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On the accuracy of UAV photogrammetric survey for the evaluation of historic masonry structural damages

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Abstract

Photogrammetric surveys via Unmanned Aerial Vehicles are nowadays a valuable tool for historic masonry structures inspection, surveillance, mapping and 3D modeling issues. When structural damage mapping and structural assessment are of interest obtaining accurate and reliable geometric models is a crucial issue. Therefore, the flight plan, the georeferencing and the data processing steps need to be properly designed.
In this paper, a procedure for the photogrammetric survey via Unmanned Aerial Vehicles of a masonry structures is used in order to obtain effective visual inspections and a 3D model of a historic masonry arch bridge located along the ancient Via Amerina (Todi, Perugia, Italy). The photogrammetric survey provides a detailed representation of the actual geometry, including lack of volumes and significant cracks along the vault and the spandrel walls, outlining a severe damage state affecting all the structure. Finally, a Total Station and a Laser Scanner were used to compare the results obtained by photogrammetry, highlighting the advantages, the limits and the weaknesses offered by their use.

Keywords: Masonry bridge; Structural damage assessment; UAV photoframmetric survey; Structure from Motion; Point cloud.

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1. Introduction

The preservation of cultural heritage is of primary concern especially in all those countries where history delivered significant architectural heritage, which is exposed to inherent degradation with time and to natural hazards (e.g. seismic loads). Within this context it is crucial to develop effective and integrated methodologies aimed at characterizing the conservation state of a structure identifying and preventing potential vulnerabilities (Bitelli et al., 2016; Breccolotti et al., 2018; Palazzi et al., 2019; Galassi et al., 2020).

Currently, visual inspections are the primary and most important practice for identifying the existence of damage and to assess the health state of historic structures. Actually, most of historic structures are characterized by a significant level of complexity in terms of constituent materials, existing damage and geometry (Tempesta et al., 2019; Zampieri et al., 2019). Moreover it is often difficult and/or impossible to have direct access to the structural components (e.g. masonry bridges, towers and more) (Gioffrè et al., 2017; Roselli et al., 2018). In this framework, the analysis of damaged historic structures and the evaluation of the geometrical irregularities effects on the structural response is still a challenge (Cavalagli et al., 2017; Severini et al., 2018; Zampieri et al. 2018); in this sense, the possibility of using accurate models which describe the actual geometry is advantageous for structural purpose.

For this reason, in the recent few years, significant interest has been posed on emerging survey technique such as Terrestrial Laser Scanner (TLS) and Unmanned Aerial Vehicles (UAVs) based photogrammetric surveys, able to model the external envelope of the tested structural system through point clouds, providing geometric data quickly and safely, instead of in-person visual assessment. In the latter case, Structure from Motion (SfM) procedures are used to achieve a 3D geometric model from its projection into a series of high-resolution images taken from different view points (Ippoliti et al., 2015; Martinez-Carricondo et al., 2020). TLS survey technique can be considered a "conventional" and reliable survey method, thanks to the advances in technology and computer graphics, and to its extensive use by practitioners and researchers (Olsen et al., 2010; Guldur et al., 2015). However, TLS technique requires specific work setting, among which the accessibility of sites, expert users and, moreover, the equipment can be considered relatively expensive (Chen et al., 2019). This may be a significant drawback especially when, working on historic structures, site conditions and occlusions caused by different kind of objects (e.g. structural components causing self-shadowing) could make the application of this technique not able or not sufficient to perform an overall survey. As an alternative, UAV-based photogrammetric technique has gained interest worldwide. With respect to TLS, using UAVs equipped with commercial cameras means to have lower cost of instruments, higher speed of data acquisition and, above all, a better representation of the 3D model through by using textures (Achille et al., 2015; Khaloo et al., 2018; Barba et al., 2019).

