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# Reconstruction of partially destroyed structures using digital methods

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## Abstract

A relevant approach to the renovation of a small town is to carefully integrate the existing cultural and historical heritage sites into the modern urban environment. For this purpose it is necessary to have digital duplicates of these objects. Photogrammetry is a relatively inexpensive and practically universal method of creating three-dimensional models of architectural objects and their measurement plans. The paper presents the results of modelling a historical architectural object using modern images and images obtained in different time periods. The modern images were obtained by a combination of drone and ground-based imagery of both exterior facades and interior spaces. The modern model and old drawings were used to find and reconstruct the interior elements lost during the building’s operation. Separate models of the lost elements were built from the archive images, and then these models were integrated into the overall model. The accuracy of the built digital model meets the requirements for the measurement drawings for the reconstruction project.

## 1. Introduction

On the territory of the Russian Federation there is a large number of unique architectural structures located in small towns or abandoned villages and hamlets, reflecting the era and national specificities of the people who lived there. These structures are of great interest to architects, historians, archaeologists and admirers of national culture. It is quite clear that it is impossible to restore all the monuments, but to preserve the most significant ones in the form of realistic measurement models is a realistic task. For what purposes can such models be used?

Firstly, some of the models can become the basis for the creation of HBIM (Heritage Building Information Modelling) and subsequently be incorporated into the context of the development of human habitat: to become a museum, an exhibition site, a functioning temple, a part of tourist content (Dominici et al., 2017, Karachaliou et al., 2019).

Secondly, in case of impossibility of conservation and/or restoration, such models can become exhibits of a kind of ”Red Book” or ”Black Book” of architectural heritage of the Russian Federation and remain in the memory of descendants.

Remote sensing techniques offer a range of solutions to create measurement models of architectural sites in varying degrees of deterioration and accessibility: laser scanning, aerial photography from unmanned aerial vehicles (UAVs), ground-based photography, and combinations of all of these (Dominici et al., 2017, Karachaliou et al., 2019, Yang et al., 2020, Pepe and Costantino, 2021).

Terrestrial laser scanning allows to obtain highly accurate three-dimensional models that represent the smallest details of architectural elements. The total point cloud in laser scanning is made up of separate point clouds obtained at different stations, so it is recommended to use special marks to improve the accuracy of alignment (Yastikli, 2007).

The advantage of laser scanning is the ability to work in low or complete absence of light, which can be important when conducting surveys in ruined buildings, catacombs, tunnels, etc (Porras-Amores et al., 2019).

The main disadvantage is still the price of the technology. The inability to work in difficult close spaces (e.g. narrow spiral staircases) and the lack of reflective marking capability in some cases also limit the range of terrestrial laser scanning applications.

A new stage in the development of laser scanning is the application of low-cost mobile systems based on SLAM (Simultaneous Localisation and Mapping) technology, which allows to increase productivity and to survey even in limited spaces, although with lower accuracy (Barba et al., 2021, Balado et al., 2022).

The application of aerial survey using unmanned aerial vehicles (UAVs) to the task of creating models of historic and ruined buildings has become an important technological advancement in the field of architectural and archaeological documentation. UAVs offer the possibility of rapid and detailed data acquisition from hard-to-reach (e.g. roofs) and extensive sites, making them indispensable tools for scientific research and restoration work (Murtiyoso and Grussenmeyer, 2017, Korumaz et al., 2014, Kniaz et al., 2020).

Nadir and perspective photography are the most common types of aerial photography, as the combination of these two types eliminates the problems of overlapping (Dominici et al., 2017) and blind areas, and captures a large area of vertical surfaces. In addition to still photography, video filming followed by storyboarding can be performed. However, when using this method, some of the frames will be blurred. Additional frame rejection will be required (Xu et al., 2016).

