ASSESSMENTS FOR 3D RECONSTRUCTIONS OF CULTURAL HERITAGE USING DIGITAL TECHNOLOGIES

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ABSTRACT:

The aim of this contribution is to show the results of evaluations on 3D digitizations performed using different methodologies and technologies. In particular, for surveys conducted at the architectural and urban scale, the recent reduction of costs related to Time of Flight and phase shift laser scanners is actually enhancing the replacement of traditional topographic instruments (i.e. total stations) with range-based technologies for the acquisition of 3D data related to built heritage. If compared to surveys performed using traditional topographic technologies, range-based ones offer a wide range of advantages, but they also require different skills, procedures and times. The present contribution shows the results of a practical application of both approaches on the same case study.
Another application was suggested by the recent developments in the photogrammetric field that enhance the improvement of software able to automatically orient uncalibrated cameras and derive dense and accurate 3D point clouds, with evident benefits in reduction of costs required for survey equipment. Therefore, the presented case study constituted the occasion to compare a range-based survey with a fast 3D acquisition and modelling using a Structure from Motion solution. These survey procedures were adopted at an architectural scale, on a single building, that was surveyed both on the outside and on the inside.
Assessments on the quality of the rebuilt information is reported, as far as metric accuracy and reliability is concerned, as well as on time consuming and on skills required during each step of the adopted pipelines. For all approaches, these analysis highlighted advantages and disadvantages that allow to conduct evaluations on the possible convenience of adopting range-based technologies instead of a traditional topographic approach or a photogrammetric one instead of a range based one in case of surveys conducted at an architectural/urban scale.

1. INTRODUCTION

1.1 Introduction and Aims

In the Cultural Heritage field, the wide range of possible applications offered by reality-based 3D modelling techniques through digital technologies is well known among scholars, as well as to the wide audience. Nevertheless one of the main reasons that limited their widespread is represented by the high costs connected with their use.
This weakness recently gave rise to researches that developed improvements to both software and hardware aimed at extending their use and at turning them into a standard practice to be adopted for the wide digitization of sites and artifacts. In particular, the reduction in costs of sensors is actually widening the use of range sensors for 3D digital surveys and the recent developments in the photogrammetric field enhance the improvement of software able to automatically orient uncalibrated cameras and derive dense and accurate 3D point clouds, with evident benefits in reduction of costs required for survey equipment.
In addition to these aspects, for low-resolution surveys, the availability of Structure from Motion (SfM) tools is spreading the practice of a fast and easy acquisition of 3D shapes also by non expert operators.

These considerations motivated the present contribution whose aim is to show the results of evaluations on 3D digitizations performed using different methodologies and technologies. In particular, for surveys conducted at the architectural and urban scale, the recent reduction of costs related to Time of Flight and phase shift laser scanners is actually enhancing the replacement of traditional topographic instruments (i.e. total stations) with range-based technologies for the acquisition of 3D data related to built heritage.
If compared to surveys performed using traditional topographic technologies, range-based ones offer a wide range of advantages, but they also require different skills, procedures and times.
The present contribution shows the results of a practical application of both approaches on the same case study. Assessments on the quality of the rebuilt information is reported, as well as on time consuming and on skills required during each step of the pipeline. For both approaches, these analysis highlighted advantages and disadvantages that allow to derive evaluations on the convenience of adopting range-based technologies instead of a traditional topographic approach in case of surveys conducted at an architectural/urban scale.
The same case study constituted the occasion to compare a range-based survey with a fast 3D acquisition and modelling using a SfM solution; as these technologies are actually spreading, evaluations on their reliability can interest different subjects.
These survey procedures were adopted at an architectural scale, on a single building, that was surveyed both on the outside and on the inside and on a wall that surrounds the related urban

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space. In this case, 3D models acquired using range-based technologies were decimated in order to compare 3D information with similar level of detail of the information and therefore derive assessments on metric accuracy and reliability provided by both methodologies.