The aforementioned aspects are of crucial interest when information about historic buildings is required. In fact photogrammetry based surveys are able to provide:

1. Virtual 3D model to be used for historical documentation and geometrical information and to analyze the existence and the localization of significant cracks and/or lacking material;
2. Photorealistic representation to be used for material characterization and degradation analysis, comprising damage mapping and quantification of damage;
3. 3D geometric models to be used as base for numerical analyses aimed at assessing the structural performance.

In this work, the accuracy of UAVs photogrammetric survey for the evaluation of historic masonry structural damages is discussed with reference to a full-scale masonry arch bridge in the neighborhood of Todi, Central Italy (Pepi et al., 2017). The bridge is characterized by an irregular segmental arch with a span and a rise of about 10 m and 4 m, respectively. The structure exhibits typical mechanical deterioration phenomena consisting in cracks below the vault, material detachment in the side walls and the arches, and lack of material on the West and East abutment. The damage level of the masonry is even worsened by vegetation grown between the cracks of the stones (Fig. 1). To achieve a reliable bridge inspection, close range digital images were firstly acquired using UAVs equipped with cameras and then processed obtaining a texturized point cloud. The accuracy of the obtained results were assessed by a direct comparison of the point clouds obtained by SfM technique and TLS survey. Finally, the texturized point cloud model was used to build an accurate 3D model and to identify cracks evaluating the volumes of lacking material.

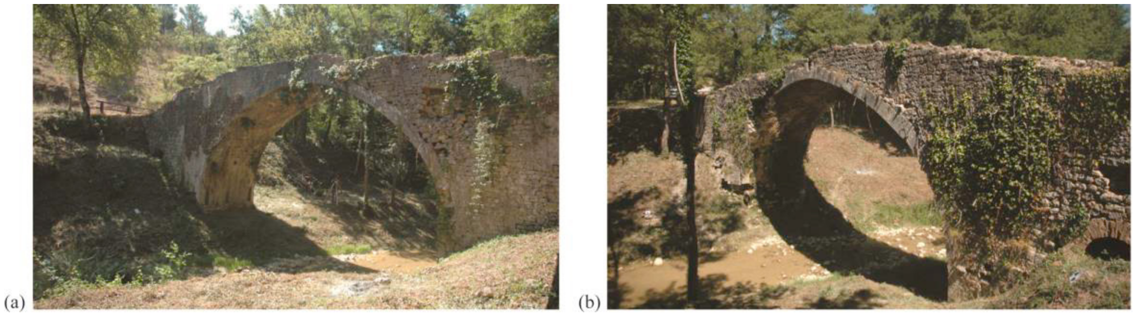

Fig. 1. Images of the historic masonry arch bridge: general view of the South side (a) and the North side (b).

2. UAV Photogrammetric survey of the ancient masonry bridge

The combination of the size and the morphological characteristics of the masonry arch bridge makes the case study as a good benchmark to test the ability of digital photogrammetry to obtain appropriate models for the purpose of structural evaluation. In particular the model must provide suitable information about the damage mapping and the geometric irregularities, as well as a photorealistic representation to be used for historical documentation and, finally, to develop suitable 3D geometric models for structural analyses. The framework used in this experimentation is able to fulfill these main aspects and it can be summarized in two main steps: data acquisition and data processing.

2.1. Data acquisition

The task of data acquisition includes site inspection, flight plan and data collection. In establishing the flight plan several issues need to be considered. First, the accessibility conditions around the structure, such as the presence of environmental obstacles and/or the surrounding vegetation; second, the lighting condition, since excessive contrast and/or brightness can negatively affect the visual qualities of the images; third, the distance from the object, and therefore the flight altitude, may be a restrictive parameter since geometry accuracy decreases with distance; finally, the camera resolution and the drone flight need to be properly defined and planned, avoiding shadows and obstacles, in order to have a suitable number of superimposed high resolution images.