An addition to unmanned aerial photography is ground-based

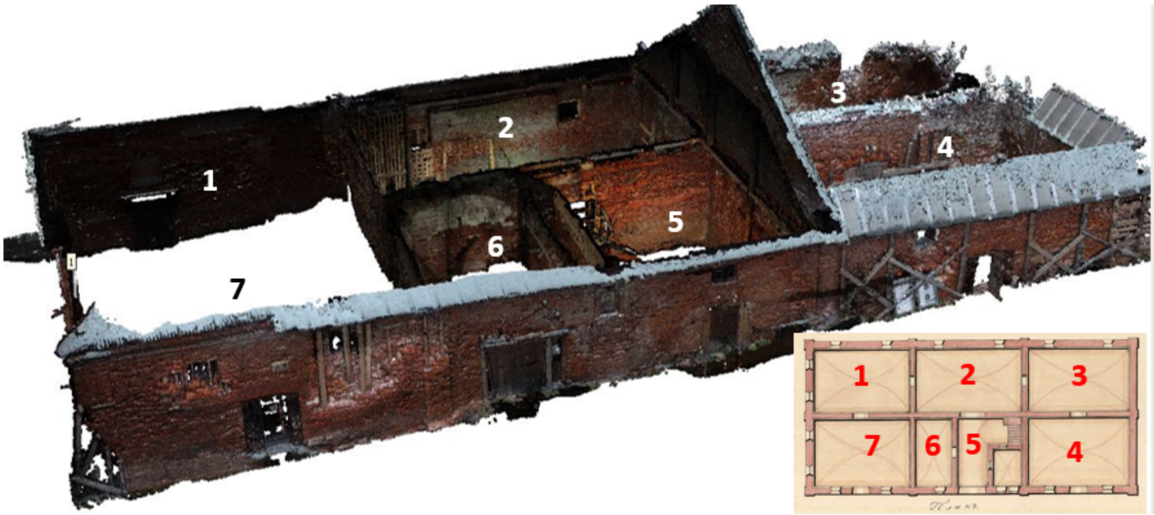

Figure 1. Digital model of a barn without a roof.

photography, which allows to obtain images of vertical surfaces, as well as objects in dead zones, such as parts of walls under roofs and canopies (Mostafavi et al., 2019). To reduce the effect of perspective distortions, the survey is often carried out using mounting structures. Both expensive professional cameras and budget versions can be used as shooting equipment (Dhonju et al., 2017), which makes the process of data acquisition more economical.

For each architectural object it is necessary to choose an individual approach to visualisation and reconstruction methods. The criteria for selecting the methodology are the accessibility of the object, the degree of complexity of forms and economic feasibility. At the same time, laser scanning and photogrammetry methods do not compete, but rather complement each other (Guarnieri et al., 2004).

The common property between photogrammetry and laser scanning methods is that they can only construct a model of an existing building or its remains. While most provincial architectural sites are in a ruined state, the question arises as to whether lost elements can be digitally recreated. Moreover, drawings of these buildings are not always available. In this case, new data recovering techniques (Casu and Pisu, 2015, Kniaz et al., 2019) can be used, or images taken in different years can be of great help in restoring the appearance of partially lost objects.

The aim of this study was to develop and test two techniques for digital reconstruction of a dilapidated building to create a virtual model and reconstruction project. Firstly, the creation of three-dimensional digital models of building parts from a set of random images of lost building elements, and secondly, graphic modelling using original drawings and digital models of preserved interiors.

## 2. Object of the study

The object of the study was the oldest brick building of Tutaev city (old name Romanov Borisoglebsk), which is located on the coast of the Volga River. Count Stroganov’s salt barn was built at the turn of the 17th and 18th centuries. It is located in the heart of the ancient city and is one of its symbols. This period similar buildings do no longer exist. It is legally defined as having the highest level of cultural value (Starodubov, 2022). For three centuries, the barn has been used for its intended purpose and was rebuilt several times. For the last twenty years, the building has been unused and gradually destroyed (Figure 2).

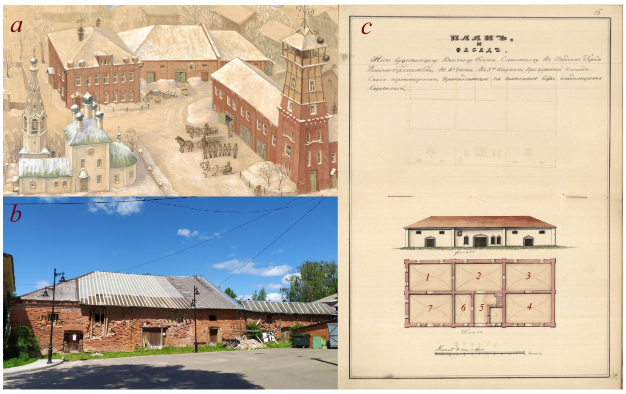

Figure 2. a) Tutaev main square with a barn, 1914 (picture by A. Varnavskaya);b) a view of the barn in 2023; c) 18th century barn plan.

