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# The critical evaluation of Multi-View Stereo approaches in 3D dense reconstruction for Cultural Heritage objects

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**Abstract:** The article aimed to analyse the possibilities of using Multi-View Stereo algorithms implemented in commercial (Agisoft Metashape and Pix4D) and open-source (OpenMVS 2.0) solutions. To critically assess the correctness of 3D shape mapping, the following parameters were analysed: density of point cloud, planarity, and roughness distribution. The analysis used photos obtained from three different types of sensors, i.e., the Hasselblad H6d-100 medium format camera (fragment of frescoes - Test Site I), low-cost Olympus C-5050Z (fragment of archaeological excavations - Test Site II) and Canon Mark II (fragment of a historic room). The analyses performed show that the best results were obtained for point clouds generated using the Agisoft Metashape software and worse for Pix4D. Evaluating the results obtained for the OpenMVS, it can be noted that better quality in terms of geometric accuracy was obtained for the patch-based algorithm than for the semi-global matching algorithm. The choice between Agisoft Metashape and OpenMVS2.0 depends on the user's knowledge and experience in programming and photogrammetry, as OpenMVS does not provide a user interface but provides an open-source alternative to Metashape.

**Keywords:** Agisoft Metashape; Cultural Heritage; Evaluation; Multi-View Stereo; OpenMVS; Pix4D

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## 1. Introduction

In contemporary societies, cultural heritage assumes a foundational role by preserving both tangible and intangible manifestations of history. Digital technologies play a pivotal role in digitising, protecting, and presenting cultural heritage assets, thereby broadening their accessibility to a more extensive audience [1]. Presently, two prevalent categories of non-invasive methodologies are employed for this purpose, specifically image-based techniques (referred to as passive methods, encompassing close-range photogrammetry and multi-view stereo approaches) and range-based techniques (such as Terrestrial Laser Scanning) [2–8].

Establishing dependable documentation constitutes a crucial facet in administrating and preserving cultural heritage artefacts. The advent of digital tools has significantly streamlined the three-dimensional (3D) documentation process to the extent that digital documentation is progressively emerging as the prevailing norm in scrutinising and rehabilitating historical objects and sites.

Among the array of available digital tools, photogrammetry is frequently employed due to its cost-effectiveness and rapid implementation. Photogrammetric methodologies empower users to generate 3D models of objects by analysing images based on the integrated Structure-from-Motion/Multi-view stereo (SfM/MVS) approaches. Although the method is not novel, the advent of automated software has significantly increased its popularity across diverse disciplines. This form of documentation is appealing to experts studying architecture or large-scale objects, such as archaeologists and architects, owing to its capacity to provide a synergistic blend of geometric precision and visual fidelity. Additionally, it serves as a foundational framework for various measurement techniques.

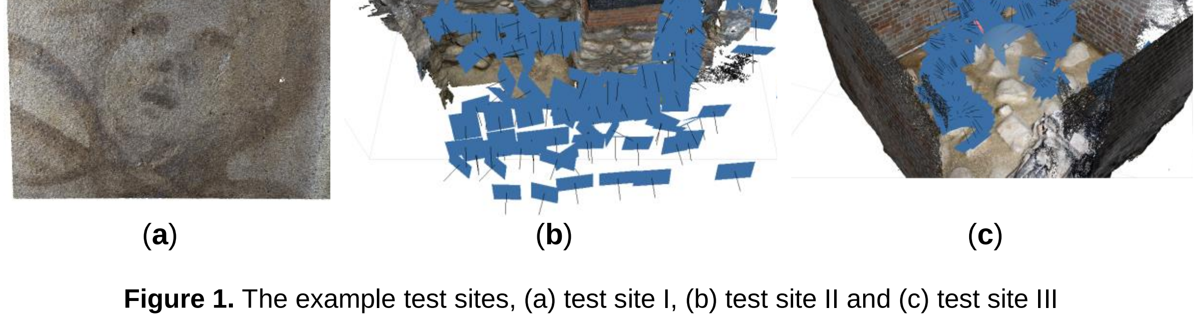
Multi-view stereo (MVS) is a computer vision technique that reconstructs 3D scenes or objects from two-dimensional images captured from different viewpoints. This method leverages the principles of triangulation to estimate the spatial coordinates of points in the scene, generating a dense and accurate representation of the object's geometry. In the MVS process, images are utilised to establish correspondences between points observed from multiple views. These correspondences are then triangulated to compute the 3D coordinates of the underlying scene points. The success of MVS relies on robust algorithms that can handle challenges such as occlusions, lighting variations, and perspective changes across the images. Advancements in computational capabilities and the availability of sophisticated algorithms have significantly enhanced the efficiency and accuracy of multi-view stereo techniques. Its ability to generate detailed 3D reconstructions from a collection of 2D images makes it a valuable tool for object modelling, scene reconstruction, and spatial analysis in diverse scientific and industrial domains.