Carefully considering the above mentioned issues, the photogrammetric survey was carried out by using two different UAVs and one manual camera from the ground: SkyRobotic SF6 (Fig. 2(a)) equipped with six propellers of medium dimensions, which gives optimal stability, and the high resolution camera Sony DSC-QX100 (5472×3648 resolution / 20.2 MP / 10.4 mm) to take nadiral images (Fig. 2(c)); DJI Phantom3 (Fig. 2(b)) equipped with the camera FC300X (3392×2992 resolution / 12 MP / 3.61 mm focal length) to take images of the South elevation (Fig. 2(d)) with the presence of obstacles (trees and vegetation) and reduced manoeuvre areas; Nikon D7000 (4928×3264 resolution / 16.2 MP / 15 mm focal length) to manually take images of the North elevation and the vault intrados (Fig. 2(e)). The flight altitude was determined setting a level of accuracy in terms of ground sampling distance lower than 3 mm able to guarantee a restitution scale equal to 1:10. Flight altitudes equal 20 m and 6 m are used for the nadiral survey and the South elevation, respectively, while a distance of 15 m were used for the manual shots. The total amount of acquired images were 307, of which, 83 were by automatic flight plan and 224 were taken with a manual flight. In a natural environment, it can be difficult to find natural points to be used as references for the orientation and the alignment of the acquired images. For this reason, 50 markers were installed prior to the image acquisition phase. In particular, 9 markers were used for a general survey overview of the bridge and 41 markers were used as both Ground Control Points (GPC) and survey accuracy check points. Each marker position was then referred to the Italian geodetic and cartographic system UTM/ETRF2000 through a connection with a GNSS and total station survey.

The choice of integrating data derived by different techniques and devices was due both to the need of overcoming practical difficulties, which frequently occur because of the presence of physical obstacles, and to assess the effectiveness of merging data from different sources on the quality of the final result.