1.2 The case study

This project was conducted within the research "Protocols for the enhancement, conservation and fruition of architectonical cultural heritage" developed at the CIRI (Centro Interdipartimentale di Ricerca Industriale) of the University of Bologna, Italy.
The aim of this project mainly relies in the development of protocols for the diagnosis, for the planning of interventions and for the management of cultural heritage. These analysis are predicted in order to both improve the state of conservation of selected case studies and to insert them in a consolidated urban, cultural and touristic context.
One of the case studies on which these investigations are being held is Piazza degli Ariani in Ravenna, Italy.
Due to its marginal location with respect to other touristic itineraries of Ravenna, Piazza degli Ariani suffers for a progressive urban degradation that is actually being faced by local Authorities. As a matter of fact, as this site hosts the UNESCO World Heritage architecture of the Battistero degli Ariani, besides other important religious and cultural exemplars, the need to increase their values and visibility is really an urgent task.
Piazza degli Ariani is surrounded by the inner octagonal volume of the Battistero degli Ariani, that was commissioned by Teodorico during the first half of the VI century A.D. and that represents a unique example of baptistery dedicated to the Aryan cult, as it is also documented through the mosaic decoration of the vault.
Beside this monument, the Chiesa dello Spirito Santo is connected to the baptistery through the Drogdone Wall that belonged to the building that, at the end of the VI century, hosted Drogdone, the Longobardic warlord that decided to support the Byzantines and defend Ravenna. After that episode, this building hosted various religious orders.
The actual asset of this square is the result of the urban stratifications of the last fifteen centuries. These transformations, in addition to the presence of different properties and to the subsidence phenomena that characterizes the whole territory of Ravenna and that progressively lowers the ground level of the square, do not facilitate the conservation and enhancement of this area.
In order to plan and promote its urban redevelopment, an accurate documentation of it is mandatory; as a consequence, a series of surveys and investigations have recently been started.
The complexity of this site and the different properties that stand on this area suggested to widen investigations beyond public properties, in order to evaluate the possibility to create new paths and ways of benefiting of this space. As a consequence, survey campaign was expanded to private courtyards that surround the square and its main buildings.

2. SURVEY PROCEDURES

2.1 The Traditional Indirect Measurement Approach

The survey of Piazza degli Ariani using a traditional approach was planned in order to build orthographic projections that can be used in technical drawings for documentation aims at different scales of complexity, ranging from 1:200 to 1:20.
In order to correctly plan the survey, these aims and the complexity of this urban space were evaluated together with other factors, such as, for example, times and skills required to conduct the survey campaign and to restore the expected level of detail of the information.
The need to find the best compromise between these different aspects and meanwhile build a detailed and accurate representation of the square through orthographic projections led to the adoption of a double approach.
On one side, the main metric information about geometry of single buildings and their context were acquired using the Geotop Topcon GPT-3005N total station, while other information that were considered less important that the first ones, such as, for example, elements on facades of surrounding buildings, were derived from orthophotos.
The survey campaign was organized in order to build a total station loop traverse around Piazza degli Ariani and its context and then measure all pre-selected main elements.
Due to the complex and irregular shape of the square and to the presence of obstacles, such as, for example, trees and tall walls, the loop traverse was built using 13 station positions.
A 3 days campaign conducted by 2 skilled operators allowed the geolocation of 1763 points.
In order to re-build all architectural elements that completely document this case study also through elevations, this number of points was not satisfactory, so that the location of secondary elements was derived from orthophotos during the post processing of data. As a drawback, these last measures are generally affected by higher errors than the main ones.
During survey campaign, some aspects and procedures highlighted difficulties and criticalities. The main ones consist, for example, in difficulties in the laser spot recognition due to bright light and in difficulties in measuring selected points due to the presence of obstacles, such as trees and walls. In this last case, additional stations were placed in areas that did not need to be surveyed.
Moreover, in some cases, the presence of leaves that were not clearly visible using the total station because of their proximity to the operator, caused errors in the measurement of the location of selected points. In these cases, errors were highlighted only during post-processing of data, so that other surveys were required.
Furthermore, another problem that characterizes both traditional surveys and range-base ones is the increasing of errors in angular measurements.
In order to prevent all these difficulties in advance and therefore reduce time consuming and costs, it is generally recommendable to use expert operators that are able to select the proper elements to measure during survey campaign and that are also responsible of the post-processing of data.
It is also generally recommended to perform the post processing of data soon after survey campaign.

2.2 3D Dense Measurements Approaches

The range-based approach was performed with the double aim of comparing its results with the ones that were acquired using a total station and a SfM solution.
These last two approaches are usually adopted in order to restore two different kinds on information. In particular, while a total station survey is generally performed in order to build orthographic projections to be used within technical drawings, the SfM one is generally adopted with the purpose of building textured meshes and use them mainly for simulations in 3D computer graphic.
Nevertheless, assessments on the quality of the restored

information that these last technologies can return in terms of definition and accuracy is interesting in order to evaluate if their field of application can be widened (Hermon et al., 2010; Fratus De Balestrini and Guerra, 2011; Dellepiane et al. 2012). The survey of Piazza degli Ariani was therefore considered as an interesting case study for these tests and derive related evaluations.