In this paper, the comparison between different MVS implementations in the open-source domain (here represented by the library OpenMVS 2.0 [9]) and commercial applications (Agisoft Metashape [10] and Pix4D [11]) was analysed in the context of different types of objects (both indoor and outdoor). To check the applicability and analysis of possibilities and limitations of each solution, 3 cameras were used: a middle-frame Hasselblad HD6-100, a full-frame Canon 5D Mark II camera, and a low-cost Olympus C-5050Z camera. The choice to use those sensors was because of the different challenges such as (1) resolution – the need for computation time, (2) pixel size, (3) object characteristics and (4) environmental factors. The following section discusses the methodology of the proposed method of evaluation, results and outcomings. In the summary section, the critical evaluation was shown.

## 2. Materials and Methods

### *2.1. Test sites description*

To assess the quality of the generation of dense point clouds using different MVS approaches applied in open-source OpenMVS 2.0 library and commercial applications Agisoft Metashape and Pix4D, images from the following test sites related to the different elements and architecture styles were used in this paper:



(**a**) (**b**) (**c**)

**Figure 1.** The example test sites, (a) test site I, (b) test site II and (c) test site III

1. **Test Site I** – *Fragment of the wall with wet fresco from the Museum of Palace Interiors in Otwock Wielki*

The bedroom wall in the Museum of Palace Interiors in Otwock Wielki is covered with painted antique ruins against a landscape bathed in the colours of the setting sun, describing a bustling coast through painted ships, goods and people in the antique chamber that precedes it. On the other hand, the paintings in the former study are inspired by the thoughts of the ancient philosopher Horace and offer advice on how to proceed in life. The frescoes were created at the turn of the 17th and 18th centuries. There are few such monuments in Poland. One of the fresco fragments was selected for analysis (Fig. 1a). For data acquisition, the middle-frame Hasselblad HD6-100 with the following specific parameters were used: (1) resolution 11600 x 8700 px – 100 Mpix; (2) sensor size: 53.4 x 40.0 mm; (3) lens: 80 mm.

2. **Test Site II** – *Archaeological excavation outside the Justice Court Tower in the Royal Castle in Warsaw*

The Justice Court Tower is the oldest brick building of the Royal Castle in Warsaw, the edifice which was almost entirely reconstructed after the destruction it suffered during the Second World War. The Justice Court Tower dates back to the 14th century. The original cellar in the basement of the tower, in the 17th century, was later converted to the city prison. The images used for this investigation are shown in Fig. (1 b). Images were used to analyse the lowest part of the wall discovered and preserved during the archaeological-architectural work. An Olympus C-5050Z camera with the following parameters was used to acquire the images: (1) resolution 2560 x 1920 px – 5 Mpix; (2) sensor size: 7.144 x 5.358 mm; (3) lens: 35 mm.

3. **Test Site III** – *Archaeological excavation inside the Justice Court Tower in the Royal Castle in Warsaw*

Like its exterior, the inner part of the Justice Court Tower (Fig. 1c) is built of different coloured bricks from different periods. A regular shape represents it without ornamentation and architectural details. For data acquisition, the full-frame Canon 5D Mark II with the specific parameters were used: (1) resolution 5616 x 3744 px – 21 Mpix; (2) sensor size: 36.0 x 24.0 mm; (3) lens: 24 mm.

The choice of sensors with different geometries influences the accuracy and density of the generated point cloud. Higher resolution influences:

- increased density of the resulting point cloud
- Improved colour mapping quality, which results in better point detection, and
- lower errors in a dense point cloud computation.

### *2.2. Generation and comparison of dense MVS point clouds*

To generate dense point clouds from a series of images, four different approaches were used, based on the commercial software Agisoft Metashape and Pix4D and using the OpenMVS2.0 library, based on Patch-Match (PM) and Semi-Global Matching (SGM) algorithms. Table 1 shows the parameters used to generate the dense point clouds.

