Handbook of Research on Emerging Technologies for Architectural and Archaeological Heritage

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A volume in the Advances in Religious and Cultural Studies (ARCS) Book Series

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Published in the United States of America by
IGI Global
Information Science Reference (an imprint of IGI Global)
701 E. Chocolate Avenue
Hershey PA, USA 17033
Tel: 717-533-8845
Fax: 717-533-8661
E-mail: cust@igi-global.com
Web site: http://www.igi-global.com

Library of Congress Cataloging-in-Publication Data

Names: Ippolito, Alfonso, 1968- editor of compilation.
Title: Handbook of research on emerging technologies for architectural and archaeological heritage / Alfonso Ippolito, editor.
Description: Hershey, PA : Information Science Reference, 2017. | Includes bibliographical references and index.
Identifiers: LCCN 2016023698| ISBN 9781522506751 (hardcover) | ISBN 9781522506768 (ebook)
Subjects: LCSH: Historic buildings--Conservation and restoration--Research. | Historic buildings--Conservation and restoration--Technological innovations. | Architectural surveys. | Archaeological surveying. | Architecture--Conservation and restoration--Research. | Architecture--Conservation and restoration--Technological innovations. | Antiquities--Collection and preservation--Research. | Antiquities--Collection and preservation--Technological innovations.
Classification: LCC NA112 .H36 2017 | DDC 720/.47--dc23 LC record available at https://lccn.loc.gov/2016023698

This book is published in the IGI Global book series Advances in Religious and Cultural Studies (ARCS) (ISSN: Pending; eISSN: Pending)

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

For electronic access to this publication, please contact: eresources@igi-global.com.

Chapter 16
Hand Held 3D Scanning for Cultural Heritage:
Experimenting Low Cost Structure Sensor Scan

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ABSTRACT

In the last years 3D scanning has become an important resource in many fields, in particular it has played a key role in study and preservation of Cultural Heritage. Moreover today, thanks to the miniaturization of electronic components, it has been possible produce a new category of 3D scanners, also known as handheld scanners. Handheld scanners combine a relatively low cost with the advantage of the portability. The aim of this chapter is two-fold: first, a survey about the most recent 3D handheld scanners is presented. As second, a study about the possibility to employ the handheld scanners in the field of Cultural Heritage is conducted. In this investigation, a doorway of the Benedictine Monastery of Catania, has been used as study case for a comparison between stationary Time of Flight scanner, photogrammetry-based 3D reconstruction and handheld scanning. The study is completed by an evaluation of the meshes quality obtained with the three different kinds of technology and a 3D modeling reproduction of the case-study doorway.

DOI: 10.4018/978-1-5225-0675-1.ch016

INTRODUCTION

3D scanning has gone a long way since its first appearance in cultural heritage digitization and modeling (Remondino, 2011; Bandiera et al, 2010; Benedetti et al, 2010; Andreozzi, 2003). The costly and bulky scanners of few years ago are lagging behind some new emerging technologies that are delivering a long term dream of the practitioner of cultural heritage: fast, accurate, low cost, "personal" scanning with a hand held device. The scanning methodology at the focus of this study is hence well distinct from the well tested, reliable, but costly active laser scanning or Time of Flight (ToF) scanning. Point cloud collection of an artifact is just the begin of several different pipelines, as a matter of fact the effectiveness of a tool should always be tested against the final use one wish to do with the collected data, such as, e. g.: documenting an artifact to diagnose problems in its preservation and plan restoration and/or protection actions; creating a digital representation of the artifact for pure archival reasons; building a photo realistic representation for use in virtual tour; making a vectorial simplified representation in order to produce, through 3d printing techniques, a copy (maquette) of the original.

Among the emerging low cost hand held scanners we have chosen the Structure Sensor device to verify a 3D pipeline acquisition on an Architectural Cultural Heritage object: the XVIII century doorway placed in the monastery of Benedettini in Catania, listed in UNESCO' world heritage list. Envisioning the massive use of this cheap and easy to use device in the next years, it is necessary to test its effectiveness in terms of easiness of 3D data collection, processing, mesh resolution and metric accuracy against the size and features of the objects in order to identify the possible fields of application. The features of the chosen case study, in terms of dimension and richness of details, well fit with the aim of this research due to the presence of both planar, complex (mouldings) and sculpted geometries.

The 3D pipeline outlined in this chapter will follow, as much as possible, a low cost and open source workflow from 3D data collecting to the digital replica.

The methodological approach involved an interdisciplinary team composed by computer scientists and architectural representation/ surveying researchers that strictly interacted in each step of the research and integrated their own contribute in order to better understand and solve some relevant and critical issues.

The chapter is structured as follows: - At first we will provide a state of the art panorama of the hand held scanners that are currently available on the market with some previsions about the ones that are likely to emerge in the short term. The review is complemented with a non-specialistic, but accurate description of the algorithms that are used in most of the commercially available devices; - The test carried out on the chosen case study is then introduced. The doorway has been 3D acquired by means of a Structure Sensor device. We have also carried out the comparison with both Image Based Modeling (IBM) and ToF laser scanner techniques in order to point out weaknesses and advantages of the hand scanning approach in relation to the other two well assessed technologies; - The chapter completes the discussion of these issues related to data acquisition with an exploration of the modeling issues to obtain a digital replica in an open source environment suitable for architectural representation and communication purposes.

Handheld 3D Scanning

The 3D scanning is used to acquire the three dimensional geometrical structure of an object in a real environment in order to manipulate it for many possible aims. Usually, the result of a 3D scanning is a set of points in the virtual space called "point cloud". Those points are used to create a surface "mesh" by a triangulation procedure. In the last decade 3D scanning has played a relevant role in many research field, among which the Cultural Heritage (Arcifa, 2010; Gallo, 2010; Stanco, 2011; Stanco, 2012; Santagati et al. 2013).

Compactness, flexibility and robustness of a 3D scanner is given by the miniaturization and integration of the electronic and optical sensors as well as by the algorithms used to acquired 3D geometry. Hence, 3D scanners may be divided in different categories with respect to some specific feature. Two main classes of 3D scanners are the active scanner class and the passive scanner class. The former operate by projecting an electromagnetic signal which is used for estimation of the point cloud depth. On the other hand, the passive scanner does not emit any signal but uses only the acquired information to infer the points position in 3D space. Among the technologies exploited in the active scanners the most common are the laser triangulation, structured light scanner and Time of Flight (ToF) ones. As for passive scanners, the depth estimation is achieved through stereo vision or range imaging techniques (e.g., Structure from Motion)

The scanner mobility is another critical aspect to consider. We may distinguish handheld scanners from not portable ones. In particular, today, the handheld scanners represent an interesting resource in many research and commercial fields as medicine, industrial engineering, architecture, Cultural Heritage preservation and so on. This is because the price affordability related to performance gained and the convenience ensured by the portability. The handheld 3D scanners are the subjects of this chapter, so we provide a survey about the most recent devices. Table 1 reports specifications summary of the described handheld scanners.