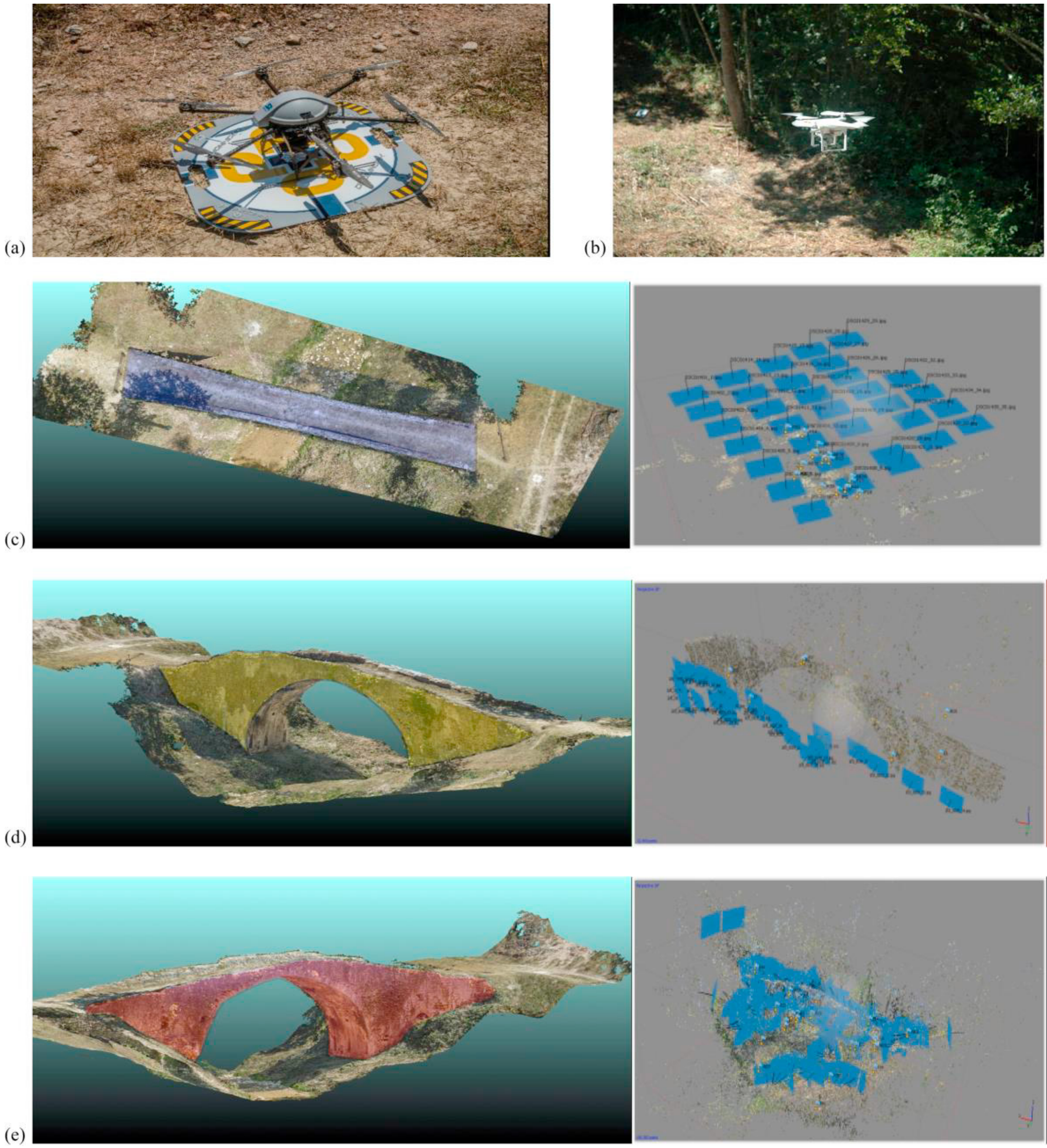

Fig. 2. Images of the SkyRobotic SF6 (a) and DJI Phantom 3 (b) drones used in the survey. Sketch of the shots acquired for the survey of the plan (c), the South side (d) and of the North side (e).

2.2. Data processing

The collected images were processed through the Agisoft PhotoScan/Metashape software to generate the 3D point cloud. Three different data sets were used: two from drone flight shots and one for manual shots in order to handle both the great amount of photo data and the different acquisition parameters. Moreover, a two-step procedure was carried out: at first, all the images were analyzed and georeferenced, also using marker coordinates; then, the frames were aligned and processed obtaining a low density point cloud.

The quality of the point cloud was preliminarily assessed estimating the differences in coordinate of the GCPs position obtained in the point cloud assembled model and those derived by the total station survey. Absolute values on average lower than 5 mm and 3 mm in plane and elevation respectively were observed, indicating a good data quality. At this stage, a sparse point cloud composed of about 29 mln points was achieved, which was manually elaborated, deleting all of the noisy points and the locally undefined areas, in order to a clean high density point cloud.

The final texturized 3D model is represented in Figure 3.

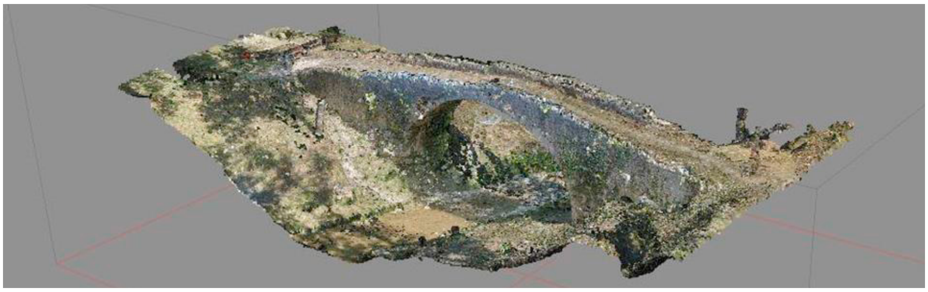

Fig. 3. Dense point cloud of the masonry bridge obtained by UAV photogrammetric survey through SfM technique.

3. Geometrical comparison between TLS and UAV photogrammetric survey

The accuracy of the sparse point cloud obtained through the photogrammetric survey was evaluated by a TLS point cloud. Owing to the accessibility condition of the site, the bridge can be considered as a good benchmark for the comparison between the two methods, being both the surveys were performed in very good conditions.