**Table 1.** The parameters for point cloud generation are used in different software and algorithms.

| Software/method (algorithm) | Quality Parameter (Image resolution) | Filtering | Number of views | Fusion mode | Iterations | Matching windows size |
|---|---|---|---|---|---|---|
| Agisoft Metashape (version 1.8.5) | Ultra high (full-resolution) | Depth filtering (Mild) | 2 – all neighbour views available | x | X | x |
| Pix4D (version 4.8.4) | Full image size | X | x | x | X | 9 x 9 |
| OpenMVS – PM (version 2.0) | 0 (full-size) | 0 (Disable) | 0 - all neighbour views available | 0 | 5 | x |
| OpenMVS – SGM (version 2.0) | 0 (full-size) | 0 (Disable) | 0 - all neighbour views available | -1<br>-2 | 5 | x |

CloudCompare software was used to assess the quality and select the best solution for 3D reconstruction. A point cloud generated using Agisoft Metashape software was used as a reference cloud. The choice of this software was based on the fact that Agisoft Metashape software is now considered one of the important and widely used applications in heritage documentation. It is now regarded as the state-of-the art for generating 3D documentation. In order to assess the quality of point cloud, the following values were used:

- **the planarity** – is quantified through the analysis of the variance in distances between individual points and a plane, determined via least squares fitting. This metric serves as a discriminative feature, enabling the differentiation of flat surfaces,
- **the roughness of point clouds** – the estimation of roughness entails a straightforward process: for each point within the dataset, the determination of its 'roughness' value is contingent upon the distance between said point and the optimal fitting plane computed using its closest neighbouring points.
- **the point cloud density** – characterises the distribution of points within a given volume by quantifying the ratio of the number of nearest neighbouring points to the volume encompassed by the dataset. The density distribution is a good measure of quality, as it shows whether an algorithm is dependent on local variations in grey degrees, texture variance and texture, or whether it allows for the global generation of a dense point cloud.

For those factors the neighbour points were searched in a 5 mm radius for Test Site I and 5 cm radius for Test Site II and III. The choice of search radius for the number of neighbours was driven by the size and dimensions of the Test Sites.

## 3. Results

### *3.1. The initial analysis of the point cloud*

The point clouds generated by the four MVS-based algorithms are shown in Figure 2. Additionally, the number of detected and matched points was shown for each solution. Based on visual inspection, the first analyses show that high-resolution point clouds could not be generated for all solutions. The analyses show that the worst results were obtained for the solution based on Pix4D software and the best results with Agisoft Metashape. Despite this, it should be emphasised that the results obtained for the SGM-OpenMVS method are similar to the solution obtained for Agisoft Metashape.

