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INTEGRATED 3D ACQUISITION OF COMPLEX WOODEN ARTEFACTS: THE PIFFETTI'S LIBRARY IN QUIRINALE PALACE (ROME)

Michele Russo [1*], Roberta Spallone [2], Luca James Senatore [1], Giulia Flenghi [1], Luisa Morozzi [3]

[1] History, Representation and Restoration of Architecture Dept., Sapienza University in Rome - (m.russo, luca.senatore, giulia.flenghi)@uniroma1.it

[2] Architecture and Design Dept., Politecnico di Torino, Italy - roberta.spallone@polito.it

[3] Historian and freelancer, Italy - luisamorozzi@gmail.com

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ABSTRACT:

Integrated surveying with active and passive systems is a well-established process for understanding artifacts at different scales and levels of complexity. But some acquisition problems still exist, related to the presence of non-optically cooperating materials, reflective surfaces, and non-homogeneous and uncontrolled illumination conditions. Especially in these cases, the integration between different 3D acquisition techniques allows us to test the response of different instruments concerning the boundary conditions, going to compare the results. This activity highlights the pros and cons of each technique, identifying the right balance for future applications with the same conditions. The case study analyzed in the article is the Piffetti Library, a wooden work from the first half of the 1800s present at the Quirinale Palace (Rome). The artifact shows multiple levels of environmental complexity (small space with movement constraints and uncontrollable light), and it is composed of several wood pieces with a very glossy finish. The presence of shelving, free-form surfaces, and sculptural details requires careful planning to survey the artifact with consistent resolution. The use of different active and passive acquisition methods is tested, defining an integrated methodology coherent with the complexity of the artifact and the context in which it is positioned. The dual purpose is to define a possible replicable protocol, arriving at the definition of reliable 3D data for subsequent analysis and virtual reconstructions.

1. INTRODUCTION

The construction of multi-resolution models of complex artifacts does not define an innovative topic. Researchers from all over the world have been dealing with these issues for the last 20 years (Beraldin et al., 2002; Beraldin et al., 2007; De Luca et al, 2006; Guidi et al., 2009, Remondino & Rizzi, 2013).
The definition of methodologies increasingly oriented towards the integrated use of advanced 3D acquisition tools now leads to the possibility of dealing with a wide range of case studies, extending from urban to architectural and detailed scales. Improving accuracy and process control conducts to the definition of even more reliable digital models. The application of special digital cameras which work at a reduced working distance or in low light conditions favors the acquisition of narrow confined spaces. The use of orientation techniques based on SLAM algorithms allows for rapid orientation if supported by socket network control systems. The consolidated use of drones integrated with ground-based acquisition systems increasingly increases 360° knowledge even of complex systems, reaching inaccessible portions. Finally, experimentation with low-cost techniques is widening the accessibility of 3D acquisition tools.
However, surveying complex, optically non-cooperative materials still represent a challenge to the 3D acquisition process. This problem is evident when the specific material characteristics of the artifact present reflective or transparent materials or surfaces with specific treatments. The problem becomes a real bottleneck if the survey subject is not movable, and it is framed in not ideal lighting conditions. This situation typically happens in the case of large statues in museums or big furniture such as libraries.
Among these specific cases, integrating active and passive 3D techniques allows extracting the best reliable knowledge model, adapting each 3D acquisition approach, and lighting conditions to the specific situation. In addition, it is also a good practice to introduce data redundancy in the application of different detection techniques, which allows for comparing different results and selecting the best one. It is possible to start a metrological analysis to test the relation between the instrument's behaviors and application conditions. Besides, the 3D model reliability represents a mandatory condition to start the subsequent processes of analyzing the existing. If the measured data define the starting point for the geometric analysis of the artifact and its interpretation for a possible virtual reconstruction, the possibility of determining and controlling the level of reliability of the data is fundamental. It is so possible to distinguish the interpretation component from the survey one, which would otherwise be indistinct and difficult to control in a process of the virtual reconstruction of components or portions that no longer exist.
The research topic concerns the 3D survey of a precious wooden artifact: the Piffetti Library. This object, now preserved in the Palazzo del Quirinale (Rome), represents a jewel of cabinet-making art of the XVIII period and a valuable artistic example. The complex operative conditions given by the lighting conditions and the artifact materials make challenging the 3D survey of this artifact. The 3D pipeline was planned considering metrological validation steps to verify the high level of data reliability. The 3D model represented the starting step for the definition of parametric modeling and immersive visualization (see in the present volume: Spallone et al., Reconstructive 3D modeling and interactive visualization for accessibility of Piffetti's Library in the Villa della Regina Museum (Turin)).

