricerche tecnologiche, 2015 [3]). For the survey of the pulpit it was necessary to define reliability protocols during the phase of acquisition of the frames, so as to guarantee the correct definition of the final texture to be applied to the model, and to check the error of alignment of the photographs. Because of the complexity and size of the clouds of points obtained it was considered useful to manage the creation of the 3D model in programs for the management of mesh models, to be able to manage the large amount of morphological information, control the size and number of triangles to obtain and optimize the mesh eliminating any errors due to digital noise. Finally, the 3d model was texturized, obtaining a high definition mapping model of the whole object.

Keywords Laser scanner survey · SfM survey · Integrated digital survey · Pisa's pergamum · Giovanni pisano

1 Introduction (G.P.)

The research project on the documentation of the monuments of Piazza dei Miracoli in Pisa has involved the Department of Architecture (DiDA) of the University of Florence for years and has been and continues today to be an opportunity to experiment with the latest and current useful technologies to the morphological description of an architectural object [1]. It is precisely in this area of research that Giovanni Pisano's project for the survey of the pulpit is included; the ambo that had been commissioned to Giovanni replaced a previous one, made by Guglielmo (1157–1162), who was sent to the Cathedral of Cagliari, which at that time was dependent on the archbishop of Pisa. Giovanni Pisano's pulpit was finished by 1310 and survived the great fire of the Cathedral on 25 October 1596. During the restoration works, between 1599 and 1601, the pulpit was dismantled and its pieces were placed in different places, including the Campo Santo and the Opera della Primaziale warehouses. It was not repositioned until 1926, when it was rebuilt in a different position from the

Fig. 1 Digital reconstruction, obtained from SfM survey of the Pergamun made by Nicola Pisano

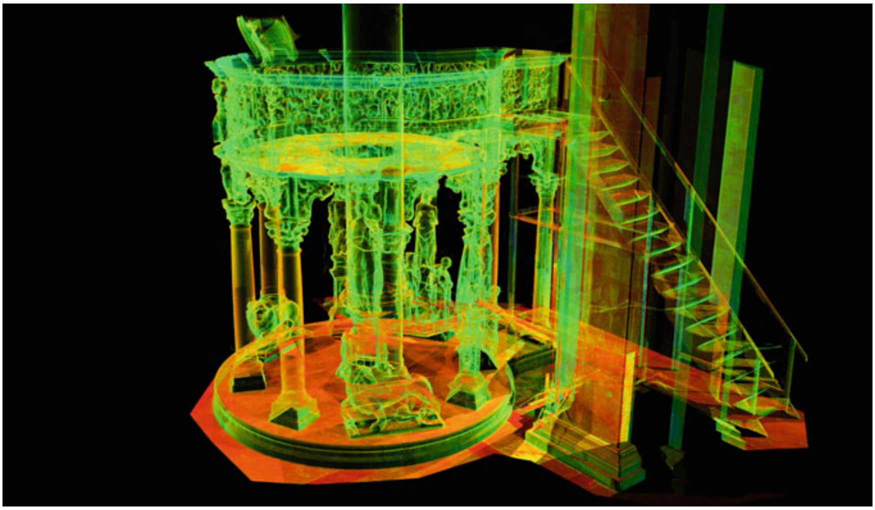

Fig. 2 3D point cloud of the Pergamun realized with laser scanner technology

original one and, certainly, with the parts not in the same order and orientation as it was intended by the author, since there was no documentation of how it was the arrangement of the various elements, including the panels, before dismantling. It is not even known whether he possessed a marble staircase or not. The four "simple" columns were donated by Mussolini because after the reconstruction some pieces (like the staircase) were missing. To honor the Duce these columns were put in plain sight, placing the caryatids in the rear part, less visible, when, it is supposed, it should have been exactly the opposite (Figs. 1 and 2).

2 Laser Scanner Survey

2.1 The Acquisition Phase (G.P.)

The laser scanner survey of the Nicola Pisano's pulpit required careful planning before fieldwork. First of all it was necessary to define the acquisition scale suitable to represent the object of the survey; due to the great presence of a sculptor, the definition scale of 1:20 was chosen.

It is appropriate at this time to introduce the concept of resolution of the survey [2]: since the remote sensing instruments make a massive measurement, not discretizing the points useful for the graphic rendering, the resolution consists in the density of the points measured by the instrument; to be more precise, it consists in the distance between the points of the acquisition mesh, which must be designed in relation to the distance between the instrument and the object of the survey, to guarantee the necessary definition.