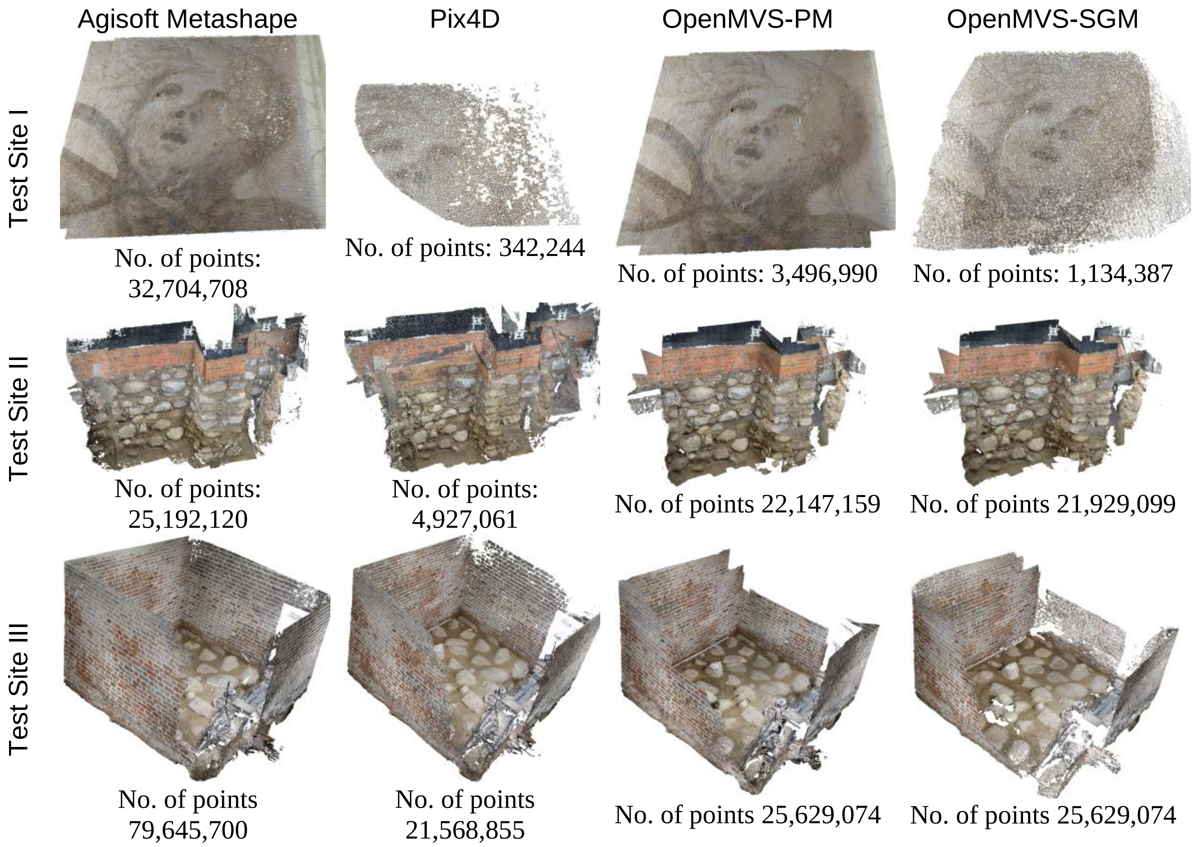



**Figure 2.** The example of dense points clouds.

Assessing the results in detail, it can be seen that the worst point clouds were obtained for Pix4D. Noticeably, the number of points is significantly lower than for Agisoft and OpenMVS. Analysing the individual Test Sites separately, for Test Site I, the frescoes were only partially correctly mapped; for Test Site II there are problems with the mapping of the walls (a noticeable effect of incorrect matching of photos and multiplication of the same fragments), and for Test Site III there are visible parts of the monuments.

Analysing the number of points, it can be seen that with Pix4D, the point cloud generated contains fewer points than the other solutions. The number of points detected using the Agisoft Metashape software is, for all cases, the highest.

### *3.2. The density analysis*

The resolution and density of these points directly impact the fidelity and reliability of the reconstructed 3D model. Point cloud density analysis examines the data points' spatial distribution and concentration, offering a quantitative measure of the information provided by the point cloud within a given area. Point cloud density analysis enables the initial identification of areas with insufficient coverage and aids in strategically augmenting the data acquisition step to improve overall model precision.