Preparatory work is currently underway to restore the building and integrate it into the modern urban infrastructure in the form of a cultural and educational centre. The task of the restorers is to carefully restore the preserved parts of the building and to recreate the lost parts, especially those close to the original design of the building. There were 7 rooms in the barn, of which only two remained under brick vaults (Nos. 1 and 7) and an external metal roof, so they were in good condition; three inner rooms (Nos. 2, 5, 6) were without brick vaults but protected by a roof, and two rooms (Nos. 3 and 4) remained in the open air (Figure 1).

The Figure 1 shows a model of the barn as a dense point cloud without brick vaults or iron roof, so that the plan of the rooms can be seen.

The height of the walls was about 5 m, and the roof was 11 m. The dimensions of the barn are 40 m long and 20 m wide. Our task was to build a three-dimensional model of those parts of the building that were destroyed.

## 3. Materials and methods

To obtain a digital model of the barn ruin, the data acquisition and processing included the following steps (Figure 3):

1. Measurement of geodetic coordinates of reference points on the walls of the building to connect the exterior facades and interior spaces.
2. Photographing all parts of the building from the ground.
3. Nadir and perspective aerial survey of the upper parts of the building.
4. Search for archived images.
5. Photogrammetric processing of the modern images, obtained in steps 2 and 3. Building a dense point cloud by the Agisoft algorithm automatically matching tie points (Verhoeven, 2011)
6. Photogrammetric processing of archive images in order to obtain models of already lost parts of the building as for step 4.
7. Integration of the models of the lost parts into a common model by tie points.
8. Construction of a three-dimensional drawing.

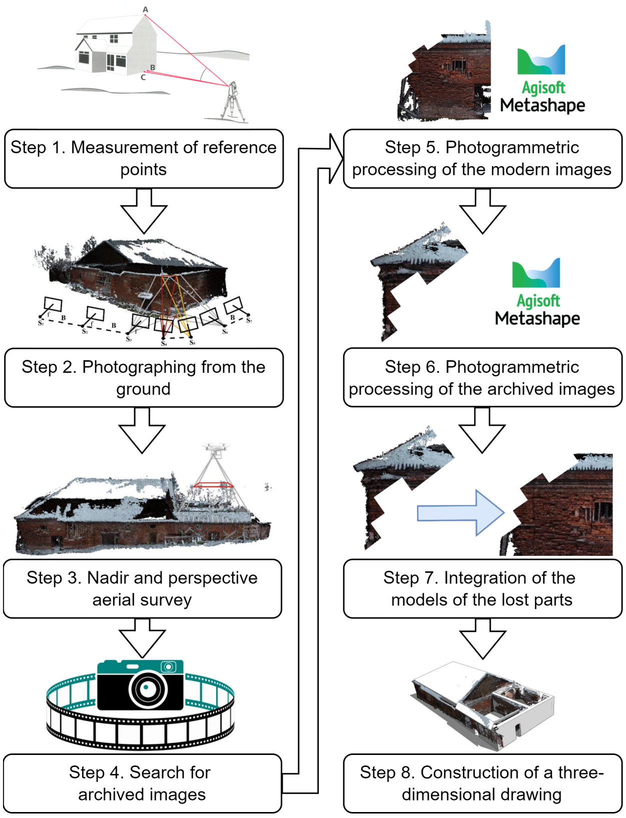


Figure 3. Technological scheme of processing.

Geodetic measurements of reference point coordinates on facades and within rooms were carried out with a Trimble Zeiss 3305 Dr total station in non-reflective mode using the linear-angular method (Skrypitsyna and Staroverov, 2018). A total of 129 reference points were measured. The average error in determining the reference points coordinates was about 5 mm.

For ground photography we used digital camera Canon PowerShot SX510 HS. Pixel size on the facade 1.32 mm/pix. The longitudinal overlap between images in a strip was 70%, and the transverse overlap between strips was 60%.