Ensuring the adequacy to the chosen scale of values means obtaining a datum that satisfies and ensures tolerances in the measurement [4]: in the case of the 1:20 scale the permissible error must be within a range of 4–6 mm (Fig. 3).

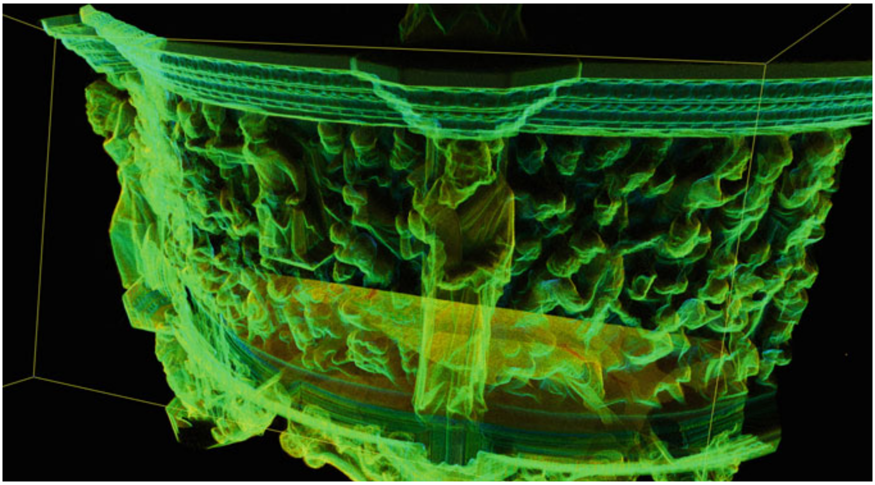

Fig. 3 Detail of the point cloud made with the laser scanner; the high resolution of the survey is shown

The laser scanner survey was therefore designed to ensure compliance with these definition parameters; for these reasons the scans were set at a higher density than what is now normally used for architectural surveys, usually drawn in a scale of 1:50 [5]. The instrument used, a Z + F Imager 5010c, has the technical characteristics to be able to provide point clouds with the density and quality required (the nominal error on the single measurement at 25 m is less than one millimeter); given the geometric conformation of the object to be detected, 25 scans were designed positioned around the pulpit at a distance never exceeding 5 m. Each scan was made at 360° with a resolution of 6 mm to 10 meters away from the point of acquisition, a distance that guarantees the proper definition of the lower part but not so much in the highest points. To avoid accuracy problems, it was decided to densify the acquisition mesh of the single scans bringing the 3 mm resolution mesh.

The individual scans acquired the morphological datum (X, Y, Z) with the intensity value of the single points, and furthermore, through the integrated camera of the scanner, the photographic images were acquired providing the RGB value at each point of the cloud [6].

2.2 *The Registration Phase (G.P.)*

The scans made around the monument create a single point cloud with polar coordinates whose origin is fixed in the laser beam receptor; to obtain a total point cloud, which describes the object of the survey, it is necessary to carry out a rigid roto-translation of the single positions on one of them; this sets its own as a reference coordinate system of the general model (Fig. 4).

This process, called registration of point clouds, is performed by recognizing homologous points between two consecutive scans (Rinaudo in Pancani 2017). The evolution of point cloud management software has led to a progressive change of cloud registration techniques: at first the registration was done with the use of targets, then with the evolution of the software and instruments, which acquire more and more quickly a large amount of information, the scans are registered by overlapping points. This method has been made quick and functional thanks to the user friendly interface of the programs that allow today to rotate in real time one scan on the other [7]. This system brings numerous advantages both in terms of reliability (when there are so many overlapping points with a very dense mesh the registration is not based on just three points/targets but on millions) and of speed (they do not have to be given anymore alphanumeric codes to the targets, a very time-consuming process [5]). Furthermore, by not using targets during acquisition, field work is considerably reduced, because it is no longer necessary to study the positioning of the remarkable points.