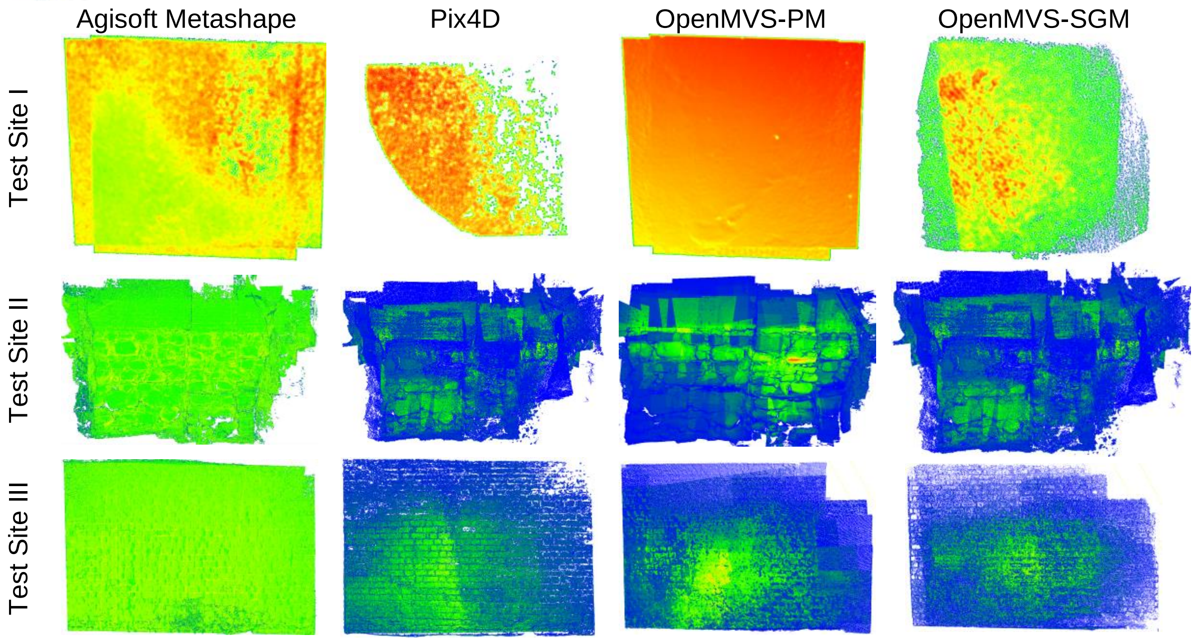


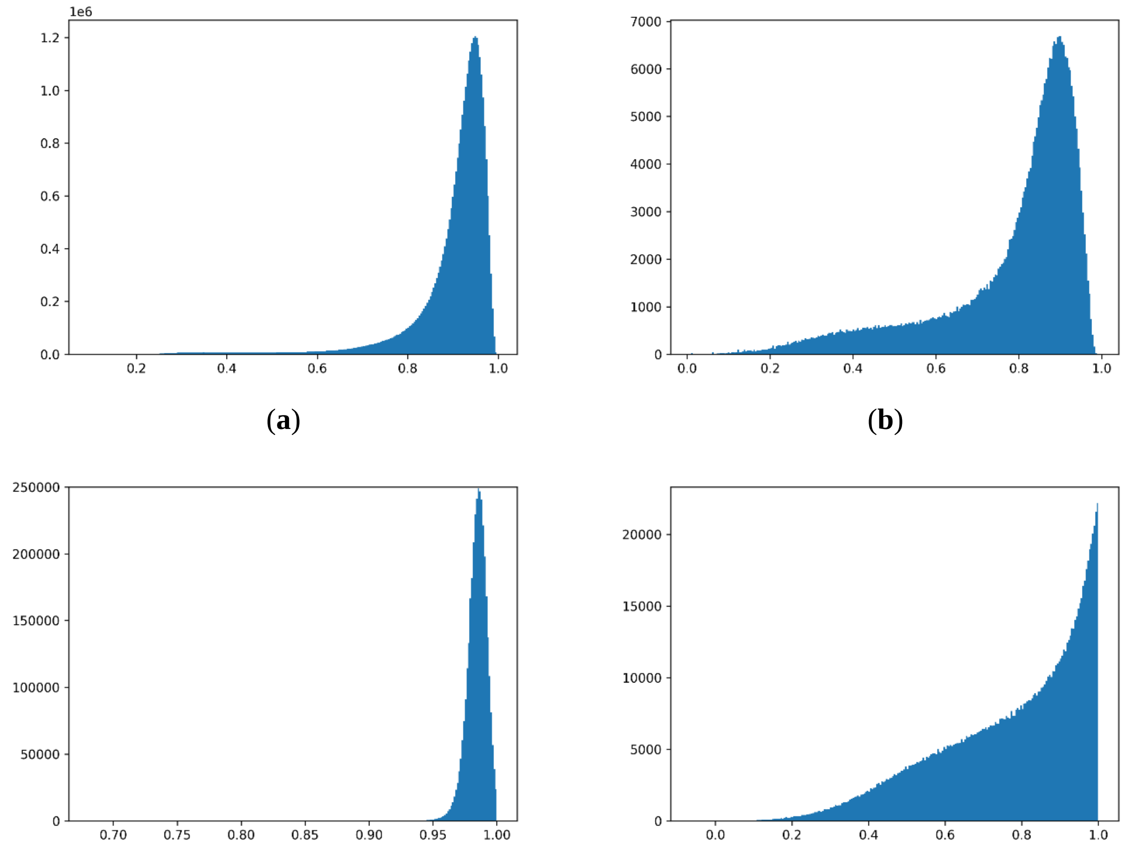

**Figure 3.** The example of different point densities for points clouds generated with different solutions.

The point cloud density results shown in Figure 3 should be analysed separately for each Test Site. When using the high-resolution images acquired with the Hasselblad Hd6-100 camera, it can be seen that the best distribution (the smallest variance) was obtained for the solution based on the OpenMVS-PM and OpenMVS-SGM algorithms, while the worst results were obtained for the solution based on Pix4D. In the case of point clouds generated from Agisoft Metashape, an increased point density is noticeable in areas with significant differences in grey degree gradients.

For the other two Test Sites, the same conclusions can be drawn. The best and, at the same time, homogeneous point distribution was only obtained for the solution based on the algorithm implemented in the Agisoft Metashape software. For the other solutions, there is a noticeable increase in the density of point clouds in the central parts of the walls. For the OpenMVS-based solution (for both PM and SGM), the significant difference in the centre of the measured object is due to the number of images used to reconstruct the 3D shape. For the OpenMVS and Pix4D methods, all usable points detected in a minimum of 2 images were used. A probable increase in the number of photos from which the coordinates of the points are determined would decrease the number of points but would contribute to their regular detection.