2.2.1 Range-Based Approach: The range-based survey of Piazza degli Ariani was conducted using a Leica ScanStation C5 TOF laser scanner. The survey campaign lasted one day and was conducted by two operators who measured the location of 216 millions of points through 18 stations.
Differently from a traditional approach, the presence of the second operator was not mandatory for the successful conduction of the survey campaign, but helped in the handling of the heavy instrument.
The survey was conducted without targets with the purpose of speeding it and therefore limit costs. As a consequence, in order to fulfil a fine global alignment, wide overlapping areas within adjacent scans was followed.
A far as the definition of single scans is concerned, the purpose of speeding survey campaign required evaluations on the best compromise between the detail of the acquired data and acquisition speed. In particular, each station was performed setting a grid of points whose reciprocal distance is 2x2 cm at 20 m of distance from the instrument. This process needed more less 20 minutes to acquire each 12 millions point cloud and the 260 correspondent high resolution images.
The post processing of data was organized following this pipeline: i. removal of obstacles or useless data, such as trees, people, cars; ii. orientation of single point clouds within a single reference system; iii. location of trimming planes to be used to draw sections in orthogonal projections; iv. 2D vectorization of the whole registered point cloud.
During the alignment of single point clouds, difficulties were encountered in the recognition of homologous points due to occlusions caused by dense vegetation of gardens.
Other difficulties were faced also in the management of the large amount of data.

2.2.2 Structure from Motion Approach: The Structure from Motion approach is based on the principle that the structure of four non-coplanar points is recoverable from three orthographic projections (Ullman, 1997; Pollefeys et al., 1998; Brown and Lowe, 2005; Snavely et al., 2006).
This approach is actually purchasing a lot of attention, both in research contexts and among the wide audience, as it can contribute to the lowering of times and costs required to survey dense and accurate 3D information about objects and scenes.
The growing attention towards these technologies is evident in the development of different packages, that have different characteristics and that are often freely and widely used. Arc3D, Acute3D, Autodesk 123DCatch, Insight 3D, Bundler, PMVS2, FIT3D, VisualSFM, Hypr3D, APERO, 3DSOM, Photoscan, PhotoBuilder (1) are just some examples.
Among them, some solutions were developed as web service technologies able to allow the remote and fully automated 3D modelling of objects from sets of markless 2D images. The Arc3D web-service, for example, was developed within the Epoch context (Vergauwen and Van Gool, 2006) and is actually widely used (Hermon et al., 2010; Fratus De Balestrini and Guerra, 2011; Dellepiane at al., 2012). Its 3D modelling process is usually associated with MeshLab, the widely known open source system that allows the processing of derived triangular meshes.
As far as web-service solutions are concerned, some of their main strengths rely on their flexibility in the alignment of images acquired using different focal lengths and uncalibrated cameras, on their evident automation during the post-processing of data, that allows their use also by non expert operators, and on the speed of their processes along the whole pipeline.
In case of web-services, the pipeline is usually as follows: 2D images are captured using uncalibrated cameras and different focal lengths, following the rule of a minimum overlap area (generally around 50%) between adjacent photographs. These images are then loaded on a remote server that stitches camera positions and derives a point cloud on which single photographs are projected. These point clouds can be turned into textured triangulated meshes and afterwards can be placed inside a reference system and scaled using measurements acquired on field. In some cases, such as, for example, 123DCatch, during the whole process, if the server is unable to calculate camera position, the user can manually stitch them together by identifying couples of homologous points.
Within the present project, we decided to adopt the Autodesk 123DCatch web server technology, that is deeply interfaced with other Autodesk packages that are commonly used in 3D modelling contexts.
This approach was performed on architectural elements that have different geometric characteristics with the purpose of testing its reliability in different situations. It was used on the Drogdone wall, on the outer surface of Battistero degli Ariani and on its inner space.
Preliminary tests on the open space of Piazza degli Ariani confirmed the results acquired by Abate et al. (2011) on squares, so that they were not taken into consideration.

The selected case studies were acquired using a PENTAX K110D camera. 2D images were captured by following 50% of minimum overlapping areas.
As far as the outer space of the baptistery is concerned, difficulties were encountered due to the presence of a wall and a banister that surround and hide the building near its foundations. These obstacles were captured in overall images, while they were not present within detailed views. This aspects caused errors in the alignment of images and therefore in the rebuilt geometry and texture (Figure 1).
123DCatch package was also tested in the inside of the baptistery, pushing its capabilities to the limit, as this technology was developed to be used by an operator who moves around a objects that have sculptural characteristics.

Figure 1. During 3D modelling of the Battistero degli Ariani using the SfM approach, the different height of the monument and of the square and the presence of a banister caused difficulties in the alignment of photographs.

Figure 2. Capturing of convergent sets of images inside the Battistero degli Ariani.