Through the visual alignment procedures, the 25 scans were combined into a single registration group, the optimization of the cloud constraints obtained from the pre-alignment process made it possible to obtain a much more reliable data. Since the object has a circular morphology and the scans have created a closed polygonal

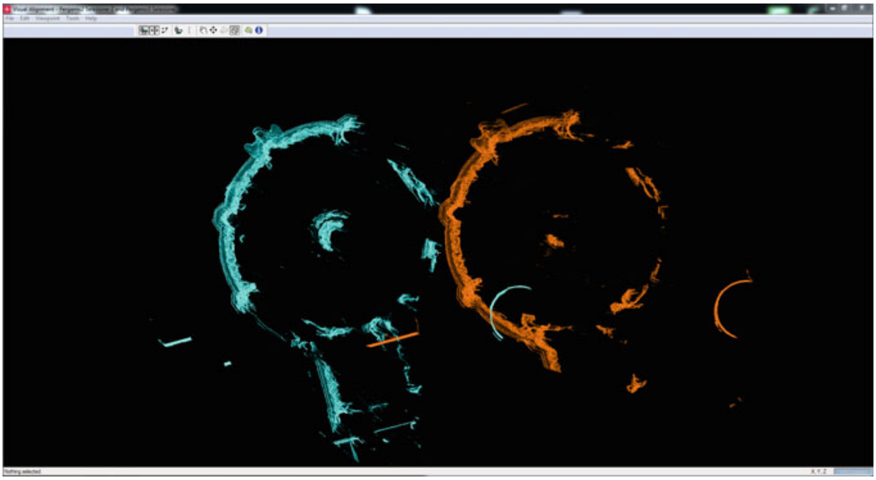

Fig. 4 Visual registration of two point clouds: the cyan one has to be moved over the orange one to complete the registration

scan position, it has been possible to obtain a recording where the single errors, that are inevitably obtained in uniting a scan to the next one, although minimal, have been compensated from the closure of the perimeter of the polygonal.

2.3 *Testing (G.P.)*

When it comes to the reliability of the digital survey, it is necessary to distinguish between instrumental accuracy and that of the definitive model that gathers all the scanning stations; while the instrumental accuracy is defined by statistical parameters coming from accurate laboratory tests, and is therefore to be considered reliable on every single scan, it is certainly improper to base on the same numerical data, which characterize the single scan, the general registered model (Fig. 5).

The verification of the recordings can not even be based only on the data coming from the software registration panel: they define for each cloud constraint used an alignment error (usually between 4 and 20 mm when the registration was successful), but this is not a usable datum because it is derived from the average of the movements of all in points that compose the single scan, calculating in this way also the possible digital noise spots or the thin surfaces that can mistakenly be assimilated (the case of grass and vegetation is exemplary).

There are no regulatory protocols to evaluate the quality of registrations of point clouds, which is why for several years the Survey Laboratory's research focuses on the definition of appropriate methodologies for testing and verifying the correctness and reliability of the registered model [2, 5].

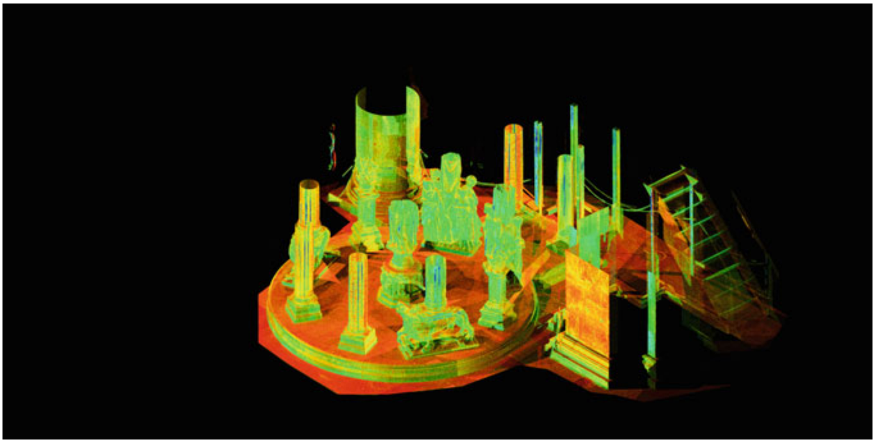

Fig. 5 The laser scanner point cloud is cut to investigate the slices of the sections