For aerial survey we used Phantom 4 PRO equipped with FC6310 camera. Table 1 shows the main characteristics of the optical sensors.

| Camera | | Canon SX510 HS | FC6310 |
|---|---|---|---|
| Focal length | mm | 4.3 | 8.8 |
| Resolution | Mp | 12 | 17 |
| Sensor size | pix | 4000x3000 | 5472x3648 |
| Pixel size | $\mu$m | 1.5 | 2.4 |

Table 1. Technical specs of the cameras.

Aerophotography was done in nadir and at an angle of 30 degrees. The flights were performed crosswise in perpendicular directions. The longitudinal overlap between images in a strip was 80%, and the transverse overlap between strips was 70%. The flights were planned in the Litchi for DJI Drones software (VC Technology Ltd, 2024) (Figure 4). This survey planning was done primarily to photograph the tops of the walls in rooms without roofs and to more confidently connect the room models to each other into a single model.

Figure 4. Planning flight missions in Litchi for DJI Drones software.

Rooms that are under the metal roof but without a brick vaults (rooms 2, 5, 6 in Figure 1) were particularly challenging for photography. These rooms are in a state of disrepair and have no lighting and we used studio lighting. In addition, it was not technically feasible to erect additional structures indoors to survey the top levels of the walls, so the upper levels were also surveyed by drone in manual mode. Flying in confined spaces requires good piloting skills. Also, visual sensors on the drone must be working properly to prevent collision with obstacles.

In total, we took 1,853 photos. All images were obtained under different lighting conditions, so to get a good result of photogrammetric processing, all images had radiometric correction.

At the steps 4 – 6 For Photogrammetric processing, we used Agisoft Metashape 2.1.0 (Agisoft LLC, 2024), an SfM-based software (Verhoeven, 2011, Pepe and Costantino, 2021). Alignment was performed separately for each room using reference points. Then models of the rooms and external walls were built as dense point clouds. At the final stage all models were compiled by reference points. The overall model was estimated from the control and check points, and the results are presented in Table 2.

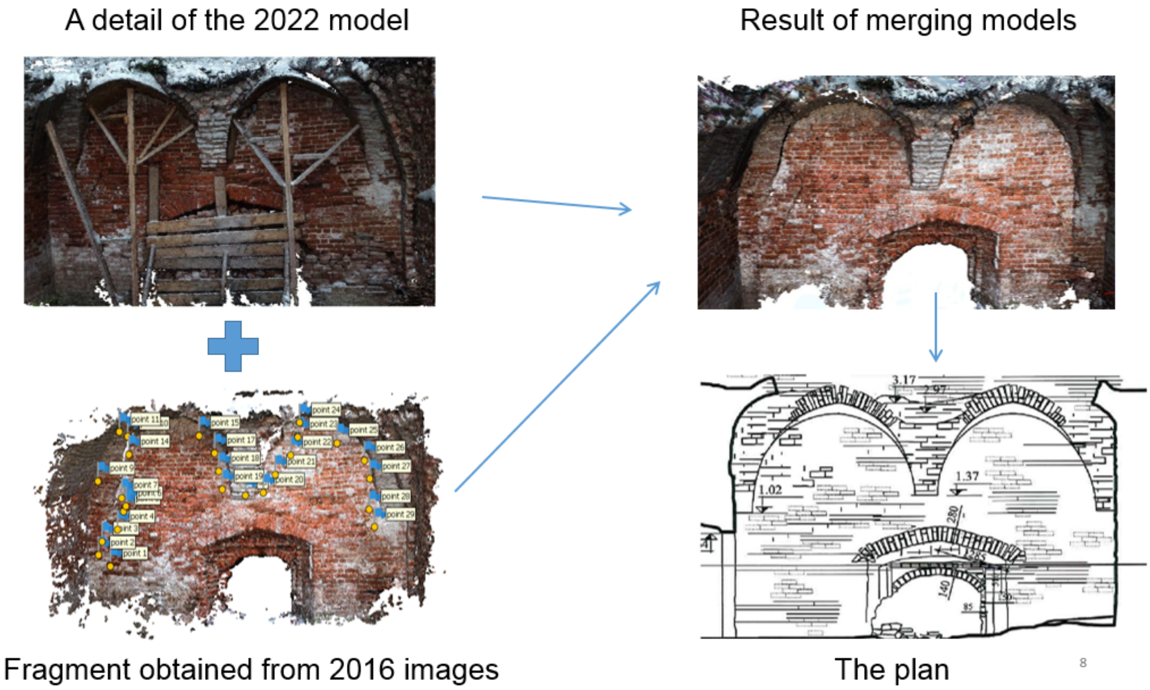


Figure 5. Reconstruction details.