In order to overcome this problem, images were captured while continuously moving the camera inside the building and trying to acquire convergent images (Figure 2).
Another problem that is usually recurrent in case of inner spaces is represented by distortions in images that are due to the use of wide lenses and that the application could not be able to compensate. These distortions generated evident errors and lacks in the reconstruction of the mesh.

3. ASSESSMENTS AND EVALUATIONS

The purpose of this paper is to show the results of the adoption of different survey methodologies and procedures on the same case studies, in order to evaluate their potentialities and weaknesses and understand for which objects and goals they can be adopted.
The presented approach is double: on one side investigations are conducted using two different methodologies that are adopted in order to restore 2D technical drawings (sections 2.1 and 3.1); on the other side, other methodologies are tested in order to evaluate results in 3D modelling and simulations (sections 2.2 and 3.2).
Both approaches use range sensors as basis for comparisons, as their use is slowly spreading for applications in different fields.

3.1 Traditional and Range-Based Approaches

As already mentioned, Piazza degli Ariani has a rather irregular shape, as it is the result of various stratifications through time and suffers for the presence of different properties that surrounds it.
It measures 53 m long and is 7 m wide in front of the baptistery. This monument is partially located inside two private courtyards which present a rather intricate vegetation.
The comparison between the dense and sparse point clouds that are respectively captured using a laser scanner and a total station are represented in Figures 3 and 4.
In Figure 4, the wider distances between the two plans derived from point clouds can be highlighted around isolated elements (area A), walls discontinuities that do not present sharp edges (area B), in narrow spaces that share small contact areas with the square (area C) and in peripheral areas (areas D).
If wide distances in A and B can be attributed to poor information and to the lower density of the sparse point cloud, the rotation of narrow spaces C can be caused by the low

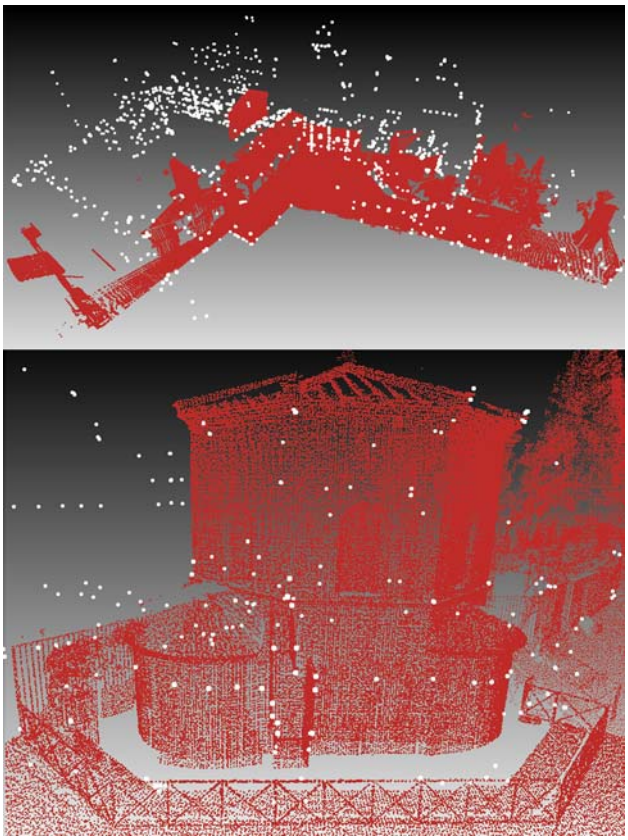

Figure 3. Alignment between the point cloud from laser scanner (red) and the point cloud from total station (white).

visibility of common points between adjacent stations in both approaches. Wide distances in peripheral areas (D) can be attributed to both approaches. For example, it depends on the system performance of both instruments.
The reliability of a measure acquired using the total station is also deeply influenced by accidental factors and by the skill of the operator.
The wide distances in (D) can be attributed also to range-based survey, in particular, to the fact that scan stations were mainly concentrated near the baptistery. Other small errors can be due to approximations performed during 2D vectorialization of point clouds.
These distances are also due to the fact that the horizontal plan obtained using the total station represents a manual interpolation among points that can be rather distant and do not exactly belong to the same vertical plane.
As far as time consuming and skills required by both approaches is concerned, the survey conducted using the total station required:

- *survey campaign*: 6 man-days (2 men working 3 days long was the time needed to measure the location of points that are indispensable to draw the plan of the square);
- *drawing of the plan of the whole square:* 12 man-days;

while the survey conducted using the laser scanner required:

- *survey campaign*: 1 man-day (a second operator is not strictly required);
- *drawing of the plan of the whole square:* 5 man-days.