* Corresponding author

2. RELATED WORKS

Defining a specific state of the art is difficult because there are a few examples of 3D surveys of similar artifacts. Furthermore, due to its characteristics, the library is a kind of artifact that can be framed between architectural and sculptural scales, as it shows both characteristics. In fact, the object exhibits on the one hand the typical material problems of small furniture products, but with a pronounced change in scale from architectural to sculptural detail. Therefore, in this case, we suggest a general introduction to the Reverse Modeling (RM) topic applied to architectural spaces and complex sculptural works, deepening some bottlenecks related to the instrument integration related to the specific case study.

Based on the integrated sensors and applied to the Cultural Heritage (CH) domain, the RM process was defined in the early 2000s (Bernardini & Rushmeier, 2002). Starting precisely from the sculptural scale, it quickly moved to the sculptural/architectural one (Gaiani et al., 2005; Guidi et al., 2006) or the architectural and urban scale. This scale variation it's crucial in understanding how the general purpose of the 3D survey research has changed in the last decades. The possibility to introduce new technologies and integrate them led to enlarging the application field, covering most of the case studies and answering their complexity towards an ever more massive acquisition of 3D data. But this scale change required comparing 3D data and verifying their reliability. It started with the first comparisons at small (Barber et al., 2002) and large scales (Böhler, 2005; Grussenmeyer et al., 2008), suggesting different states of the art about active and passive acquisition techniques (Remondino, 2011). This metrological comparison mostly came out from the desire to verify the same level of accuracy of the short-range acquisition as the long-range one, defining a new methodological approach for multi-scale artifacts. The process is constantly being refined because there is a continuous evolution of 3D acquisition instruments, which can sample with increasing accuracy, speed, and flexibility the different types of surfaces present in the Cultural Heritage domain. This leads to a dynamic reality in which each specific case study can become the testing ground for new acquisition technologies based on established processes for critical evaluation of results.

These increased capacities open the possibility of testing active and passive sensors in challenging conditions given by complex artifacts with optically uncooperative materials (Guidi et al., 2009) or in adverse light conditions. In the Cultural Heritage domain, these conditions are common in the sculptural field, in which it is often easier to manage external conditions, recreating ideal acquisition conditions for comparative metrological experimentation. It allows for defining practical protocols when dealing with certain materials (Evgenikou & Georgopoulos, 2015) with specific survey methodologies (Nicolae et al., 2014) and under predetermined lighting conditions (Guidi et al., 2013).

Sometimes, however, the presence of boundary conditions such as the inability to move case studies or control external acquisition settings makes the testing process much more complex. This paper compares active and passive surveying techniques on an artifact of extreme material and formal complexity. The integration between active systems based on phase variation (ToF-PM), hand-held triangulation systems based on infrared emission, and photogrammetric systems provides a metric comparison on the 3D acquisition of complex objects with a hybrid sculptural/architectonic scale towards possible future acquisition protocols which can be applied in similar conditions.

3. THE CASE STUDY

The Piffetti Library was not created for the Palazzo del Quirinale but for the Villa della Regina (Morozzi, 2008), one of the Turin residences of the Savoy family. The library dated back to 1735-1740 is documented in the apartment of King Charles Emmanuel III in an inventory of the Villa dating from 1755. The precious wood paneling of the room was complemented by a wall table made of tortoiseshell and ivory - with scenes depicting the Siege of Pizzighettone and the Battle of Guastalla (1734) – two walnut spittoons and six stools. The library was transported to Rome in 1876 to be adapted (1879) to one of the rooms in the flat of Queen Margherita, wife of King Umberto I (González-Palacios, 1996). The original structure consisted of a high plinth and shelves for the books, while the wooden floor and ceiling were made when the library was moved to Rome. The creator of this masterpiece was Pietro Piffetti (Turin 1701-1777), one of the leading cabinet-makers of his time, under the service of the Savoy court (Antonetto, 2010). After a period of apprenticeship in Turin, Piffetti completed his training culture with an extended stay in Rome. Returning to Turin in 1731, the cabinetmaker was appointed the first cabinetmaker to King Charles Emmanuel III of Savoy. The Piffetti Room now houses the eponymous artifact in the Quirinale interior. It is a small room measuring 4.9 x 4.8 x 5.5 meters. In the walls, there are three access doors, a window, a mirror, and the library, which occupies the remaining area of the walls at a height of 3.2 m. The library consists of a poplar structure, while the veneering is set with different types of wood, such as rosewood, olive, boxwood, and yew. The whole is embellished with elegant ivory inlays. Two small consoles – one of them was added in 1879 – with ivory inlays simulating sheets and prints resting on the top upholstered in tortoiseshell complete the room (Figure 1). One of the fake ivory sheets bears the signature of Pietro Piffetti included in the scene depicting the Siege of Pizzighettone. Above the shelves are eight majolica vases and four gilded wooden sculptures representing the Seasons. The books stored in the library date back to the late 19th century, and many of them – property of Queen Margherita –have bindings decorated with the Savoy coat of arms. The 3D survey project of the actual Perfetto's Library (Figure 2) has been carried on thanks to the scientific agreement between the SDRA Department (Sapienza), the DAD Department (Politecnico di Torino), the Piedmont Regional Museums Directorate (Dr. Chiara Teolato), with the support and permission of Segretariato generale della Presidenza della Repubblica.