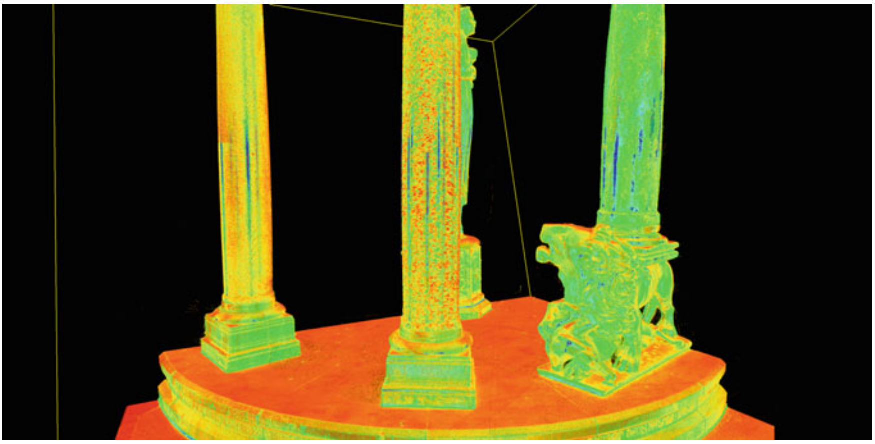

Fig. 6 The laser scanner point cloud is cut to investigate the slices of the sections

The solution adopted to quantify the error value in the registration of the scans is based on the verification of the distance between the section slice, each belonging to a different laser scanner station. The three-dimensional point model is cut from vertical and horizontal planes in different points, to investigate the remarkable points in which it is considered more probable to see a misalignment: more attention is given to the edges, the moldings and so on. The distance between the section slice of the models is now measured and when it occurs that this value is greater than the tolerance allowed by the survey definition scale, it means that the registration is not sufficiently reliable and needs to be improved (Fig. 6).

To ensure a reliable registration, it is necessary to check each individual rototranslation operation, therefore every single cloud constraint realized: only by proceeding carefully to the verification of the sections it is possible to guarantee a final model within the tolerances of the return scale.

2.4 Results and Problems of the Laser Scanner Survey (G.P.)

The laser scanner survey obtained from the 15 stations corresponded to the tolerance parameters required for the 1:20 scale of representation, nevertheless the result obtained was not completely satisfactory (Fig. 7).

First, by analyzing the RGB data coming from the instrument's integrated camera, it was noted that for the individual scans the color of the points could be considered satisfactory, but it was not equally appreciable for the registered model: switching from the intensity display mode to the RGB data, the point cloud suddenly became very confusing and its morphology was not easily understandable; this fact was caused by the strong differences in lighting in the cathedral that led the integrated camera to make frames at very different exposures depending on the surrounding conditions; in this way joining points with different exposure the data became very confused.

Secondly, the digital model appeared to be excessively noisy with evident echoes in the limit points (in edges or in curved surfaces where the laser beam strikes in a tangent direction): probably the choice of a single beam interferometers instrument (single beam) is not optimal during the acquisition phase to record the data of surfaces as complex as the sculptures.

The laser scanner scans presented some problems in the ability to describe the complex morphology of the monument. There was not a scaffold to scan from the top so the instrumental height was almost fixed; since the scans from altitudes around

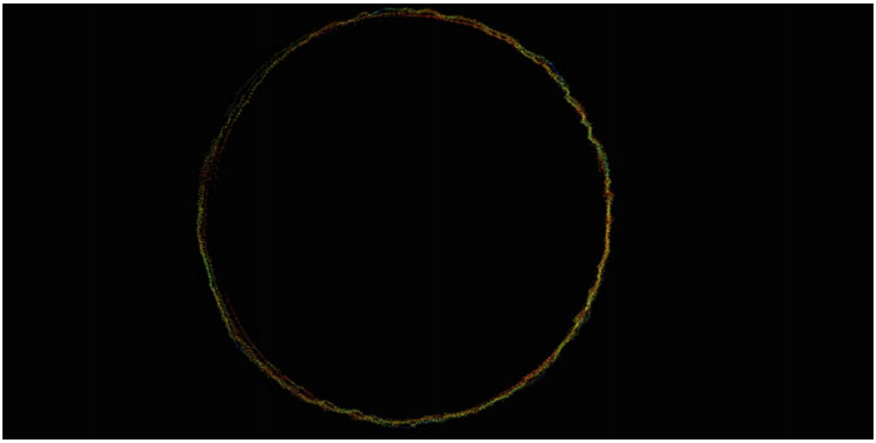

Fig. 7 Horizontal section of a column: it is clear the misalignment and the data error

50–60 cm in height were precluded by the numerous visitors to the Cathedral, the product had many areas in the shade, and was therefore insufficient to describe the complex morphology of the pulpit.

Finally, unfortunately, due to the characteristics of the marble material of the pulpit, the laser scanner survey did not really appear to be highly reliable: if you make a section with a horizontal plane, the columns of the object do not have a regular geometry, but the circumference is definitely deformed, especially at the points of orthogonal incidence of the radius with respect to the instrument (where the intensity value is higher).