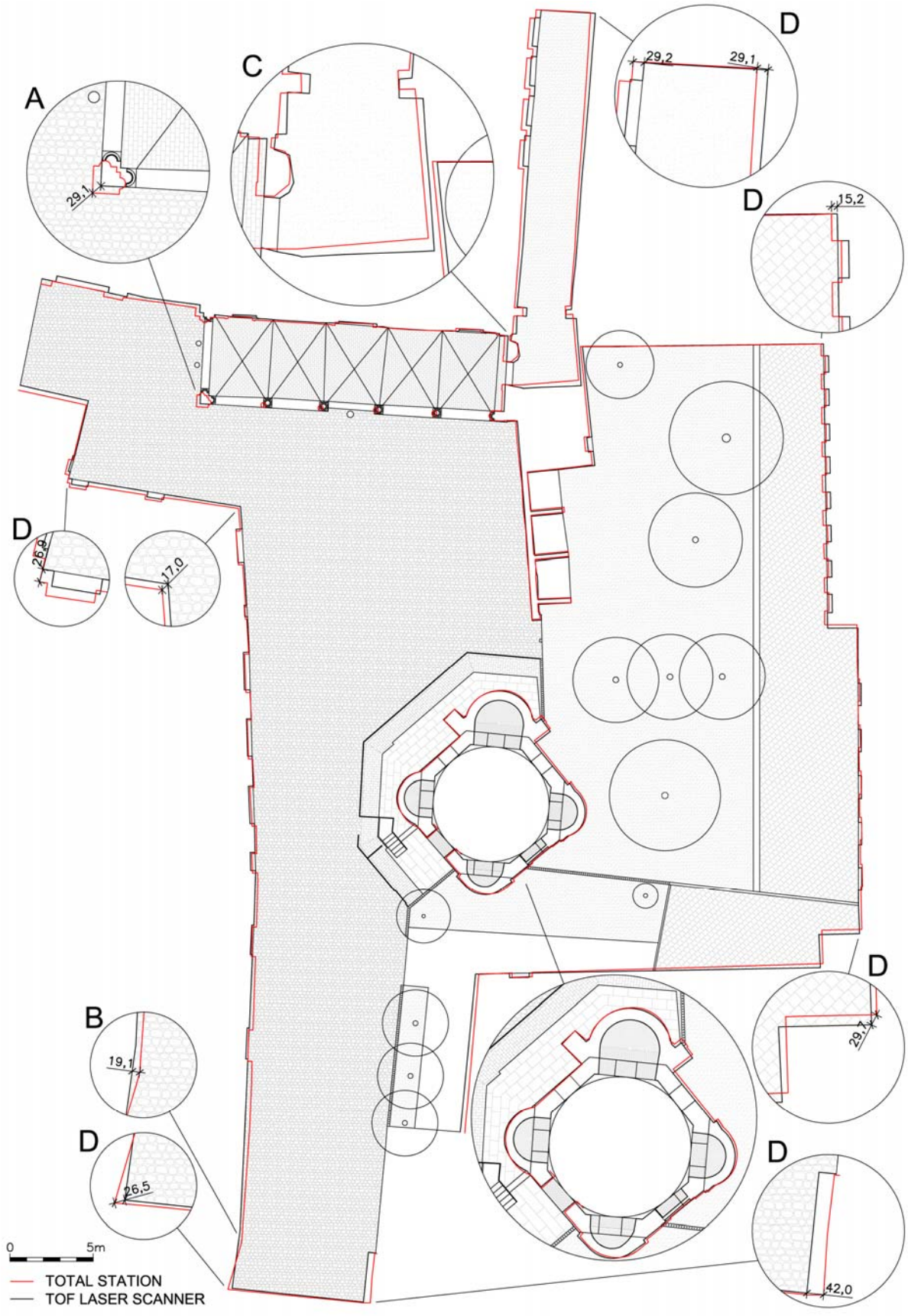

Figure 4. Comparison between the plan of Piazza degli Ariani derived from laser scanner and using a total station. The wider distances between the two point clouds can be highlighted around isolated elements (A), walls discontinuities that do not present sharp edges (B), in narrow spaces that share small contact areas with the square (C) and in peripheral areas (D).

The second approach was faster than the first one. Moreover, it strictly required just one operator during survey campaign, with evident benefits in reduction of costs. In addition, this operator does not need to be have particular topographical skills, as surveys conducted without targets are extremely easy and can be eventually conducted using pre-defined settings of the instrument.
Following this approach, the operator who conducts the post processing of data can be different from the one who carries on the survey campaign, as schematic drafts can report the location of scan stations and therefore allow the correct orientation of single point clouds by a different operator.
Another positive aspect that can be highlighted using this approach is the possibility of managing a lot of information that can be used for different needs and in different times. While a topographic survey using a total station provides the geo-location of points that are pre-selected following a precise representation aim, surveys conducted using laser scanners allow multiple uses of collected data and are therefore much more versatile.
Moreover, in case of complex shapes (Figure 5), laser scanner surveys can ease an accurate and detailed documentation, as the acquired information is much more complete.
As a drawback, the post-processing of huge amount of data acquired using this kind of technologies requires higher computational power than a traditional approach.