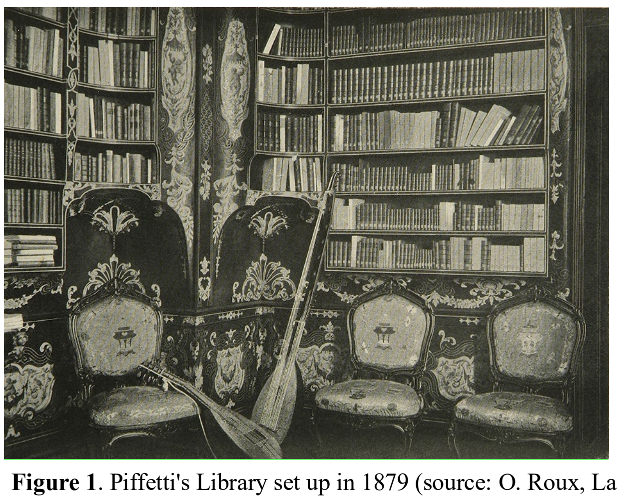

Figure 1. Piffetti's Library set up in 1879 (source: O. Roux, La prima Regina d'Italia, Milan 1901).

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Figure 2. Actual Piffetti’s Library.

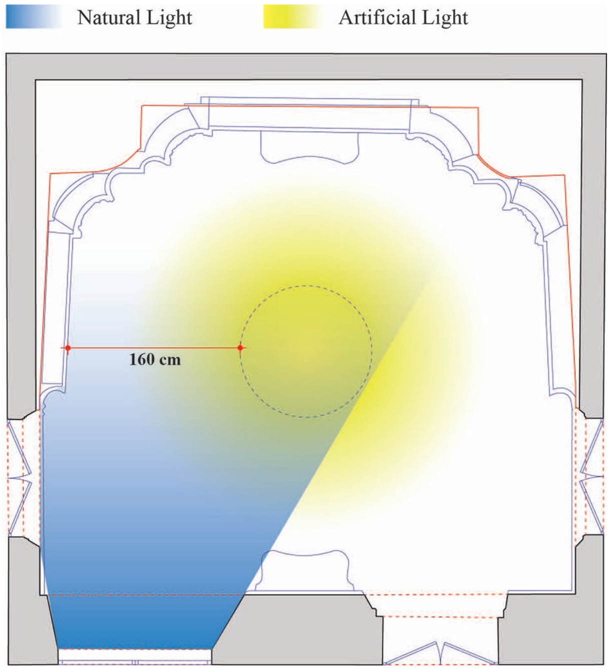

Figure 3. Schema of light sources in the room.

4. METHODOLOGY

The survey of this unique artifact and the environment in which it is placed required careful planning to reduce possible bottlenecks in the 3D acquisition process. The value of the location made it necessary to pay more attention to all activities and logistical issues, searching for the most suitable but compromised solution concerning the boundary conditions. For this reason, different configurations of light and active and passive instruments were tested to verify the quality of the acquired data. The use of different acquisition methodologies made it possible to evaluate for each survey process the role of the external factors in the 3D survey complexity. In conclusion, some steps were planned to verify the reliability of the data at different scales to validate the integration between other acquisition systems.

4.1 Survey bottlenecks

The first problem is the low illumination level, supplied by a window and a chandelier placed in the center of the room (Figure 3). The window shutters were closed to reduce the component of direct and indirect natural light and color. In addition, the survey was planned in the morning to avoid the presence of direct sunlight from windows, which given the orientation of the facade intervenes in the afternoon. But it was impossible to eliminate the natural light component due to the complexity of inserting black curtains or closing the window completely. This meant that we still had to deal with a component of blue diffuse light present on some surfaces of the library. In addition, the chandelier, at a height of 300 cm and with a diameter of 100 cm, limits the acquisition distance and instrument positions to 150-160 cm concerning the library surface. The light intensity is very low and not adjustable. During the acquisition phase, all other access doors to the environment were closed to minimize other illumination components. For all these reasons, the survey’s planning included using a shielded photographic lighting system to reduce the light component present in the room overlapping a more diffusive diffuse and controlled light.