Microsoft Kinect

Microsoft Kinect is massively employed in the home entertainment field and it is a device widely available in commerce (Figure 1). It consists of an infrared emitter, a sensor and a RGB camera. Exploiting structured light through a red dots pattern, Kinect can scan an object returning a mesh into RGB-D space, so meshes could be textured. It also contains an array of microphones to be used as interface for remote voice control. In the present day Kinect v2.0 is released (Figure 1). This version of the sensor shows several improvements with respect to the previous versions: for instance, depth camera resolution has been increased from 320×240 to 512×424, color camera resolution has been increased from 640×480 (VGA) to 1920×1080 (1080p, HD), the field of view (FOV) now reaches 70×60 degrees. The algorithms of skeleton tracking have also been improved, since now up to 6 people could be tracked (previously the limit was set at 2), with 26 bones per skeleton. Microsoft provides a SDK to develop and implement new applications with its sensor. Kinect requires wired energy supply and a processor unit to perform computations, so it is not an independent sensor. For completeness of information Asus developed Xtion PRO Live sensor (Figure 2): this sensor and Kinect v1.0 are quite similar to each other, with respect to their aspect, specifics and infrared technology adopted. These sensors are quite affordable and for this reason they are among the most diffused ones for the private users. Some examples of applications of these devices to cultural heritage could be found in the works of Cappelletto (2014) and Remondino (2011).

Scanify Fuel 3D

Scanify Fuel 3D (Figure 3): is a handheld device, thought to be handled like a steering wheel. It consists of two 3.5 Megapixels RGB cameras, three Xenon flashes (light emitters), three LED guide lights and two triggers (it makes the sensor easier to be used with a single left or right hand). It is based on a

Figure 1. Kinect V1 (on the left) and Kinect V2 (on the right)

Figure 2. Asus Xtion PRO Live

combination of photometric and image-stereo technology for 3D scan, so it can reach a depth accuracy of 0.35 mm. Thanks to photometric technology, acquisition time is under 0.1 second, reducing noise from scanned object movements. Furthermore, it performs its own motion compensation exploiting an optical target placed in the scene: this marker could be tracked, so the scanner can accurately estimate all the relative positions and orientations between itself and the target. The movement compensation could be a valuable feature when scanning human faces. However, acquired data must be processed by proprietary software and successively exported in standard format like .OBJ or .PLY. Fuel 3D does not provide any SDK, since algorithms to combine photometric and geometric 3D imaging systems are incorporated within Scanify software.

Google Project Tango

“Project Tango” is the name given by Google to its smart-tablet device capable of making 3D scans. Currently, it is provided only to developers: a registration to a whitelist of developer users is required in order to acquire a Tango device. An invitation is sent through e-mail with further instructions to obtain the sensor. As said, the sensor itself is embedded within a tablet that performs computation, so this makes Tango an independent handheld scanner. Besides to depth perception, it can also perform motion tracking and area perception. The features of Tango are completely described by thr online available documentation, in which Google developers documents API implemented for C, Java and Unity applications. This brings to very customizable applications developable with this sensor, but of course requiring professional programming skills by users. The sensor is shown in Figure 4. We do not have access to this device at the time of writing this survey.

Figure 3. Scanify Fuel 3D

Figure 4. Google Project Tango

Artec Eva and Artec Spider

Artec Spider and Artec Eva are two active handheld scanners produced by Artec 3D company. Both are semi-professional scanners which allow to acquire a high resolution mesh by using structured light technology. The Artec Eva (Figure 5) is available in two versions: lite and standard. The lite version is cheaper than the standard one, but it has not a camera sensor to acquire color information to register also the textures of the scanned 3D objects. The Eva is able to acquire 2,000,000 points per second with accuracy up to 0.1 mm and a resolution of 0.1 mm. The relative accuracy over the distance between the object surface and the scanner is up to 0.03% over 100 cm, however the recommended working distance is 0.4 – 1.0 m. The frame rate is 16 fps. The acquired meshes in each frame can be automatically aligned. As regard the Artec Spider (Figure 6), it has better accuracy (0.05 mm) at a higher price, but it is able to acquire 1,000,000 points per second with a resolution of 0.1 mm. The recommended working distance is lower than the one of the Artec Eva (0.17 – 0.35 m). This is because the Spider scanner is designed to scan small objects with a high complex geometry.

The color sensors mounted on the Artec Spider and Artec Eva standard is a camera with a resolution of 1.3 Mega pixels. It guarantees a medium quality of the acquired textures. Both the scanners are designed to be handheld, in fact they are very lightweight (0.85 Kg) and presents a convenient handle for a practical scan. It is important to note that these scanners need to be linked to a computer with mid-high range hardware. The cost of the scanners is around 9,000$ for the Artec Eva Lite, 13,000$ for the Artec Eva and 15,000$ for the Artec Spider.

Artec 3D scanners are employed for different applications, such as industrial manufacturing, plastic surgery, quality control and study of cultural heritage. In the field of the Cultural Heritage it has been employed in several contexts for digital preservation and analysis. In 2014, for example, Artec Spider has been used to acquire a set of 16 pieces of Hellenistic silverware of the collection called "Morgantina Treasure" which is dating from 3rd century B.C. (Alberghina et al, 2015). In this case the device has been able to acquire the complex geometry needed to reproduce metal objects details. The 3D models of the objects are accessible through a web interface.

Adams et al. (2015) produced a digital archive of 89 non-hominin holotype fossils discovered during a paleontological excavation by using Artec Spider. In the same year Artec EVA was employed to scan a Napoleon monument cast by the french sculptor Emmanuel Frémiet in 1867 (Moreno, 2015).

Figure 5. Artec EVA

Figure 6. Artec Spider

Occipital Sensors: iSense and Structure Sensor

This scanner consists in a small sensor which belongs to the category of active scanner and exploits the structured infrared light to create a 3D map of the scanned scene/object. The Occipital company designed two kind of sensors for two different markets: iSense for consumers and Structure for developers. Although the sensors are technically identical, the second one can be used to develop your own software for 3D acquisition and it is compatible with several other software suites (e.g., Skanect). To this aim, Occipital provides its own SDK and maintains OpenNI 2. The Structure Sensor is the handheld scanner that we have used in our case study.