3.2 Range-Based and Structure from Motion Approaches

The Drogdone wall measures 12 meters long and 6 meters high. Its 3D modelling through 123DCatch was built using 56 images that were acquired with a 6.1 megapixel PENTAX K110D camera.
Figure 6, a, b show distances measured in some crucial points, and highlights how the geometry of bricks and mortar are detailed also when derived using the SfM approach.
The average deviation between the two point clouds is 0.22 cm.
The inner surface of the baptistery was built using 77 images.
Figure 6, c shows distances measured in some crucial points.
In this case the average deviation between the two point clouds is 0.77 cm.
The outer surface of the baptistery was built using 93 images acquired with the same camera.
In this case the average deviation between the two point clouds is 0.93 cm.
Figure 6, d shows distances measured in some crucial points.
As far as metric accuracy and detail of the rebuilt geometry is concerned, the use of 123DCatch restored the best results when used on the almost flat Drogdone wall.
The 3D modelling of the outer surface of the Battistero degli Ariani restored good quality results, but showed evident problems due to fixed obstacles.
The 3D modelling of the inner space of the baptistery showed wide lacks that are mainly due to the evident deformation of 2D images.
In addition, as 123DCatch automatically fills some lacks, it is not always easy to evaluate whether wide deviations are due to errors in measurements or to the filling of holes.
Beside metric assessments, as it was expected, in the Drogdone wall and in the outer surface of the baptistery, the good quality of radiometric characteristics and the performance of the texture blending algorithm of 123DCatch allowed to build good quality 3D models to be used for 3D visualization aims.
The wide lacks that affect the 3D model of the inner space derived from the SfM approach does not allow to use the whole model for 3D visualizations, but just portions of it.

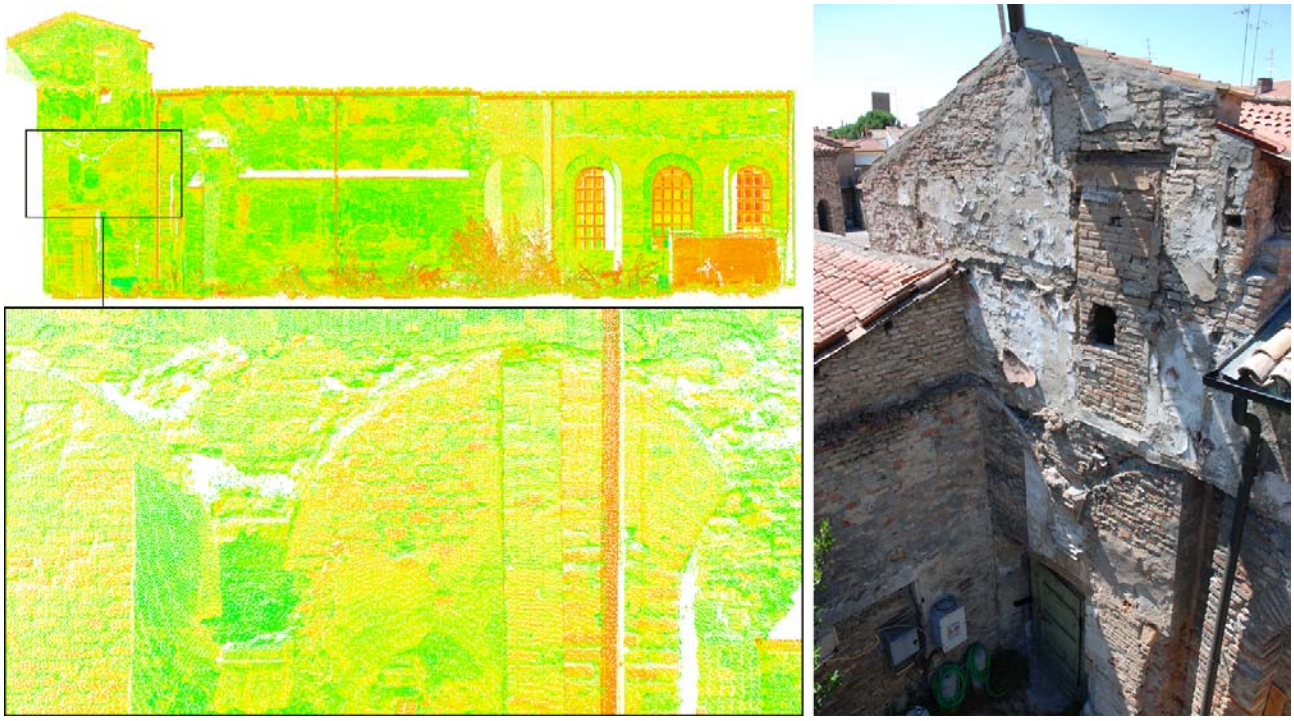

Figure 5. Complex wall of the Chiesa dello Spirito Santo facing a courtyard. In this case, laser scanner survey can ease its accurate and detailed documentation, as the acquired information is much more complete.