The second bottleneck was defined by the geometrical complexity, materials, and surface finish of the artifact. Geometrically, the object surfaces alternate very regular, sharp-edged areas, such as those of shelves, with transition areas between sides or wall connections characterized by freeform surfaces with complex sculptural inserts. This geometric variation in finish, shape, and complexity makes it more difficult to identify a single detection methodology that fits different acquisition conditions. Besides, each surface features a variety of materials and wood finishes in different colors, which may produce a different instrumental optical response.
The presence of natural and/or artificial lighting in the room must be considered for the geometry and material factors, generating different types of reflections in the case study (Figure 4). Very dark wood species and glossy surface treatment make light management even more complex. This is evident especially in the surface perpendicular to the ray direction (variable of freeform surfaces) and in the edges of shelves, highlighting the change of direction (Figure 4).

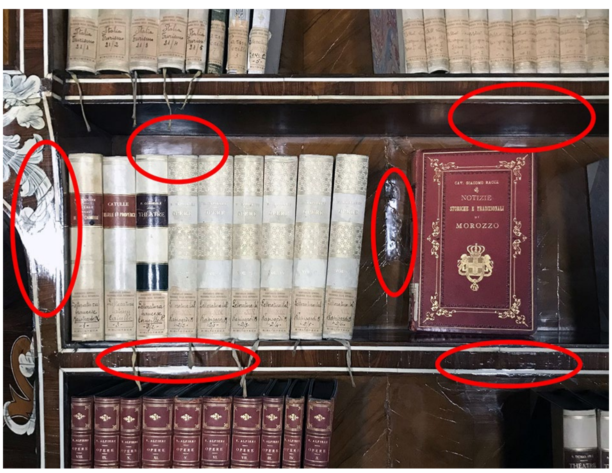

Figure 4. Some light reflections are highlighted on the surface material coming from different sources.

4.2 3D data acquisition

The external conditions intervene in the quality of the acquired geometric data, depending on whether the technique is active or passive. For this reason, different active methods, based on ToF CW AM and fringe projection triangulation-based instruments, and passive methods have been tested in the process about the level of detail. All acquired data were oriented according to the TLS acquisition reference system.

Studio Azimut surveyed the architectonic space in 2016 with a 3D laser scanner Focus 3D (Faro). The books were temporarily removed to acquire both the internal surfaces of the library and the architectonic walls with an average resolution of 0.5 cm. The simple shape of the environment necessitated a few stations (Figure 5), providing some at different altitudes to reduce the presence of shaded areas. The highest scan was placed over a staircase at a height above 3.5 meters to survey the library's closing part.

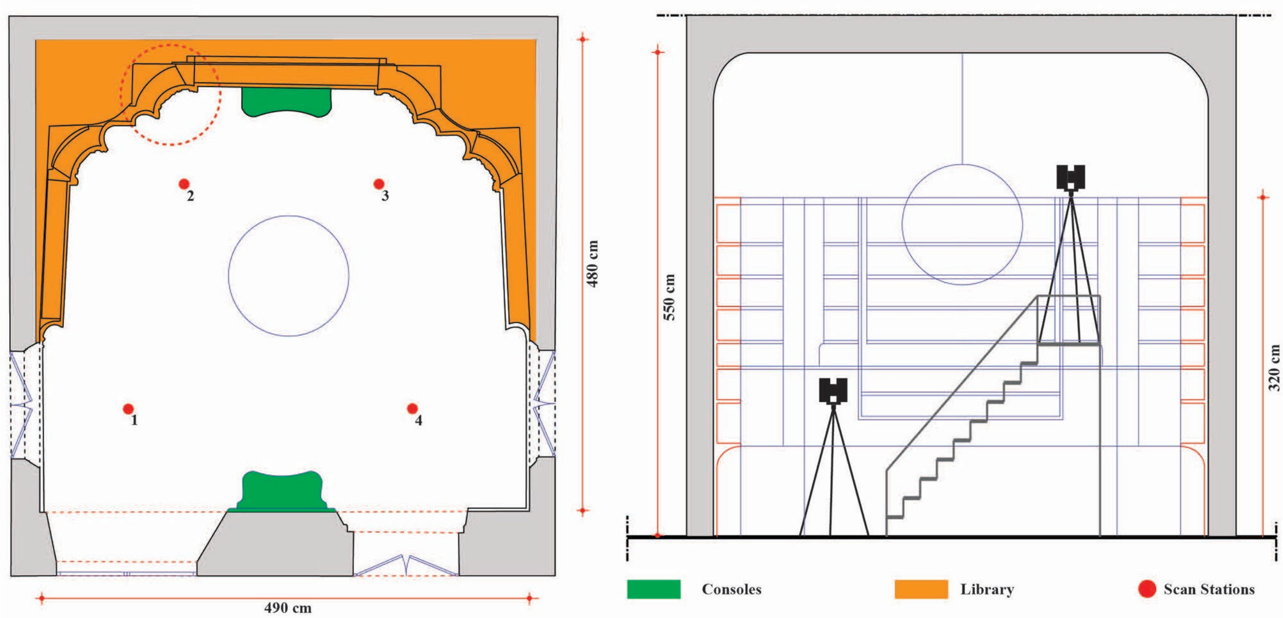

Figure 5. Range-based acquisition schema.