The TLS survey was performed involving 8 acquisition workstations. The scans were georeferenced through the same 9 markers employed in the photogrammetric survey and a final point cloud of about 31 mln points was obtained.

The comparison between the two different models was carried out by extracting the coordinates differences of points at to two different levels: comparison per section lines and comparison per surfaces (Buffi, 2018). Taking the TLS dense point cloud as a “reference”, 85 points belonging to a longitudinal (A-A) and a transversal (B-B) sections as illustrated in Figure 4(a) were firstly selected. An average absolute value of the differences between these corresponding points equal to 0.013 m was estimated. Secondly, points on the two point clouds surfaces were selected and a direct comparison was carried out using CloudCompare open source software. Figure 4(b) shows a map of the differences between the North side surfaces of the masonry bridge, resulting in the range of ±1 cm.

4. Analysis of structural damage through SfM

In this Section, the first results about the use of 3D point cloud obtained by UAV photogrammetric survey as a valuable data source to be queried for structural purposes are discussed. The large data content of the texturized model can give accurate information for both virtual visual inspections aimed at evaluating the damage state and the development of 3D solid model for structural analyses.

Besides the availability of orthophotos, obtained by converting the point cloud model into a texturized mesh model, that result very useful for material survey, degradation mapping and each kind of visual inspection for the restoration purposes, the 3D point cloud provides significant information about cracks and lack of material, in particular about their position and linear and/or volumetric dimensions. To measure the volume of the lacking material, the damaged areas boundaries were manually extracted and random points were generated to fill the space. Finally, a triangular mesh was generated for the calculation of the 3D volumes.

The high resolution of the point cloud allows carrying out a detailed damage mapping in terms of localization of cracks and micro-cracks, areas of masonry walls affected by significant erosion of mortar joints and local lack of blocks. As an example, Figure 5 shows a comparison between a photo image (Fig. 5(a)) and a view of the texturized 3D model (Fig. 5(b)) of the same degraded area, in which a low-thick crack (window 1) and a lack of stone (window 2) are observed.