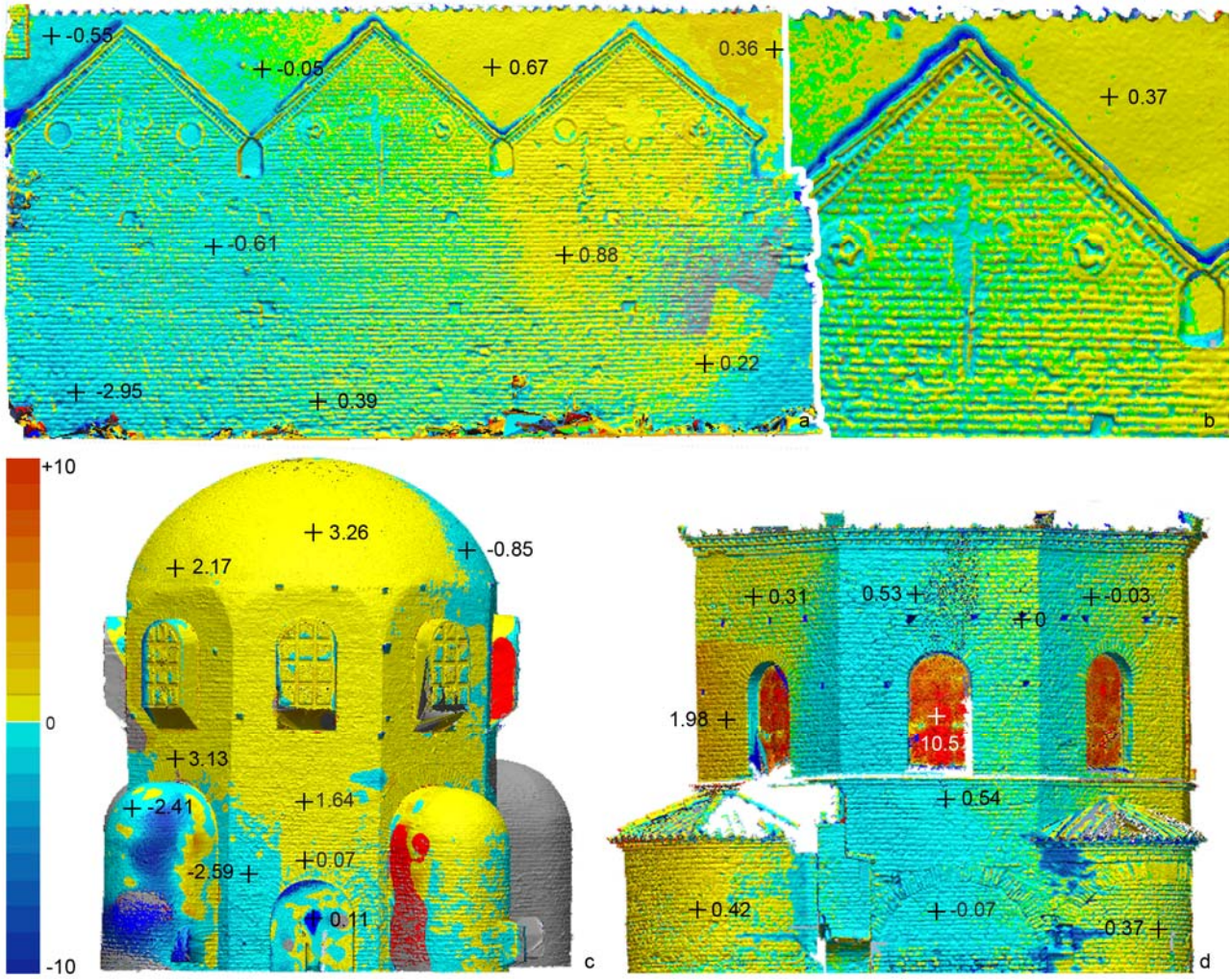

Figure 6. Deviation between meshes of the Drogdone wall (a, b), of the inner surface of the Battistero degli Ariani (c) and of its outer space (d) derived by laser scanner and by the SfM tool. Distances measured in some crucial points highlights how the geometry of bricks and mortar are detailed also when derived using the SfM approach. Red and dark blue areas show the maximum distance that is generally due to incorrect automatic filling of lacks performed by Autodesk 123DCath.