This survey was integrated with the summer of 2022 by a photogrammetric campaign aimed, on the one hand, at verifying the imaging capabilities under such complex conditions and, on the other hand, at acquiring a more reliable color and material detail. The complexity of the photogrammetric survey required several attempts to understand how best to respond to challenging lighting conditions. Specifically, different attempts were made by moving different artificial spotlights (50x70 cm 150 W LED Softbox), but all configurations led to the definition of many reflections on the wood surfaces.

The definition of a lighting system that minimizes the presence of reflections on shiny variable surfaces is highly complex. Discounting more expensive systems that allow controlled illumination in terms of intensity and distribution, such as annular flash or polarized lights, a "low-cost" solution may consist of the use of photographic spotlights placed symmetrically to the camera. In Figure 6 there are three possible configurations of use: parallel axis (1), convergent axis (2), or divergent axis (3). If we assume to apply them on regular surfaces, the parallel axis requires closer proximity of the spotlight against a more consistent illumination distribution over the surface. In this case, reflection conditions occur more in the peripheral area of the frame. If the spotlights have converging axes, they can move apart, but the light on the object is less coherent and more concentrated on the photographed area, resulting in more reflections on the acquired site. Finally, spotlights with diverging axes drastically reduce reflections but also reduce light, requiring the exposure and ISO parameters to be increased.

In addition, increasing the distance or changing the angle between the light sources and the surfaces to be acquired reduces the light spot, but the lights were not powerful enough to provide acceptable illumination.

An additional variable, mainly present in our case study, is the geometric variability of surfaces in space, which makes it impossible to control this moving system since each change of position implies a different incidence and reflection condition.

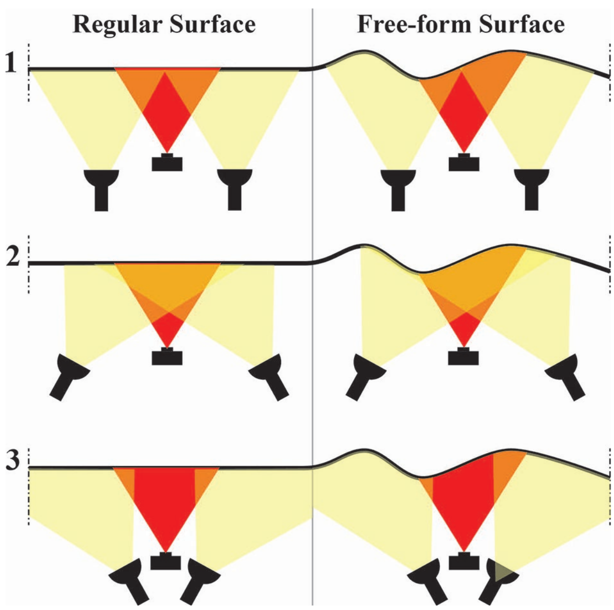

Figure 6. Photographic conditions with different surfaces and spotlights distribution.

Figure 7. Different space lighting with existing light (top) and spotlight (bottom).