Because of all these problems, it has been considered necessary to integrate the data of the laser scanner survey with other detection methods, in this case we opted for the SfM acquisition systems.

3 Structure from Motion Survey

3.1 The Acquisition Phase (M.B.)

The photographic survey of San Giovanni's pulpit has foreseen several precautions: the morphological complexity of the object has required numerous photographic shots to reconstruct the sculptures that compose it in three-dimensional space; the high detail necessary to describe on a suitable scale the sculptures also required to provide a very high definition of the frames, not considering the scale of representation 1:50 to be sufficient for the description of a complex architectural object, in the same way as previously for laser scanner survey. It is clear that these two requirements highlighted in the phase of the "acquisition project" of the survey led to the awareness of carrying out a decisively massive photographic intervention, despite the modest dimensions of the object (Figs. 8 and 9).

Before proceeding to the survey of the pulpit, its morphology has been carefully studied, in order to design the most correct method to resume the architecture in its complexity so as to obtain a three-dimensional model as complete as possible of information. The pulpit was conceived as a circular platform supported by a trilithic structure that supports the parapets finely decorated with high relief sculptures; the vertical structural elements of the perimeter, which alternate between columns and caryatids, support the marble floor together with the central caryatid; along the north side of the church the circular perimeter is modified with the addition of two columns supporting the rectangular plan to which the wooden ladder rests, which allows the celebrating presbyter to ascend to give rise to his orations. This structure, regular in its morphology, however, presents great complexity due to the sculpture that characterizes the "low" part of the object: if the parapet for the presence of sculptural palimpsests requires to be photographed from many angles in order to be able to create the lateral surfaces of the sculptures in space, it is evident how the sculptural and architectural elements in the lower register require to be photographed at 360°.

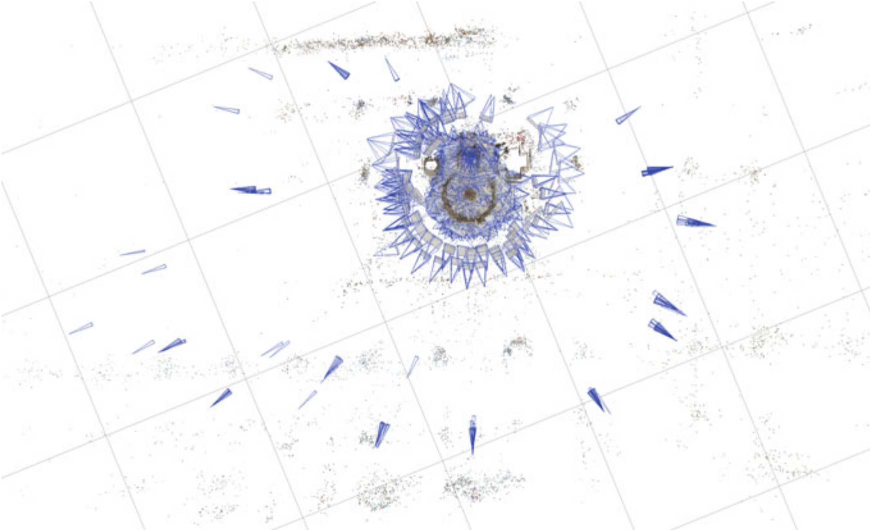

Fig. 8 3D sparse cloud obtained by the Structure from Motion reconstruction, where man can see the in planimetry the disposition of the cameras