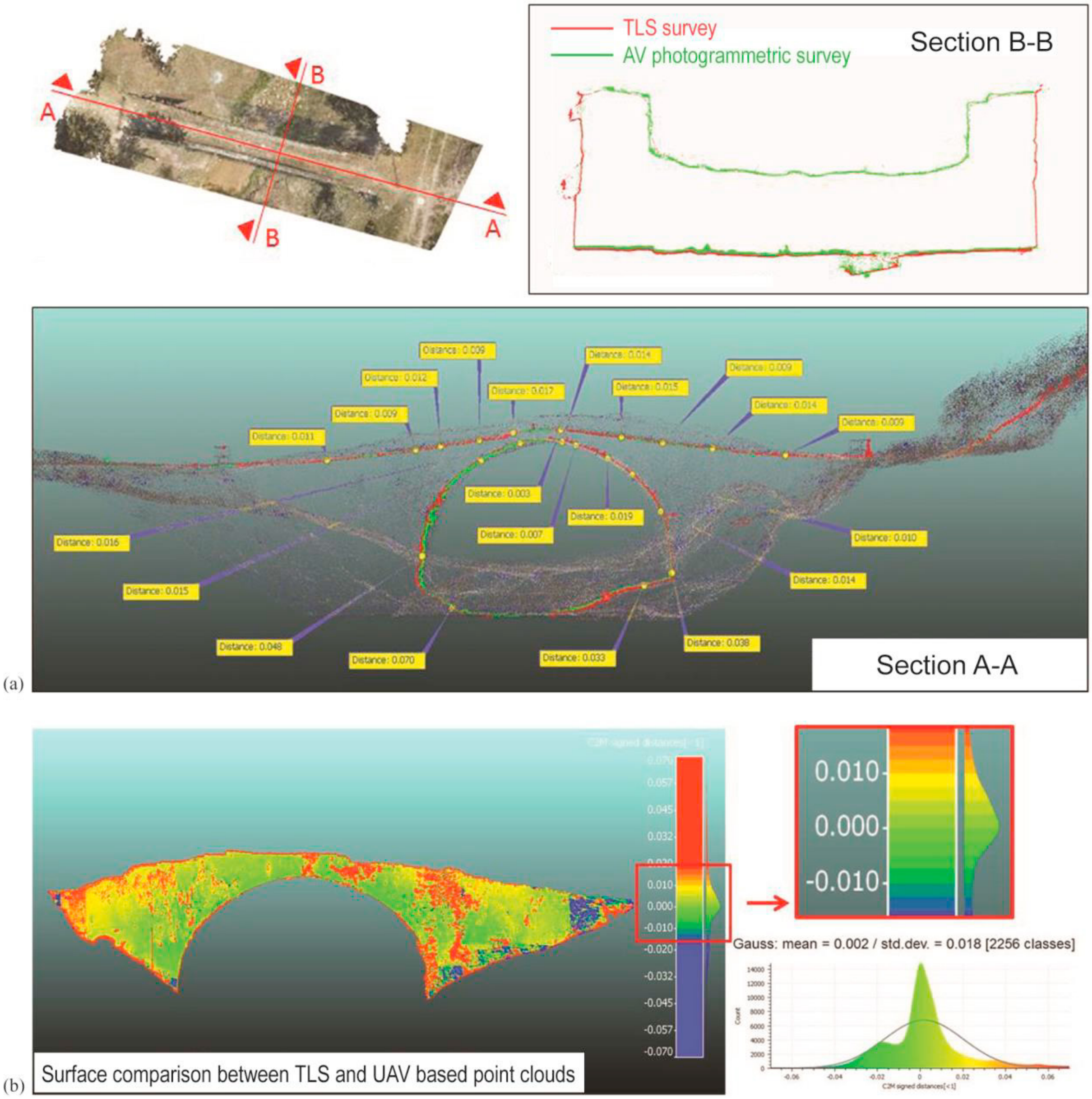

Fig. 4. Comparison between the point clouds obtained by TLS and UAV photogrammetric surveys: (a) line comparison on a longitudinal (A-A) and transversal (B-B) sections; (b) surface comparison on the North side of the bridge.

In the case of severely damaged structures, as for the case of study, the possibility of lacking volumes estimation is useful in the restoration and strengthening design processes. Figure 6 shows the procedure applied to a significant area of the bridge South side, where a total of 0.25 m^3 of lacking structural portion was estimated. Other than the quantification of damages, the point cloud could be particularly useful for building accurate solid model to be used for structural analyses aimed at assessing the health state of the structure. This is of utmost importance especially when the damage assessment of inaccessible structures is required, such as large bridge and high structures, due to the possibility of carrying out the analysis without a direct access, using only the results of the photogrammetric survey.

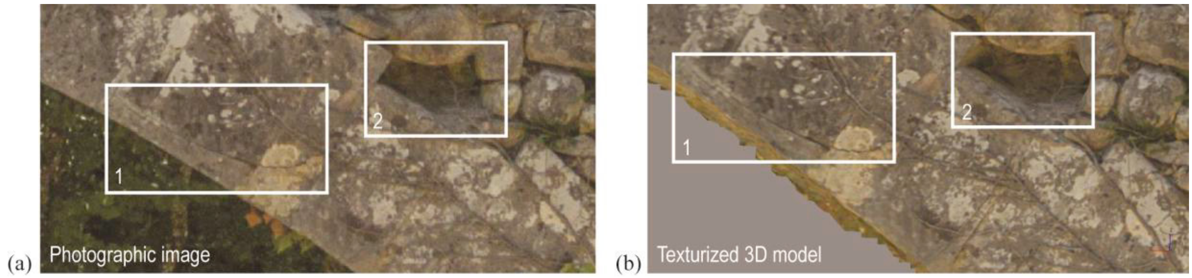

Fig. 5. Visual comparison of a damaged area of the bridge between the photographic image (a) and the texturized 3D model (b): identification of a micro-crack (window 1) and a lack of stone (window 2).