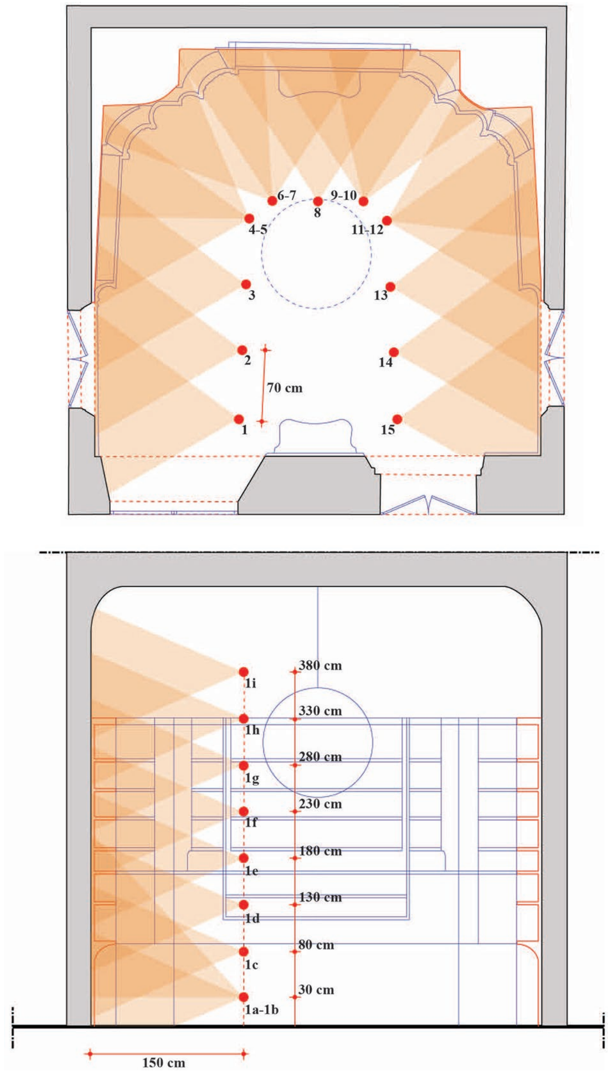

Figure 8. Photogrammetric acquisition schema with vertical and horizontal baselines and image overlapping.

Therefore, in the end, only the fixed chandelier's light was used (Figure 7), adapting the parameters to the low but fixed light in the room. While not representing the ideal solution, the presence of a still light in the environment made it possible to minimize the presence of reflections in the various photographs. In the definitive configuration, a Kodak color checker was inserted in the middle of each vertical photogrammetric stripe. Unfortunately, the variation in the intensity of illumination and color occurs in every direction concerning an artifact of this type. Thus, the ideal operating condition would require checker placement and white calibration for each photograph. However, this process is incompatible with the required acquisition times. Therefore, the compromise was reached by inserting it for each vertical block, evaluating the variation in the color of the different stripes, and defining a reliable average color.
The last campaign used a 6D Mark II (Canon) equipped with a 36 x 24 cm CMOS sensor (6240 x 4160 pixels) with a fixed 24 mm lens. The acquisition phase defined a photogrammetric block of 178 images at a working distance of 150 cm, a horizontal baseline of 70 cm, and a vertical baseline of 50 cm, achieving an average GSD of 0.4 mm on the library surface (Figure 8). Besides, 34 GCPs were extracted from the range-based cloud to frame the photogrammetric system within a grid of known coordinates, reducing possible orientation errors.

The third and last survey campaign focused on the acquisition of details, to verify the response of the different techniques on limited areas of the library. Specifically, testing at the sculptural scale revealed the level of accuracy in the acquisition of surfaces especially about the different materials of which they are composed. The low niches connecting the central and side parts of the bookcase were considered the test area. These areas were chosen because they present a geometric pattern defined by polycentric curves, are easily accessible, and are rich in wooden materials and decoration. Given the small size and the precision required, the photogrammetric technique applied at shorter distances was compared with an active acquisition through an iReal 2S 3D Laser Scanner (Scantech) triangulation infrared instrument. The triangulation instrument was devoted to the acquisition of the whole free-form area of the niche, focusing on specific stripes/sections that pass through different materials, to see the response of the fringe projection in the different optical conditions. At a photogrammetric level, a campaign aimed at acquiring details has been planned. In a smaller shooting area, the spotlights have been positioned convergently on the shooting area and have never been moved. This made it possible to reduce the exposition factor and lens aperture. Also in this case, for the introduction of artificial lights, the color checker has been inserted.

4.3 Data process and comparison

The acquired data were processed separately. The range maps coming from TLS have been aligned and optimized in the JRC Reconstructor program (Gexcel), to then be managed within the ReCap PRO program (Autodesk) for displaying and extracting the GCPs. The data coming from the triangulation system were oriented in real-time through the "feature detection" mode and translated into point clouds and mesh models in the proprietary software.

Besides, the images, after being pre-processed through color calibration, were all oriented within the Metashape program (Agisoft), always keeping as a reference the GCPs extracted from the point cloud to reduce frame orientation errors. For timing reasons, the bright spots present in every single image were not masked, aware that this activity would have provided better results. At the end of the bundle adjustment, the average orientation error on the GCPs was 4.8 mm, close to the accuracy of the range-based tool from which the geometric information was extracted.