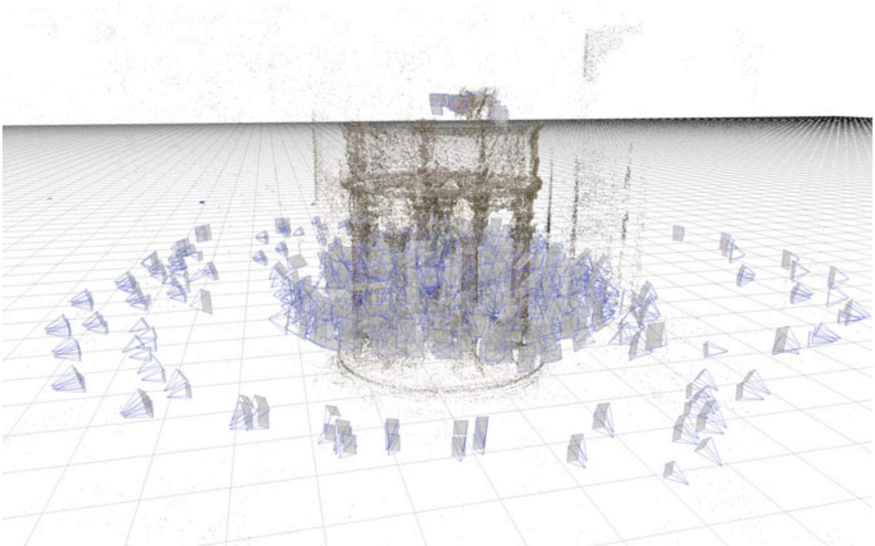

Fig. 9 3D sparse cloud obtained by the Structure from Motion reconstruction

To be able to acquire these objects from all angles theoretically it would be enough to arrange the filming positions so as to create a circumference around the pulpit in order to be able to take all the surfaces from multiple angles; unfortunately, however, in this case it is not a verifiable condition: the strong differences in lighting between the outside and inside of the first level do not allow only the external elements to be resumed with good quality; moreover, also due to the poor lighting conditions, in order to acquire the frames with a shutter speed which avoids the micro-blur effect, it is necessary to open the diaphragm of the camera; this thing does not allow to obtain a large depth of field to focus the distant points from the focusing point.

In the choice of the correct instrumentation to be used, the lighting conditions in which the Pulpit is located have been considered: the cathedral of Pisa, which is one of the most splendid examples of the Tuscan Romanesque style, has a window surface percentage that is much lower than the walled one: this characteristic not only causes a low level of indoor lighting, but also high spots where the sun's rays enter. For this reason it was necessary to provide for the use of tools that could achieve high quality frames despite the light present was noticeably unfavorable to photographic shooting. In order to guarantee a high level of definition, which is able to describe the sculptures in its details, and a frame of good quality at the exposure level, two different cameras were used, both full frame, i.e. 24 × 36 mm sensor format: a mirrorless Sony A 7R, capable of producing high quality frames even with a rather high sensitivity, so as to encourage shooting without a tripod; and a Sony A900, which by mounting a telescopic lens has been used for long distances to eliminate points hidden by the architectural elements and the morphology of the sculptures (Fig. 10).

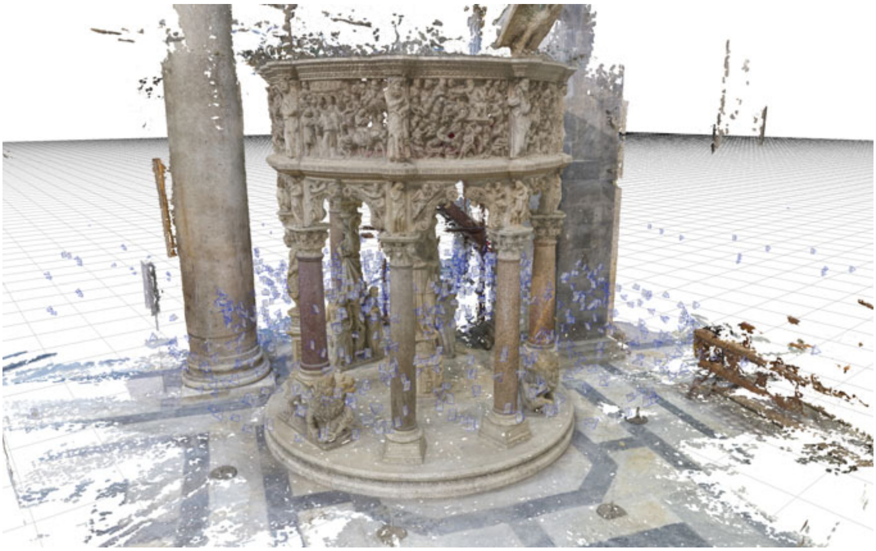

Fig. 10 3D dense cloud obtained by the Structure from Motion reconstruction

To better reconstruct the surfaces of the pulpit, it was decided to make frames following three levels of investigation: a first general moving around the object at close distance, a second rotating around the elements of the first level, a third taking the second level from a great distance.

Obviously, each of these photographic sequences, filming objects from different distances, required to use lenses with different focal lengths. For the first one a Sony Zeiss Sonnar T * FE 55 mm f1.8 ZA was used, rotating around the pulpit at a more or less fixed distance never exceeding 5 meters, with the exception of the portion hidden by the pillar of the church, at the same laser scanner survey mode. To be able to have more shooting points the frames were acquired both from man height and from a height of less than one meter from the ground. For the second sequence was used a Sony FE 28 mm f/2, ideal for moving around objects even at close distances, less than 2 meters, and with this lens were acquired all the columns, the caryatids the floor and the ceiling of the lower level. The third and last sequence was made with a telezoom Sony 70–400 mm f/4–5.6 G SSM, as already mentioned to try to eliminate the hidden points of close-ups, especially as regards the morphology of the high-reliefs of the upper level.