| Type of point | Number of points | XY | Z | Total |
|---|---|---|---|---|
| | | mm | mm | mm |
| Control points | 104 | 1.9 | 1.6 | 3.4 |
| Check points | 24 | 4.1 | 2.6 | 5.7 |

Table 2. Assessment (root mean square error) of the photogrammetric accuracy of the barn model.

The error on the check points does not exceed 6 mm, in accordance with the Russian regulations, it allows to create drawings of 1:100 scale by point cloud.

As mentioned, the building is in the process of being destroyed. Its walls are preserved by retaining structures, many details are preserved only in photographs. We had at our disposal a number of amateur photos of the barn taken 8 – 10 years ago. These photos showed parts of the interior that have been lost at now (the brick vault of one room 6) or hidden behind protective structures (the arched entrance between rooms or windows). These images were taken from different angles and in different seasons (summer and winter), but they had overlaps. This allowed us to create fragment models of the building lost parts from these images.

Initially, a sparse dense cloud was constructed from the found images containing the destroyed part of the building. Then we made a visual assessment of the identical locations on the archival and modern images to find enough common points to connect the models. The coordinates of the connecting points were determined by the modern model, and used as a reference for the archive models.

In this way, the archival model was orientated into the coordinate system of the modern model. In order to integrate the archive cloud into the main model, a preliminary preparation was made, which included removal of destroyed fragments from the modern point cloud. The parts of the images in which the archival parts were planned to be integrated were masked in the modern images, after which the dense point cloud was rebuilt.

Figure 5 shows an illustration of the process of integrating an archival model into a modern model to create a three-dimensional drawing of a passage between two interior rooms. In the same way, models of window openings were built in, which are currently hidden under protective structures. In the same way, models of window openings were built in, which today are hidden under protective structures and cannot be studied and measured.

## 4. Results and discussion

The resulting model of the barn became the basis for creating a measured drawing and reconstructing parts of the rooms that had been lost in multiple remodeling projects. The desire of the barn’s owner was to return its layout as close to the original as possible under the conditions.

So, the last step was a graphical reconstruction of the interior rooms by point cloud using drawings from the 19th centuries. For example, on the Figure 6, you can see process of digital redesign of the room 5.

Dense point clouds repeat the texture and color of the walls and brickwork features, which makes it possible to reliably identify the stages of the building’s reconstruction, determine the places of fixing of collapsed brick vaults, find and measure bricked-up niches and paths between rooms.

For the graphic reconstruction, we used the Blender Software (Blender Online Community, 2023). The Point Cloud Visualizer addon (Uhlik, 2024) was used to work with the point cloud. This extension allows you to import and export point clouds in popular formats (PLY, LAS/LAZ, E57 and PTS), visualize points with various effects and shadows, and render images. When exporting from Agisoft Metashape, the point cloud was thinned to a density of 1 point/cm$^2$. This value was selected experimentally and allowed to maintain detail with a low load on the workstation.

The overall model of the room was created based for separate elements. This approach to modeling made it possible to simplify work at the stage of selecting wall design options and configurations of openings and vaults.

Dense point clouds repeat the texture of the walls and brickwork features, which makes it possible to reliably identify the stages of the building’s reconstruction, determine the places of fixing of collapsed brick vaults, find and measure bricked-up niches and paths between rooms.

In short, those details that could not be shown on the drawings during field measurements. In addition, we discovered niches and entrance that were not shown in the archive plans.

Each part of the common model was created by a separate element – a wall, an arch, a staircase, etc. This approach to modeling made it possible to simplify work at the stage of selecting options for wall layout and configuration of openings and vaults. After creating a new version of the model, consultations were held with architects, comments on individual elements were easily corrected without the need to edit the whole model.