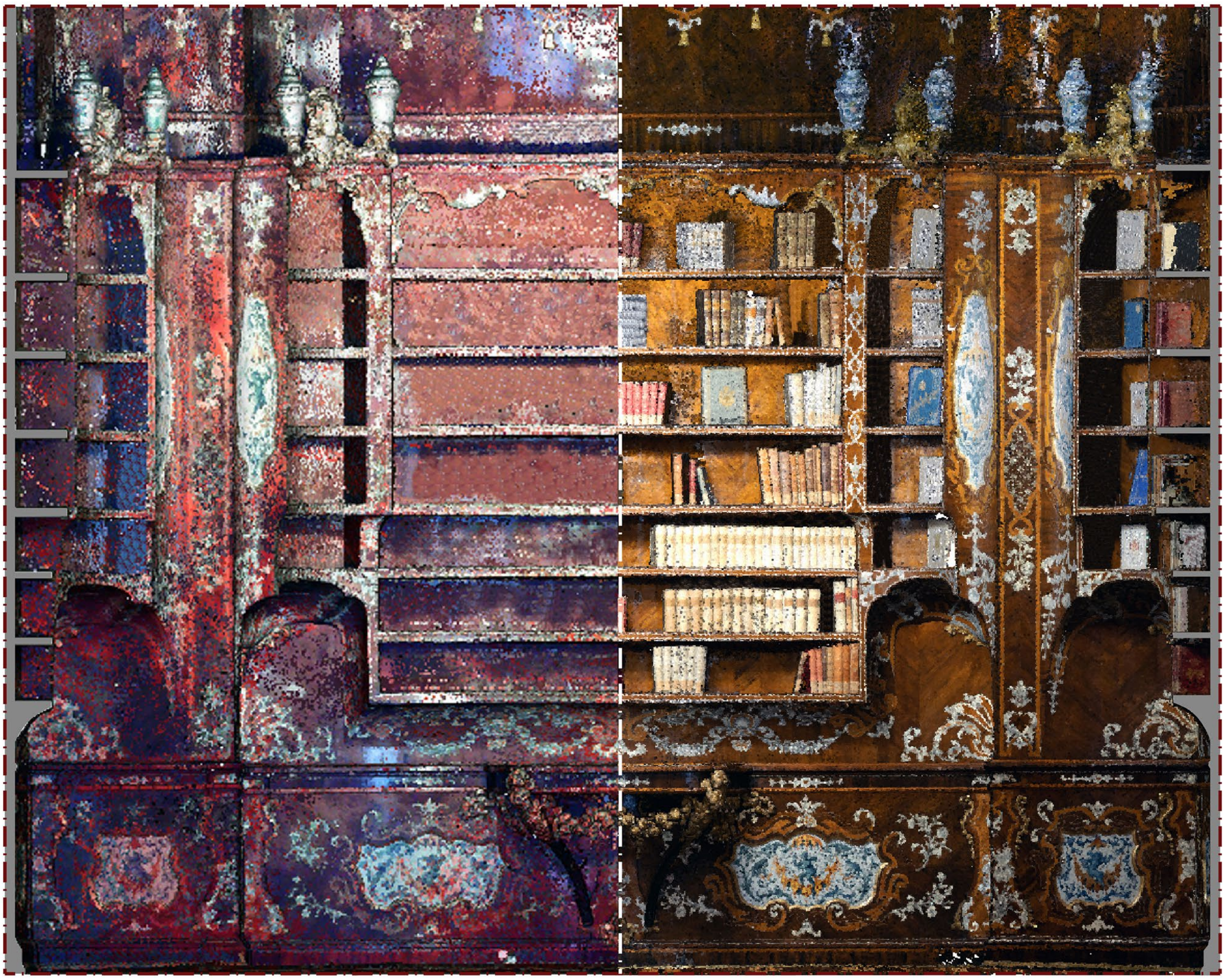

Figure 9. The front side of the library. On the left is the range-based data, and on the right, is the point cloud from photogrammetry.

All point clouds in the same reference system were visually and metrically compared to identify the critical points for each survey approach. A first check on the graphic rendering (Figure 9) highlights the better result of the photogrammetric cloud, which presents a higher point density and a color closer to the real case study. From the metrological point of view, a separate comparison at an architectural and details level was planned. In the first one, the TLS cloud (gold standard) was compared with the photogrammetric one (Figure 10). The comparison showed a geometric uniformity between the point clouds (Mean Dist.= 0.004 m; Std. Dev. 0.003 m), excluding the books which were not present in the first survey. A 5 mm error is mainly concentrated in the edges where there is a sudden change of depth and light in the data acquisition, leading to noisier and less accurate data. The comparison of the details still shows coherence between previous data (Figure 11).