The choice of the focal length was primarily based on the study of the resolution to be guaranteed to the frames to fit in the scales of definition of the three-dimensional model; while in the case of the laser scanner survey, directly acquired in metric scale, it is possible to evaluate the definition on the basis of the set point mesh, as regards the photographic survey the evaluation of the definition values must be designed on the basis of the pixels that define the surfaces (Fig. 11).

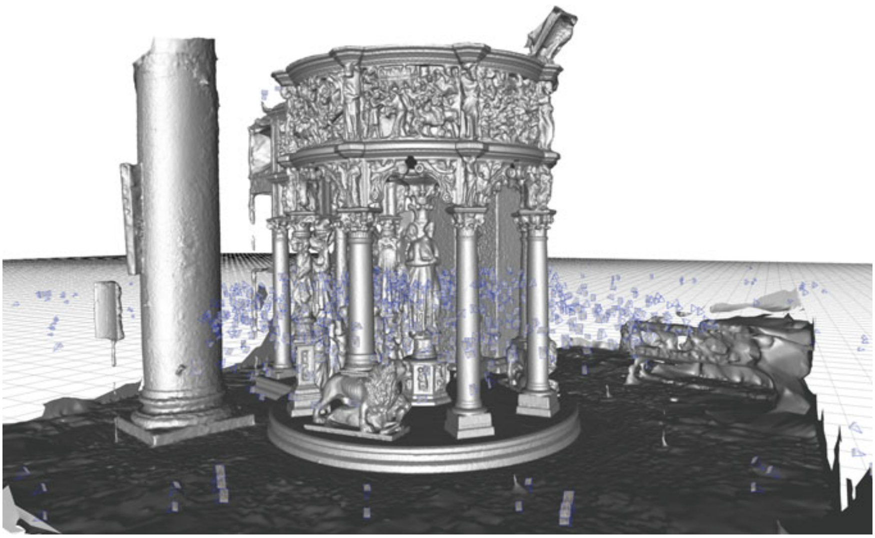

Fig. 11 3D mesh obtained by the triangulation of the dense cloud

3.2 Data Processing (M.B.)

Approximately 1200 frames were acquired at the end of the photographic shooting operations; 300 with the Sony Alpha 900 at 24MP, and 900 with the Sony A 7R at 36 MP: a very high-level dataset that is highly descriptive of the pulpit. Before proceeding with data processing in the software dedicated to the reconstruction of the three-dimensional scene, a careful quality control on the frames was made: we tried to have safety shutter speeds to avoid the micro-blur effect in the photographs [8]; especially for acquisitions from close distances when moving around the object there are repeated changes of exposure, the risk of having frames out of focus or with an incorrect exposure should be avoided. For this reason the frames in.raw format have been imported into a software with the purpose to verify the correct focus and to adjust the parameters. In this way the white balance was equalized for all the shots so as to have the most uniform color possible. Due to the different surface exposures, it was also decided to limit the presence of over-shaded and shaded areas, minimizing the Highlights and Shadow parameters. Finally we tried to make the exposure of the surfaces as homogeneous as possible by varying the parameter according to the frame (the photographs were taken in aperture priority, leaving free to vary the shutter speed). Once verified, all the files were saved in.tiff format with a compression that did not lose the original quality (.lzw) (Figs. 12 and 13).

The dataset obtained was very large, over 60 GB of data, which is why we decided to experiment with the use of different data reconstruction software in order to determine which was the most appropriate for such a mass of information; the research