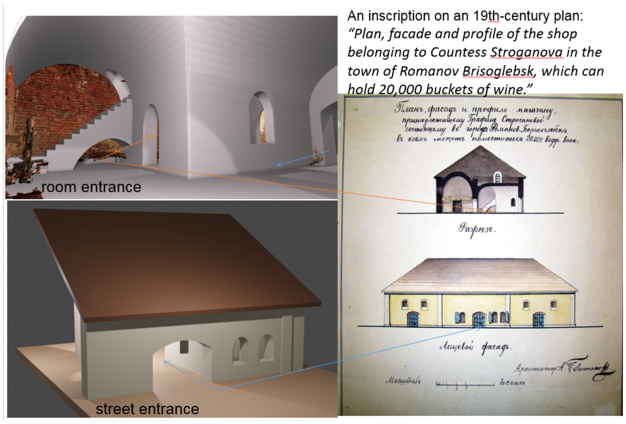


Figure 6. Reconstruction of the interior rooms.

When combining the model and the archive drawing, a discrepancy was found in the planned position of the rooms.

Figure 7 shows that the position of the wall in the modern point cloud between rooms No. 5 and No. 6 does not match the data in the old drawing. Based on this, it can be assumed that these premises were not built according to the project. This factor may have an impact on plans for the restoration of a historic building and requires further in-depth study by specialists. In Figure 7, you can see the point cloud and the drawing, top view, orthogonal projection.

## 5. Conclusion

The aim of the study was to create a three-dimensional model of the Stroganov’s barn, measuring accuracy, closest to historical drawings. This was achieved in two ways: photogrammetric

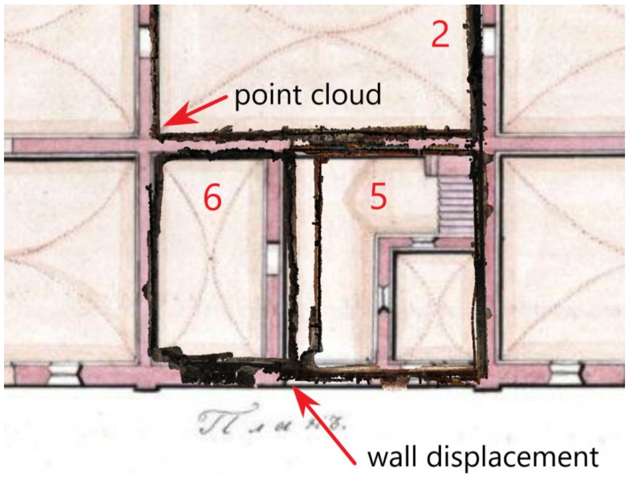


Figure 7. Wall displacement between neighbouring rooms.

and graphical. In the first case, modeling took place by completing the destroyed parts in a modern digital model with models built from sets of amateur photographs. In the second case, old drawings were used to recreate the lost elements, and their placement inside the building took place in accordance with the traces that remained in the brickwork.

The constructed barn model is geometrically accurate and an informative source for restoration. The basis for achieving quality results and the required accuracy using photogrammetric method is strict following of work execution technology.

The obtained graphical three-dimensional models and profiles will become the basis for the Count Stroganov’s barn architectural restoration project.

## 6. Acknowledgements

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## References

Agisoft LLC, 2024. Agisoft Metashape Professional, Version 2.1.0. https://www.agisoft.com/.

Balado, J., Frías, E., González-Collazo, S. M., Díaz-Vilariño, L., 2022. New trends in laser scanning for cultural heritage. *New Technologies in Building and Construction: Towards Sustainable Development*, Springer, 167–186.

Barba, S., Ferreyra, C., Cotella, V. A., di Filippo, A., Amalfitano, S., 2021. A SLAM integrated approach for digital heritage documentation. *International Conference on Human-Computer Interaction*, Springer, 27–39.

Blender Online Community, 2023. Blender - a 3d modelling and rendering package.

Casu, P., Pisu, C., 2015. 3D Reconstruction for the Interpretation of Partly Lost or Never Accomplished Architectural Heritage. *Geospatial Intelligence*, 686-721. https://doi.org/10.4018/978-1-4666-8379-2.ch023.