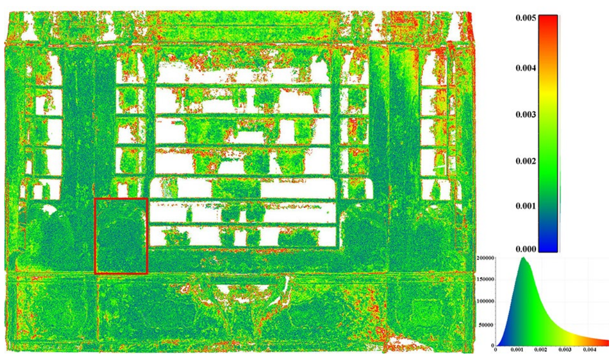

Figure 10. Comparison of general range-based and image-based data. In red the detail analyzed in Fig. 11-12 (scale in meters).

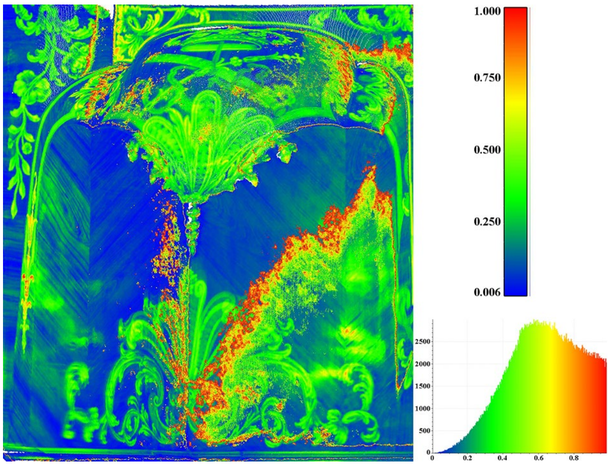

Figure 11. Comparison of detailed range-based and image-based models (scale in millimeters).

The distance (Mean Dist.= 0.003 m; Std. Dev. 0.002 m), highlights a fraying on one of the two sides, probably due to an alignment drift of the range-based data. To deepen the behavior of the two methodologies in this area, two meshes were generated and sectioned, passing through different materials (Figure 12). The range-based data is clean and the transition between different materials does not lead to a noise increase.

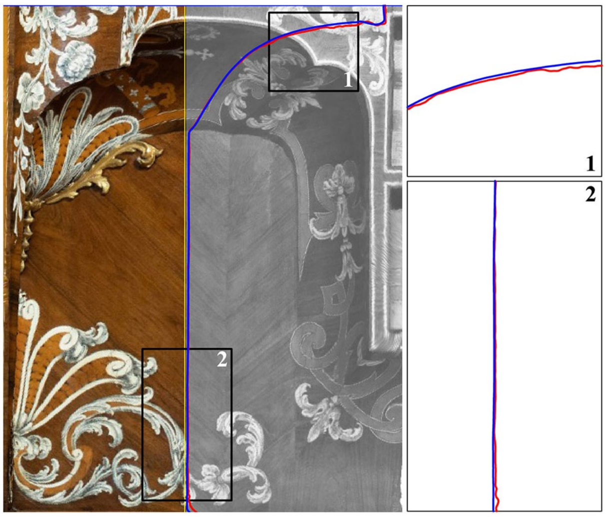

Figure 12. Vertical section of the polygonal model of detail and comparison between photogrammetric and range-based data.

The edges are slightly rounded, which may lead to thinking that some filtering algorithms are introduced in the meshing phase. On the contrary, the photogrammetric datum is less regular and above all shows some variations in the passage from the dark wood to the inlaid white one.

Figure 13. Photogrammetric ortho-image with a metric grid overlapped.

5. RESULTS AND CONCLUSIONS

The article deals with a 3D acquisition of a unique and valuable artifact: the Piffetti Library. This artwork, now preserved inside the Palazzo del Quirinale, presents material and geometric complexity, and a challenging light boundary condition.
The integration of the different point clouds at architectural and detail scales allowed for defining a multi-resolution model of the entire space. Data redundancy permitted a critical comparison between the results, identifying the most suitable surveying integration. The comparison showed that photogrammetry is the best methodology for acquiring a reliable color and defining orthophotos (Figure 13); on the other hand, range-based techniques are more accurate in the transition between different materials and do not suffer from specific lighting conditions. Therefore, if the range-based data allows to obtain reliable information for the parametric reconstruction of the model, the photogrammetric data provides useful information for the texturing of the virtual model. At last, the uniqueness of the case study makes it difficult to define a scalable process, even if it is possible to identify some common problems. They could lead to defining a protocol for instrument behavior in other similar contexts, reducing the bottlenecks of a standard 3D survey process. The results obtained in this experiment can represent a starting step for the definition of this protocol, experimenting in the future also Deep Learning procedure to improve image quality and automatizing masking activities. This paper is the result of an ongoing research project carried out by all the authors. In the written part, M.R. was responsible for the paragraphs 1, G.F. for par. 2, L.M. for par. 3, L.J.S. for par. 4, and R.S. for par. 5.

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