As far as times and skills required by both solutions is concerned, they are almost the same if photographs are correctly captured. In particular, as far as range-based surveys is concerned, for each case study, the survey campaign lasted half a day, while the post processing time aimed at building the polygonal mesh took one day.
As far as the SfM approach is concerned, survey campaigns lasted half a day, but in some occasions this process highlighted some criticalities that arose during the alignment of the sets of photographs. In those cases, additional surveys were required in order to set the most suitable shooting area dimension and guarantee the right overlap. The building of the textured 3D models (Figure 7) took half a day for each artefact.

4. CONCLUSIONS

The present contribution is motivated by the recent advancements in range-based and SfM approaches.
These technologies were tested on the same case studies and results were compared among each other and with a traditional solution with the purpose of evaluating the convenience of adopting range and image-based approaches instead of a traditional one.

As far as the drafting of 2D technical drawings is concerned, the range-based approach provide the best results in terms of metric accuracy, definition and times and skills required.
In addition, this solution is much more versatile, as it provides a more complete documentation.
As far as 3D modelling using 123DCatch is concerned, this technology allowed to limit costs of both hardware and software and to obtain good quality results in terms of geometric and radiometric information, when lens distortions are not so evident. Nevertheless this approach needs a particular attention during the shooting of images in survey campaign.
Further improvements can be reached by comparing the range-based survey with other SfM solutions in order to evaluate which one is able to provide the best quality data at the same scale of complexity.

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4.2 Acknowledgements

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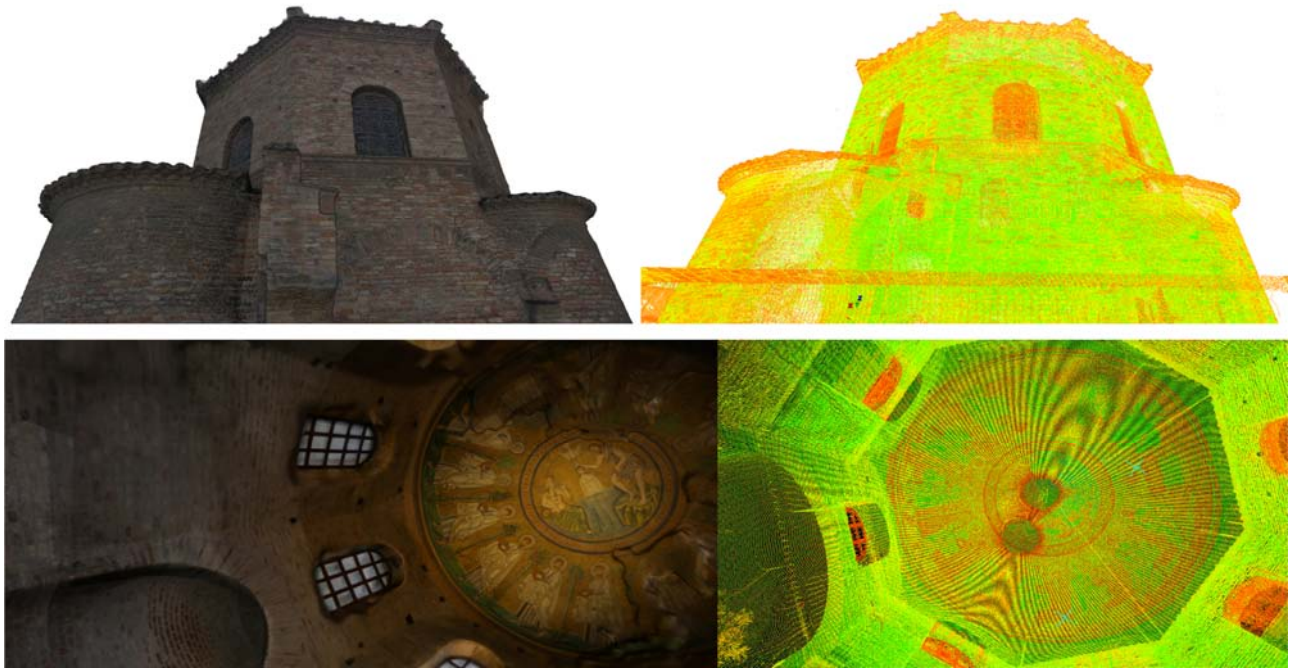

Figure 7. Left, textured 3D models of the inside and the outer surface of the Battistero degli Ariani built using the SfM approach. Right, point clouds derived from laser scanner.