The sensor can acquire objects up to 12 meters but a distance between 0.4 and 3.5 m is recommended. It has an accuracy of 0.5 mm which gets worse when the distance from the sensors and the volume of scan are increased. Since this scanner uses infrared structured light, it does not work well in full sunlight. This happens because the infrared light emitted by the sun interferes with the light pattern that the scanner projects on the objects surface. Hence, it is not advisable to use it in outdoor environment. Actually, in our study case, we take into account only indoor or partially covered outdoor environments. The sensor has not a camera to acquire texture information but it is possible to pair it with another camera as described below.

The Structure Sensor can be used in three different modalities. In the first and second modality the sensor is clipped onto an Apple iPad (or iPhone) through a proper bracket to make it a real hand held 3D scanner. In this case the camera of the iPad is used to acquire color information. The scanning session can be started using one of the applications developed by Occipital which are freely available on the App Store. In the first modality, it is possible to use these applications to acquire and to process the cloud points of an object to produce the final 3D model. Successively the produced model can be exported through email in different format (e.g., OBJ, STL). Unfortunately, the email exportation involves a compulsory heavy decimation of the acquired mesh. To solve this problem, the second modality allows to connect the iPad to a general purpose computer by using two softwares: Structure app on iPad and Skanect on the computer. The link between the two devices is a Wi-Fi connection. Specifically, to exploit this functionality the iPad and the computer have to be connected to the same Wi-Fi network (the same access point is recommended). In this way, the processing of the 3D cloud points is performed by the program Skanect which runs on the general purpose computer. This grants a higher computational capability than the iPad. This mode of exportation allows to save the mesh in the computer mass memory without decimation. The third, and last, modality of use is the direct connection of the sensor with a personal computer. In this case, no Apple devices are required and the scanner is directly connected to the computer by using a cable (called Hack Cable) provided from the Occipital (included in the Launch Bundle). The cable guarantees a higher framerate and a higher throughput than the Wi-Fi connection, but in this case the texture information cannot be acquired. This happens because the Structure Sensor exploits the iPad camera for this aim. In this mode the handheld scanning is less convenient because the visual feedback of the scanned surfaces is redirect from the sensor to personal computer, making acquisition process less practical. The Structure Sensors, clipped on an iPad, is shown in Figure 7.

The price of the Structure Sensors is relatively affordable, indeed the Launch Bundle (with cable and Skanect license) can be purchased with about 500$. If we include for the complete system the cost of an iPad, a total cost will be about 1,000$. At the best of our knowledge the Structure Sensor has not yet largely exploited in the field of the Cultural Heritage.

Figure 7. Structure Sensor clipped on the iPad

Table 1. Specifications summary of the described handheld scanners

Scanner	Accuracy	Resolution	Acquisition Speed	Texture
Kinect V1	n.a.	n.a.	30 fps	Yes
Kinect V2	n.a.	n.a.	30 fps	Yes
Asus Xtion PRO Live	n.a.	n.a.	n.a.	Yes
Scanify Fuel 3D	0.35 mm	n.a.	10 fps	Yes
Google Project Tango	n.a.	n.a.	n.a.	Yes
Artec Eva	0.1 mm	0.1 mm	2,000,000 per second	Yes (standard ver.)
Artec Spider	0.05 mm	0.1 mm	1,000,000 per second	Yes
Structure Sensor	0.5 mm	1.0 mm	30/60 fps	Yes (with iPad)

Case Study: Benedettini Doorway

To provide a realistic evaluation of hand held scanning techniques we choose to work on an architectural object that was likely to be interpreted for the concomitant presence of simple and complex geometrical shapes. For this reason, we chosen the eighteen century doorway in the complex of the Benedettini in Catania: this doorway, realized with limestone, is made by the plane surfaces of the jambs and architrave, the complex surfaces of the moldings (bed cornice, cymatium and tympanum), the sculpted decorations of the frieze and the capital.

The doorway is located in the gallery at the first floor of the monastery and it provides access to one of the cells of the friars nowadays used as offices for the Department of Humanities of Catania University.

After some brief historical notes on Benedictine Monastery of Catania, a UNESCO heritage monument, this section deals with the 3D data collection, processing and modeling by means of Structure Sensor Scan in order to provide a full low cost and open source 3D pipeline. Furthermore, a comparison with other 3D acquisition techniques is carried on: Image Based Modeling and ToF scanning. IBM techniques could constitute a valid alternative or complementary technique to be used in a low cost approach, so the test will evaluate the level of accuracy and the possibility of integration of this two low cost techniques; ToF scanning will provide a ground truth for the metric accuracy tests. In the results subsection all the outputs will be highlighted and discussed.

Historical Notes

The Benedictine Monastery of Catania was founded by a Cassinese congregation in 1558. Unfortunately, the original structure suffered two natural calamities: Etna eruption of 1669 and a strong earthquake in 1693. The monastery was reconstructed only nine years later, in 1702 (Hittorff, 1835). Since a high number of monks moved in the Benedictine Monastery from other minor monasteries, the construction itself compared to the original plan was expanded. The “Marble” (Western) Cloister was renewed with fine late-baroque decorations. A new Cloister, called “Eastern”, was build together to its garden and the Caffeaos in eclectic style. Furthermore, on the North side was planned and built an area to host the novices’ aisle, the dining rooms, the night choir (chapel). On the ground covered by lava eruption were built two gardens: the botanical garden (also called the “wonders garden”) and the novices’ garden. Near to the Monastery, the huge church of San Nicolò l’Arena was conceived as a small Sicilian Saint Peter, but its facade remained unfinished. Several famous Sicilian architects not only from Catania, but also from Palermo, Messina and Siracusa, gave their contribution in the reconstruction of the Monastery: Ittar, Battaglia, Battaglia Santangelo, and Palazzotto. Among these artisans, Giovanni Battista Vaccarini is one of the most important one: indeed, he designed the kitchen, the main dining-hall and the library (nowadays called “Biblioteche Riunite Civica e Ursino Recupero”). The great Palermitan architect has studied in Rome and knew other master architects like Fontana, Michetti and De Sancis, but his main references were Bernini and Borromeo, who inspired his work.

The Monastery was confiscated in 1866 by the Italian state and re-used a couple of years later for civil scopes. More than a hundred years later, in 1977 the Monastery was donated by the Municipality to the University of Catania, that hosts within it the Department of Humanities. This donation was part of the project of regeneration of the historical centre in which the architect Giancarlo De Carlo supervised yet another restoration of the Monastery. As a result, the very value of the Monastery has increased and it is now to be considered a best practice example of Contemporary Architecture funded by the Sicilian Regional Government. Eventually, the Monastery has been given back to the community with a rich history of centuries of cultural, social and architectural influences. For this reasons in 2002, UNESCO included the Monastery in the World Heritage List (Website Benedettini, 2015).