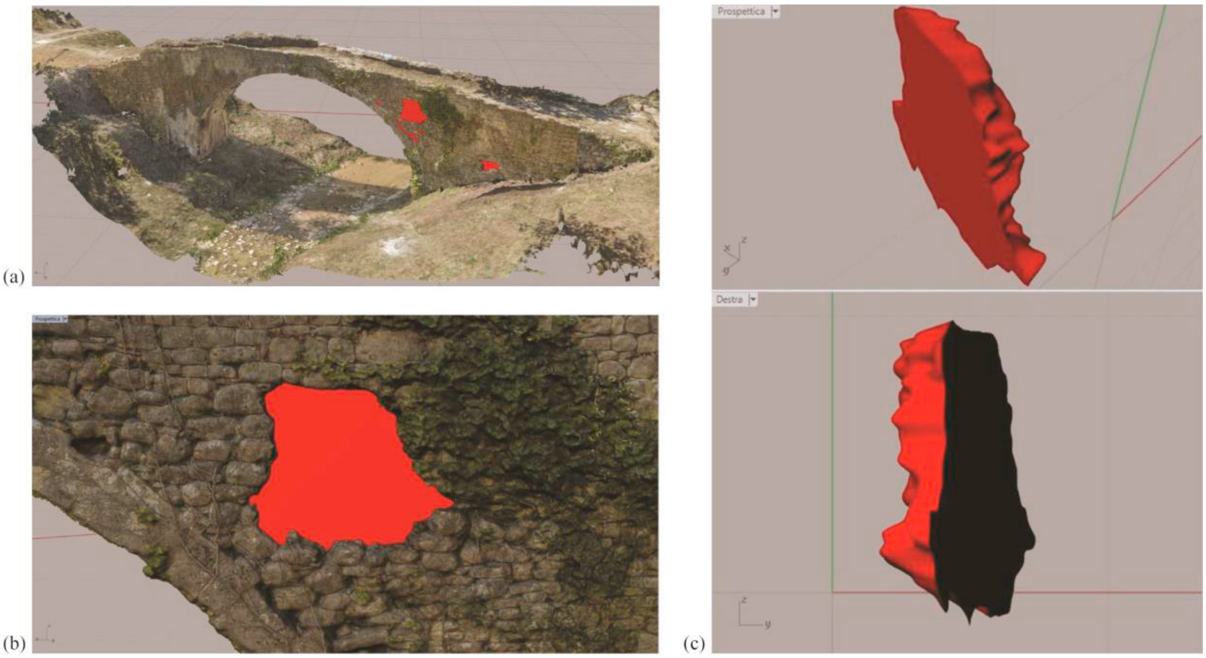

Fig. 6. (a) South side of the masonry bridge, highlighting in red the most relevant areas of lacking material, e.g. single stones, mortar layers and structural part. (b) Focus on a significant area of lacking structural volume. (c) Volume estimation of lacking material in the spandrel wall.

5. Conclusion

In this work the UAV photogrammetric survey of a masonry arch bridge is carried out with the aim of assessing the structural damage, and in particular of localizing and mapping cracks, micro-cracks and lacking material without direct access, relying only on the virtual visual inspection provided by the texturized point cloud.

In a first step, the point cloud derived by UAV photogrammetric survey was compared with a point cloud based on a TLS survey, obtaining mean differences of about 1 cm. It is demonstrated that the UAV based survey method can provide significant advantages reducing time operation without losing significant accuracy.

In a second step, the application to a severely damaged historic structure, the use of UAV based photogrammetry demonstrated to be very effective in quickly highlighting damage and in the estimation of lacking volumes of material.

Finally, it is proven as such a methodology, largely used in several engineering applications, can be very effective for the survey of inaccessible structures and for the quantitative estimation of damages of historic masonry constructions.

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