Fig. 12 3D textured mesh

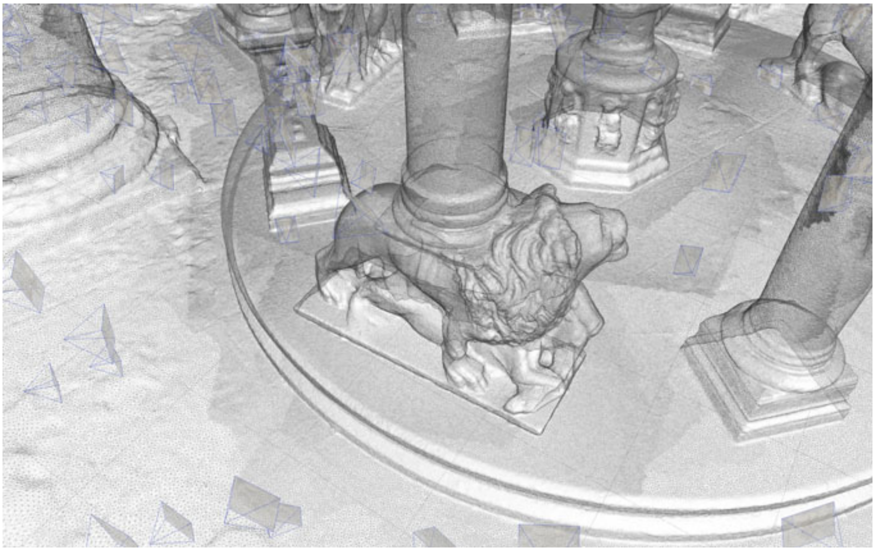

Fig. 13 Detail of the 3D mesh model where it is possible to see the resolution and the isometric triangles

group has been using SfM software for the reconstruction of three-dimensional scenes [5], useful for documentation and extractions of rectified textures (most of the times Agisoft Photoscan pro). The constantly evolving programs are able to provide today, under favorable shooting conditions, highly reliable models: reliability varies according to the resolution of the frame but can reach, for the scale 1:50, 2 cm [9]; unfortunately, the management of data of this size would have required the use of overly performing calculation machines, which are not present in the laboratory (The guide to Agisoft Photoscan provides that for every megapixel you should expect the use of a certain amount of RAM by the computer, reaching in this case too high level of memory).

The recent developments of other software for the management of photogrammetric data have led rather to the experimentation of new applications able to manage the photographic data more quickly: in this context the 3D Zephir program was used. The program is the subject of an agreement between DiDA and the manufacturer, 3D Flow, with the aim of experimenting with its applications in the architectural field in order to perfect its operation and update its functionality (Fig. 14).

The program's workflow basically follows the state of the art of the other SfM acquisition management software: it is divided into 4 processes, during the first the acquisition points of the frames are arranged in space (SfM process); in the second the data of the point clouds is densified; in the third one proceeds to the realization of a mesh surface based on the triangulation of points; finally the model obtained is texturized.

Fig. 14 Detail of the textured 3D mesh where it is shown the high resolution of the texture

The algorithms that realize these processes make the calculation of operations easier and less time consuming: something that we could pleasantly appreciate by inserting a photo dataset larger than 60gb. For other objects where the exposure is better and the data should not be post-produced, it is sufficient to use jpegs to reconstruct the scene.

The photographs have been subjected to the quality control of the software in order to identify the potentially dangerous frames for the quality of the alignment; after this phase, the positioning errors of the cameras were verified, eliminating the few badly arranged ones. After having densified the datum, on the basis of 6 control points the three-dimensional point cloud has been scaled obtaining an error lower than the tolerances, caused in part in the human action of the choice of the homologous points.

To check the quality of the mesh, it was extracted and imported into a software dedicated to the management of reverse engineering processes (Geomagic Wrap 2017), to test the quality of the triangulation of the points. the model obtained apparently had a regular arrangement of the triangles of the surface, a good quality index, which was verified by the software which, by activating a surface optimization algorithm, found imperfections, tips etc. [9]. Only in the portion of the model in which it was difficult to acquire the three-dimensional data of the statues of the second register; the rest of the surface was substantially error-free. On the contrary, usually the meshes coming from the Photoscan software have percentages of much higher imperfections. Verified the quality of the mesh has been re-imported into Zephir and texturized.

4 Conclusion

4.1 The Integrated Survey, Developments and Problems (G.P.)

Despite the fact that the new photogrammetric survey management platforms allow to combine data coming from laser scanner and photographic acquisitions [10], it was considered preferable in this case to avoid this procedure for several reasons: in the first place, the data of the laser scanner survey, as previously analyzed, is not highly reliable, or rather it may be inaccurate in some places, as can be seen from the horizontal sections of the columns. Combining the unreliable starting data with a more precise one, as in this case the photogrammetric one, would not lead in any way to an integrated survey more efficient than the original; for this reason, on the contrary, it was preferred to combine the two surveys to scale the photogrammetric one on the basis of some control points similar to the laser scanner survey. Obviously, these points have been selected on the less reflective surfaces so as not to take the spatial coordinates of unreliable points and thus give the photographic model highly reliable measurements (at least within the required representation scale).

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