The last restoration of the Monastery lasted thirty years and has led to the discovery of some ruins from the Roman time. An entire Roman neighborhood with the two main axes the Cardum and the Decumanus Maximus, houses of the late Hellenistic and imperial time has been found under the monastery. Nowadays, visitors can see the remains of this ancient society in the Monastery main court and under the old Monastery stables. Even a domus (Roman house) is still visible near the Monastery library, integrated in the structure since the 16th century.

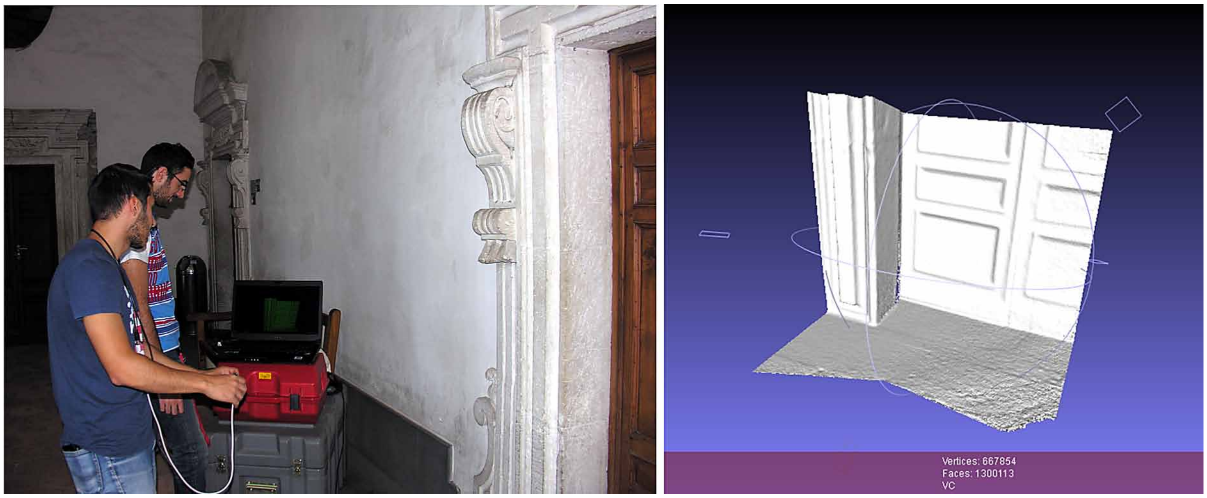
It is significantly beautiful that today young undergraduate students walk in Monastery locals just like monks did centuries ago. This fact can give us the idea of how the role of the Monastery is not lost, but really persists through the age.

Structure Sensor Scan

For a proper acquisition of the doorway model, we decided to use the Structure Sensor in the third modality described in the previous section. Our decision is motivated by the fact that the iPad low performance influences the final result. Moreover, the exportation process through email is slow and requires an unacceptable decimation. The second modality (iPad linked to computer) was discarded too because of the low framerate that the Wi-Fi connection suffers in certain situation. Hence, we chose to use the Structure Sensor through a direct cable connection to the computer with Skanect. Although this approach involves the loss of color information, color and texture are not considered in the comparison performed in our study.

The resolution of the final geometry acquired with the Structure Sensor depends on the scanned volume and on the specific features of the acquired object. Several tests performed before data collection highlighted the difficulty to acquire the doorway in a single scan: the loss of details would invalidate the pipeline and the following verifications. For this reason, we decided to use a scanned volume of 1 m^3 and acquire all the parts of the door by starting from the bottom left position in successive phases. For the subsequent alignment process, we have acquired each part of the door so as to ensure about the 30% of overlapping between two adjacent pieces. Overall, 23 meshes have been acquired in accordance with the previously described settings and have been exported in OBJ format.

Figure 8. The bottom-left part of the doorway acquired through the Structure Sensor.



The whole acquisition process has required about 2 hours and a high caution by the human operator to avoid geometry aberration at some acquisition step. The average number of vertices for each mesh is about 600,000, while the face are about 1,000,000. It can be noticed that the acquired meshes presented a certain amount of noise (e.g., isolated faces). In the post-processing phase, we have used the software Meshlab to remove many artifacts and reduce the points redundancy (by Quadric Edge Collapse Decimation). In this process, the 80% of the points in each mesh has been removed without visual-perceptible loss of details. All the processed mesh has been aligned by using the Point Glue tool of Meshlab and saved in OBJ format.

Considerations on Structure Sensor Behavior with Different Light Conditions and Object Materials

The 3D scanner behavior during objects acquisition often depends on the environment light conditions and the surface material of the acquired object. For instance, devices which exploit structured infrared light, such as Structure Sensor, are not suitable for outdoor usage, since the sunlight is a massive interference source. Specifically, infrared waves of the sun can disturb the infrared pattern which the scanner employ to acquire depth information. As a human which looks directly to the sun, these devices become totally blind. For this reason, infrared technology is best suited for indoor usages.

The other criticism of infrared scanner is related to the surface materials. Rays bounce up not opaque surfaces, as polished marbles or plastics materials. Generally, every surfaces that acts like a mirror could cause a misalignment in the infrared sensor, with the result of an incorrect 3D estimation. A pragmatic solution to solve this problem is to cover the reflective surface with a proper matter, by making it opaque. However, in accord with cultural heritages fragility and size this solution is often not feasible. Similarly to reflective materials, infrared technology is not suitable for transparent materials too: they are invisible for the sensor. In the same way, black objects adsorb the infrared light, so that they results totally invisible for the most of 3D infrared scanner.

A third weakness of most of 3d scanning technologies, emerge when an extremely flat surface is acquired: plane surfaces typically have few structural details. In this case the 3D scanner warn often the user with a message like "Not enough geometry". A practical solution for flat surface acquisition is to put some markers on the plane. Pins represent an irregularity on the plane that augment the geometry complexity to allow the 3D scanner to perform a correct alignment.

Structure Sensor device, adopted for this study, suffers of the aforementioned troubles. The door of our study-case is mainly made up of three materials: opaque limestone in the door jamb and decorations; opaque wood in the door; polished metal for the handle, the lock and the plate on the wall. Acquisition results shown how the opaque materials have been acquired without any substantial modification, while, according to the above discussion, the polished elements have been slightly flattened or distorted. Moreover, the indoor environment has been chosen to avoid sunlight interference.