Dhonju, H., Xiao, W., Sarhosis, V., Mills, J., Wilkinson, S., Wang, Z., Thapa, L., Panday, U., 2017. Feasibility study of low-cost image-based heritage documentation in Nepal. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, Copernicus Publications, 237–242.

Dominici, D., Alicandro, M., Rosciano, E., Massimi, V., 2017. Multiscale documentation and monitoring of L'Aquila historical centre using UAV photogrammetry. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-5/W1, 365–371. https://isprs-archives.copernicus.org/articles/XLII-5-W1/365/2017/.

Guarnieri, A., Vettore, A., El-Hakim, S., Gonzo, L. et al., 2004. Digital photogrammetry and laser scanning in cultural heritage survey. *ISPRS XX. Symposium, Com. V., WG*, 2.

Karachaliou, E., Georgiou, E., Psaltis, D., Stylianidis, E., 2019. UAV for mapping historic buildings: from 3D modelling to BIM. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W9, 397–402. https://isprs-archives.copernicus.org/articles/XLII-2-W9/397/2019/.

Kniaz, V. V., Remondino, F., Knyaz, V. A., 2019. Generative adversarial networks for single photo 3D reconstruction. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W9, 403–408. https://isprs-archives.copernicus.org/articles/XLII-2-W9/403/2019/.

Kniaz, V. V., Zheltov, S. Y., Remondino, F., Knyaz, V. A., Bordodymov, A., Gruen, A., 2020. Wire structure image-based 3D reconstruction aided by deep learning. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B2-2020, 435–441. https://isprs-archives.copernicus.org/articles/XLIII-B2-2020/435/2020/.

Korumaz, A. G., Korumaz, M., Tucci, G., Bonora, V., Niemeier, W., Riedel, B., 2014. UAV systems for documentation of cultural heritage. *ICONARCH International Congress of Architecture and Planning*, 448–459.

Mostafavi, A., Scaioni, M., Yordanov, V., 2019. Photogrammetric solutions for 3D modeling of cultural heritage sites in remote areas. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-4/W18, 765–772. https://isprs-archives.copernicus.org/articles/XLII-4-W18/765/2019/.

Murtiyoso, A., Grussenmeyer, P., 2017. Documentation of heritage buildings using close-range UAV images: dense matching issues, comparison and case studies. *The Photogrammetric Record*, 32(159), 206–229.

Pepe, M., Costantino, D., 2021. Techniques, Tools, Platforms and Algorithms in Close Range Photogrammetry in Building 3D Model and 2D Representation of Objects and Complex Architectures. *Computer-Aided Design and Applications*, 18-1, 42–65.

Porras-Amores, C., Mazarrón, F. R., Cañas, I., Sáez, P. V., 2019. Terrestial laser scanning digitalization in underground constructions. *Journal of Cultural Heritage*, 38, 213–220.

Skrypitsyna, T., Staroverov, S., 2018. Shooting building facades using remotely piloted vehicle. *Engineering survey*, 12, 46-52.

Starodubov, Y., 2022. Stroganovs' salt barn in Romanov-Borisoglebsk. Experience of study, preservation and museification. *Russian North-2022: problems of study and preservation of historical and cultural heritage*, 68–77.

Uhlik, J., 2024. Addon Point Cloud Visualizer for Blender, Version 3.0. https://blendermarket.com/products/pcv.

VC Technology Ltd, 2024. Litchi for DJI Drones, Version 4.26.3. https://www.flylitchi.com/.

Verhoeven, G., 2011. Taking Computer Vision Aloft – Archaeological Three-dimensional Reconstructions from Aerial Photographs with PhotoScan. *Archaeological Prospection*, 18, 67 - 73.

Xu, Z., Wu, T. H., Shen, Y., Wu, L., 2016. Three dimentional reconstruction of large cultural heritage objects based on UAV video and TLS data. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B5, 985–988. https://isprs-archives.copernicus.org/articles/XLI-B5/985/2016/.

Yang, X., Grussenmeyer, P., Koehl, M., Macher, H., Murtiyoso, A., Landes, T., 2020. Review of built heritage modelling: Integration of HBIM and other information techniques. *Journal of Cultural Heritage*, 46.

Yastikli, N., 2007. Documentation of cultural heritage using digital photogrammetry and laser scanning. *Journal of Cultural heritage*, 8(4), 423–427.