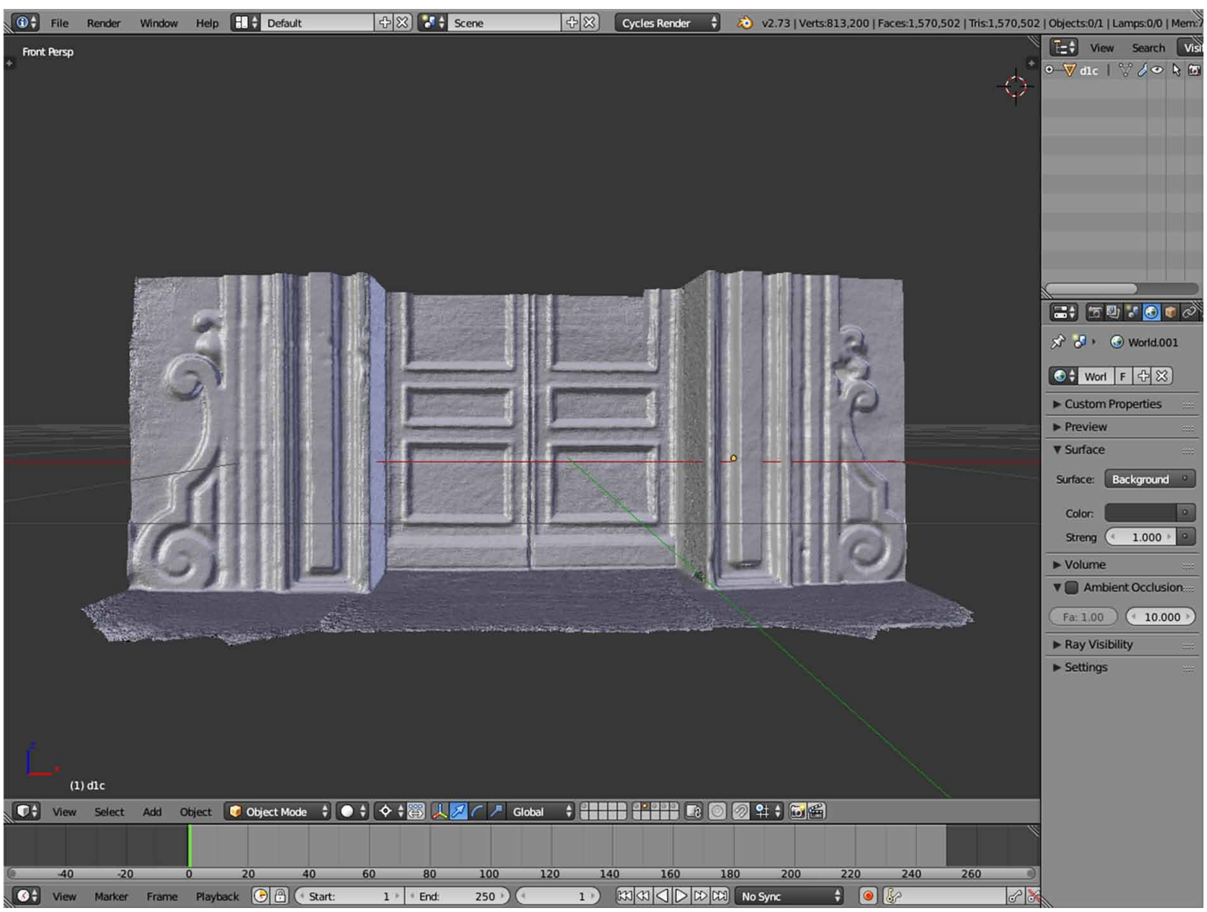
3D Modeling

A 3D version of the doorway has been modeled using the open source software Blender. In this section we present a brief report about the procedure that has been adopted to model each part of the object (Figure 10-11). In particular, we distinguish six main parts of the doorway model: Bottom Decor, Door Frame with Frieze, Door Caissons, Top Decor, Top Part, Frieze. The wall and the floor are simple parallelepipeds. To get all the precise measures of the object, we have used data coming from the Structure Sensor scan (as general scheme) and photo references taken during the survey in situ.

Figure 9. View of the Structure Sensor behavior on three different materials (from left to right): wood, metal, limestone

Figure 10. The final 3D model where the six main parts highlighted.

Figure 11. 3D modeling step in Blender



The *Bottom Decor* has been modeled in three steps:

Step 1: The bottom spiral has been created by Curve extrusion and Subdivide Surface;
Step 2: The mid area has been modeled by starting from a Circle and using the vertex of a Semi-Curve. The faces have been merged by Bridge Edge Loops and an extrusion has been performed;
Step 3: Direct re-topology has been employed for the top area.

All the three sub-parts have been mirrored along the horizontal axis.

To model *the Door Frame with relative Frieze*, we started from a vertex and extruded it by following a scan profile. To complete the entire Frame, it has been necessary a reference pattern. To this aim, we have used an entire low-detailed scan of the door, realized through Structure Sensor.

To get the *Door Caisson* sizes, we used photographic material. The first quarter of a single Caisson has been modeled by Curve and extrusion. The rest three quarters has been obtained through Mirror replication, along X axis and Z axis. This single Caisson has been used to produce all the others by modifying the scale and the position. The Loop Cut tool has been exploited to simulate the grooves of the Caissons.

Similarly as the Bottom Decor, also the *Top Decor* has been modeled in three distinct steps:

Step 1: The lateral motif has been realized by Curve extrusion and the volume has been obtained by another extrusion along the axis X. To produce the grooves on this part, we exploited the Loop Cut tool;
Step 2: The second part of the Top Decor has been realized through Curve and extrusion;
Step 3: Finally, the bottom region has been modeled by starting from a Cube, which was scaled along X axis and replicated.

To create the *Top Part* of the door, we have used the photos taken during the acquisition phase as reference pattern.

Step 1: The bottom region is a Curve converted in mesh and rotated of 45°;
Step 2: The rest of the Top Part has been created through Curve "path" (semicircle).

Finally we have modeled the *Frieze* by drawing the half of the decors shape and used the Mirror tool to obtain the entire area. This flat Mesh has been in turn rounded by extrusion and Sub-surfing. To refine the mesh and to add the details, we have used the "Sculpt Mode".

All the six aforementioned parts, have been placed e rescaled in a single 3D environment in order to produce the final model shown in Figure 10.

Comparison with other 3D Acquisition Techniques

The promising results of this research require a verification of the reconstructed 3D geometries with a comparison with other well established and known technologies for 3D scanning in the field of Cultural Heritage. To this aim the same doorway has been acquired both by means of low cost Image Based Modeling techniques (nowadays applied in several fields) and ToF Laser Scanning in order to have a ground truth to carry out a visual and metric comparison. The pipeline followed is by the time used in literature (Remondino, 2011; Santagati et alii, 2013; Inzerillo & Santagati, 2013; Ballabeni et al, 2015; Galizia et alii, 2015) and foresees the alignment of the different models in the same reference system and the calculation of the distance between the meshes by means of Hausdorff distance algorithm application.

Image Based Reconstruction

The well known IBM techniques are closely dependent on the quality of the dataset (network, image resolution, radiometric quality). In this case, the data set has been easy due the planar aspects of the entire architectonical object. For this reason it was enough to do two laps both for the overall doorway and for the details (Figure 12). Table 2 reports all the specifications inherent the dataset including, Ground Sampling Distance (GSD). The acquired dataset has been processed by using low-cost photogrammetric suite Agisoft Photoscan.

Differently from free web-based packages (123D Catch, Recap, ARC 3D), Photoscan gives the user the possibility to properly set the parameters of the 3D reconstruction. The reconstruction takes place in two steps: at first the software performs a 3D alignment between the images and gives back a sparse point cloud, then it is possible to obtain a dense reconstruction where also the mesh and the textures are computed. The right choose of sparse and the dense reconstruction parameters will affect the quality of the 3D model in terms of sharpness of edges and smoothness of surfaces.

In this case the geometric features of the doorway led us to chose a high quality reconstruction and a moderate depth filtering reconstructions with a generated model of 30 Millions of vertices and 3,8 of triangles. Then we proceeded with the texturing of the model (Figure 13-14) that has been exported in .OBJ format for the following tests.

Figure 12. Agisoft Photoscan IBM reconstruction

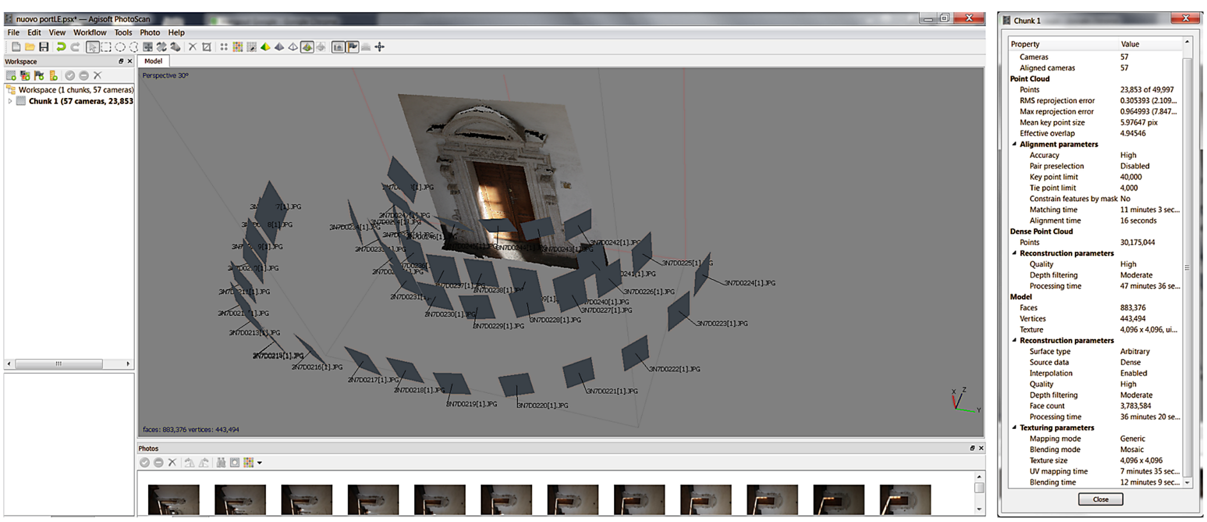


Table 2. Specifications summary of the Image Based Modeling dataset.

Camera	Resolution	Focal Length	Number of Images	GSD	Processing Time
Canon Eos– 1Ds Mar II	21 Mpix	24 mm	57	0,001 m	95 min

Figure 13. View of a detail of Image Based Reconstruction in different visualization modes: textured, shaded and x-ray

Figure 14. View of the overall doorway reconstructed by means of Image Based Modeling in different visualization modes: textured, shaded and x-ray

Time of Flight 3D Acquisition

For the 3D acquisition of the doorway model through a ToF laser scanner, we used HDS 3000 by Leica Geosystem. In order to have coverage of the doorway as complete as possible we decided to carry out three scans: one frontal and two lateral (Figure 15). The specific aim of this study leaded to choose a scan step very dense (about 2 mm) to have a very detailed point cloud. In these cases, as reported in previous literature works (Callieri et alii 2009), the size of the noise exceeds the sampling rate so that it hides the details: in the following meshing phase it is mandatory to apply a specific combination of surface reconstruction and smoothing algorithms in order to avoid spikes meshes.

The first step was the registration of the three point clouds into a unique reference system, then the scans were assigned to different layers in order to easily erase the "mixed point" noise generated in the areas where the laser beam hits the surfaces tangentially. At the end of this step the overall model resulted in a collection of 3.6 million of points. The point clouds have been exported in .PTX format for their processing in the open source software Meshlab software (Cignoni et alii 2008). In Meshlab we carried

Figure 15. In situ 3D acquisition and view of the point cloud

out the merging of the separate scans into a unique model, then we applied the pipeline suggested by Callieri et al. (2009) by testing and choosing the parameters that better solved the problem to smooth the surfaces without losing details.

The Poisson reconstruction algorithm was applied. This algorithm tends to reconstruct a watertight surface and a lot of new and not useful geometry is often created. Hence before to go ahead applying the other algorithms, it has been necessary to delete the new geometry by using the selection filter "select faces with edges longer than.." and by deleting manually the isolated faces that still survived. Then the HC Laplacian and finally the Twostep smoothing have been applied. For each one of the algorithms particular attention has been paid into properly balance the parameters in order to maintain details. Figure 16-17 show the different processing steps up to obtain the expected result.

Figure 16. Mesh processing steps on a detail: from the spikes meshes to the final smoothed model

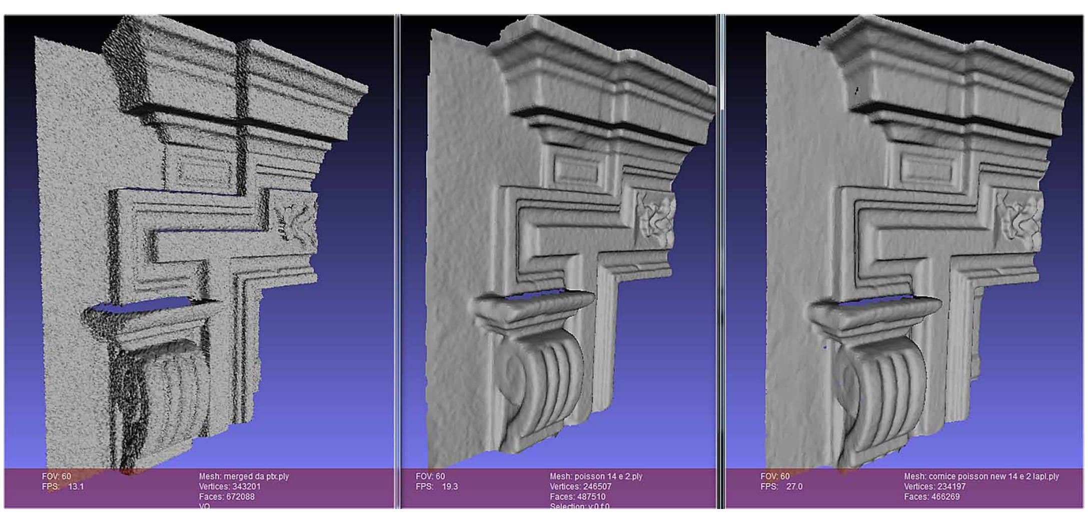


Figure 17. Mesh processing steps on the doorway: from the spikes meshes to the final smoothed model

This procedure has been applied both on the overall model and on smaller portions with the same size of Structure Sensor acquisition scans for the further metric comparison. It can be noticed that after the post-processing smoothing the number of points of the doorway complete model is 1 million.

Results

The mesh models obtained through Structure Sensor technology have been compared with the TOF models, furthermore Image Based models have also been compared with ToF models. The comparison has been carried out considering both the single scans and the overall model that, in the case of Structure Sensor model is made by the assembly (alignment) of 23 scans in Meshlab.

A first consideration that can be done, in terms of visual accuracy of the 3D reconstructions, is that the Structure Sensor single scan models are more detailed and less noisy in respect to ToF and IBM reconstructions. This is what we already expected due to the type of sensor used.

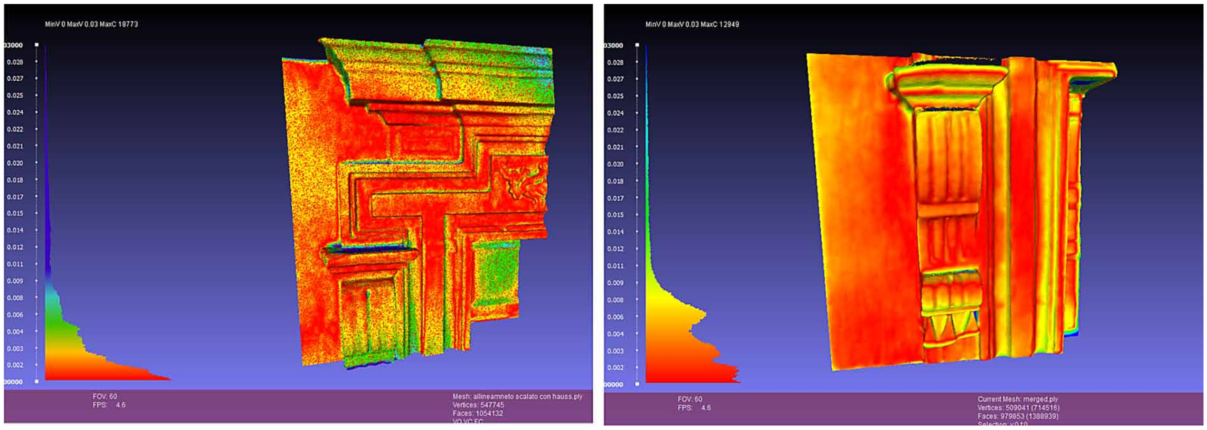
Such as for the metric comparison among the single scans models, we chosen two different parts of the doorway that present complex surfaces and many details. For clarity of presentation we will give them the name of model A (frames and mouldings of the jams and entablature) and model B (capital).

In both cases, the alignment between Sensor Structure model/ToF model involved an alignment error of 0.003 m. Then, the Hausdorff distance, calculated between the two mesh assigning as range values 0.00 and 0.03 m, gave back these statistic values:

Model A Mean: 0.004344 m and RMS: 0.006879 m;
Model B Mean: 0.004775 m and RMS: 0.006797 m.

Beyond, the single statistic values, it is very interesting to read the trend of the histogram and observe the distribution of the distances between the two meshes directly on the 3D model (figure 18), where the red color means the minimum distance between the two meshes and the blue means the maximum one.

Figure 18. Hausdorff distance and subsequent quality histogram between TOF model and Structure Sensor model of two chosen details



In the case of the comparison between IBM and ToF models, the alignment error is also equal to 0.003 m. In the Hausdorff distance calculation, we applied as range values 0.00 and 0.03 m, so that to have comparable results. The calculation gave back these statistic values:

Model A Mean: 0.002613 m and RMS: 0.004948 m;
Model B Mean: 0.003712 m, RMS: 0.005490 m.

In figure 19 it may be deduced the trend of the histogram and the visualization of the distribution of the distances on the model.

Moreover, after doing so, we carried out the alignment between the overall doorway model acquired by Structure Sensor /ToF model. A detailed visual analysis of the Structure Sensor overall model revealed some mismatches in the overlapping areas. These alignment errors could be interpreted as fallacies of

Figure 19. Hausdorff distance and subsequent quality histogram between Image Based model and ToF model of two details

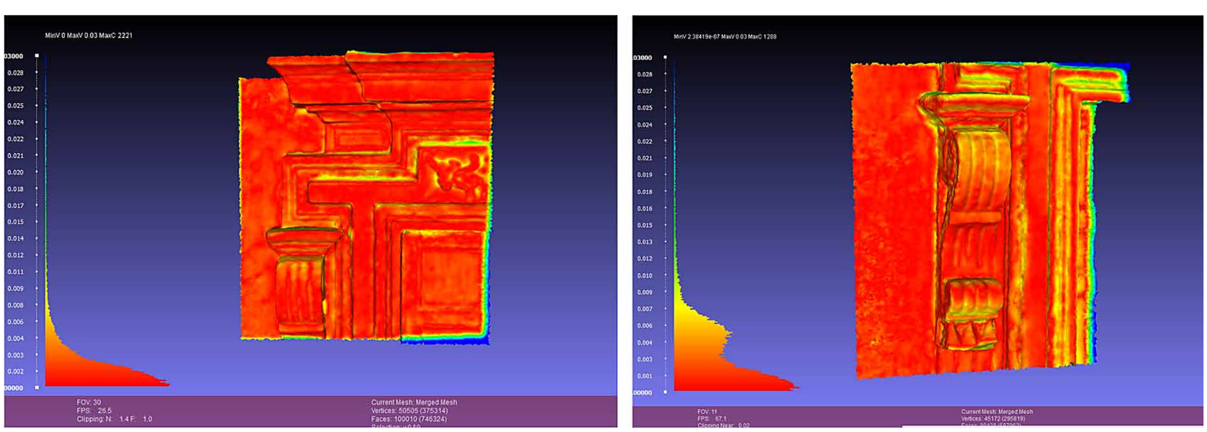
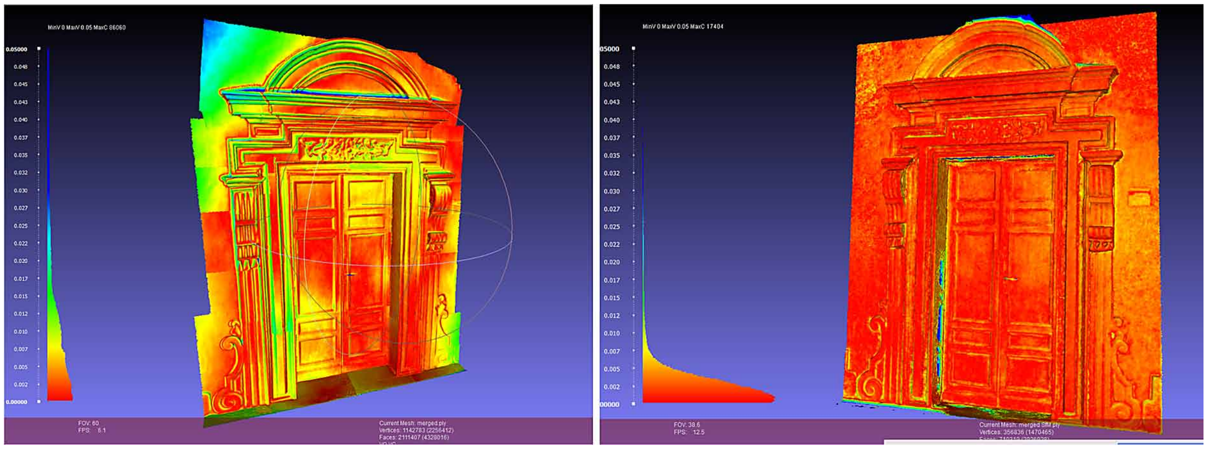


Figure 20. Hausdorff distance and subsequent quality histogram between TOF model and Structure Sensor model



the alignment step probably due to boundary geometric inconsistencies of the single scans. In order to take into account these mismatches, we calculated Hausdorff distance giving as range values 0.00 – 0.05 m. The calculation gave back these statistic values:

Mean: 0.009619 m and RMS 0.014104 m;

However, from figure 20 (left) it can be inferred the slippages among the single scans and the single elements mismatching.

Finally, we compared the IBM model of the overall doorway with the ToF model. The alignment error is equal to 0.003 m. For the calculation of Hausdorff distance, we chosen the same calculation range of the previous test in order to have comparable results. The processing gave back these statistic values:

-mean: 0.003427 m RMS: 0.006673 m which are compatible with other results reported in current literature studies (Barazzetti et al, 2010; Remondino et al, 2012; Kersten et al, 2012; Campos et al, 2015).

The obtained results can be deduced from figure 20 (right) that shows the outcomes of Hausdorff calculation directly on the model and the trend of the histogram.

FUTURE RESEARCH DIRECTIONS

The methodology developed in this study allowed us to analyze and verify the performances of Structure Sensors in Architectural Cultural Heritage field. The chosen case study highlighted the weakness and the advantages of using this kind of sensors.

According to the achieved results, the Structure Sensor is suitable for little size objects (~1 mt), in this case the performances are very high. Nevertheless, for larger objects the need to proceed by aligning several scans may produce the same problems encountered in this study.

Some problems could be avoided by improving data recording transmission between the Ipad and the laptop: the mere use of the sensor separated from the Ipad increases the mechanical instability and the noise during data recording.

The future research directions will be addressed into the overcoming of these limits; will choose other case studies (of larger and smaller size and different materials) in order to refine the applied methodology and to develop data collection protocols able to enhance the criticalities occurred during scan registration step. These tested technologies, if optimized, could have a wide range of applications; for example in these last years the attention of researchers has been focused on the semantic-awareness of 3D models in cultural heritage field, to structure an informative knowledge system for architectural details (Apollonio et al, 2013; De Luca, 2012; Fai et al, 2011; De Luca et al, 2007) in order to be used in Heritage Building Information Modeling projects.

The goal is to achieve a low cost indoor procedure where other low cost techniques, such as IBM workflows, reveal more criticalities and require more expedients in environmental conditions setup.

CONCLUSION AND DISCUSSION

In this study we developed an investigation methodology aimed at the verification of the low cost Structure Sensor scanner in Architectural Cultural Heritage field. The methodology was structured in order to cover a low cost and open source 3D pipeline from 3D acquisition to the digital replica. Our methodological approach involved also a metric and visual verification of the Structure Sensor carrying out a comparison with other well assessed technologies: ToF scanning and IBM.

The results of our tests highlighted that Structure Sensor technique constitutes a valid methodology if it is implemented/integrated with other low cost 3D acquisition technologies, e.g. IBM approach by using low-cost photogrammetry packages (Agisoft Photoscan). As it could be envisioned, the weakness of this technology is the resolution of the sensor: if the object is too large or too detailed it is necessary to carry out several scans to cover it, and this could create several problems in the subsequent registration step (as for the doorway studied in this chapter). Instead, on architectural details the resolution of the Structure Sensor allows to obtain very detailed 3D models that could serve to integrate ToF scannings or IBM models.

It could be envisioned that the constant and rapid technological evolution, in the forthcoming years, shall enhance the performance of this sensor making it very competitive in the market.

ACKNOWLEDGMENT

The authors would like to thank prof. Giancarlo Magnano di San Lio, dean of the Department of Humanities of University of Catania, for the access to the doorway.

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KEY TERMS AND DEFINITIONS

Bridge Edge Loops: Blender tool used to join a series of adjacent edge loops (a set of connected edges across a surface.). It creates a group of faces, joining two selected edge loops.

Extrusion (Blender): Blender command which allows to duplicate vertices, edge and face along a chosen dimension. For example it allows to create parallelepipeds from rectangles or cylinders from circles.

Hausdorff Distance: A distance used to measure the difference between two subset in a metric space. It is defined as the greatest of all the distances from a point in one set to the closest point in the other set.

HC Laplacian Smoothing: Extended version of the Laplacian Smoothing algorithm. It smooth the mesh by computing the new vertex position as the average of the nearest vertices.

Loop Cut: Blender command to split a loop of faces by inserting a new edge loop intersecting the chosen edge.

Poisson Surface Reconstruction: An algorithm which use the points and the normals to build a 3D surface. The algorithm considers all the points at once and is therefore highly resilient to the noise.

Quadric Edge Collapse Decimation: An algorithm available in Meshlab which is able to reduce the face number of a 3D mesh and preserve boundary and/or normal.

TwoStep Smoothing: A smoothing algorithm which consists in two main step. First, similar normals are averaged together. Second, all the vertices are fitted to the new normals.