### *3.3. The planarity analysis*

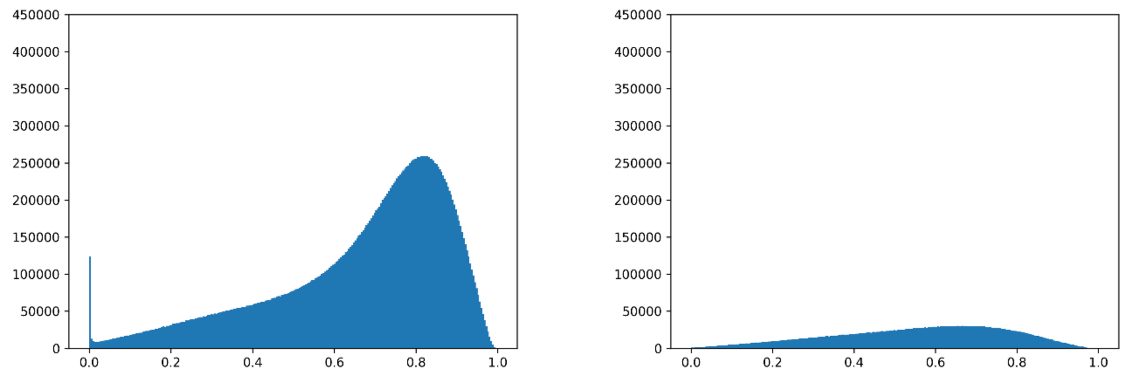
Planarity, defined as the degree to which a surface deviates from being flat, provides essential insights into the geometric characteristics of objects. Principal Component Analysis is a widely utilised technique for planarity analysis, decomposing the covariance matrix of point clouds to extract principal axes and eigenvalues. The magnitude of eigenvalues reflects the degree of planarity, enabling the identification of flat or curved surfaces within the point cloud. Figures 4 - 6 show the results of the planarity parameter analysis. Due to the different number of points, a single scale on the y (frequency) axis was not adopted to show the actual distribution of this parameter. It should be noted that the greater the deviation from a value of 1, the fewer points represent the flatness of the selected fragments. Fragments whose shape approximately corresponds to the plane were selected for all test fields.



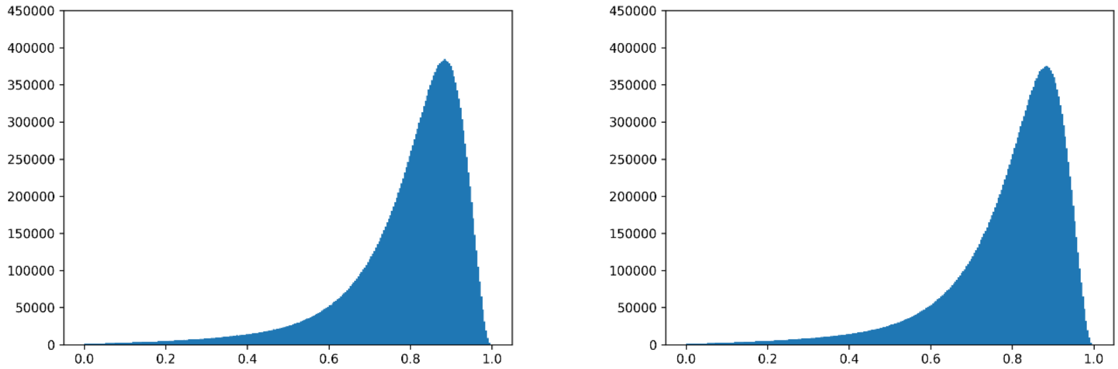
(a) (b) (c) (d)

**Figure 4.** Histograms of planarity parameter values for points forming reference planes generated from: (a) Agisoft Metashape, (b) Pix4D,(c) OpenMVS-PM ,and (d) OpenMVS-SGM for Test Site I.

By analysing the distributions of the values shown in the histograms (Fig. 4), it can be seen that the smallest spread of data was obtained for OpenMVS-PM and the largest for OpenMVS-SGM. Evaluating the Agisoft histogram (Fig. 4a), it adopts a chi-square distribution, which demonstrates the correctness of the planarity mapping. However, it should be noted that the approximately 10 times higher number of generated points using Agisoft than OpenMVS-PM, did not significantly improve the planarity determination.



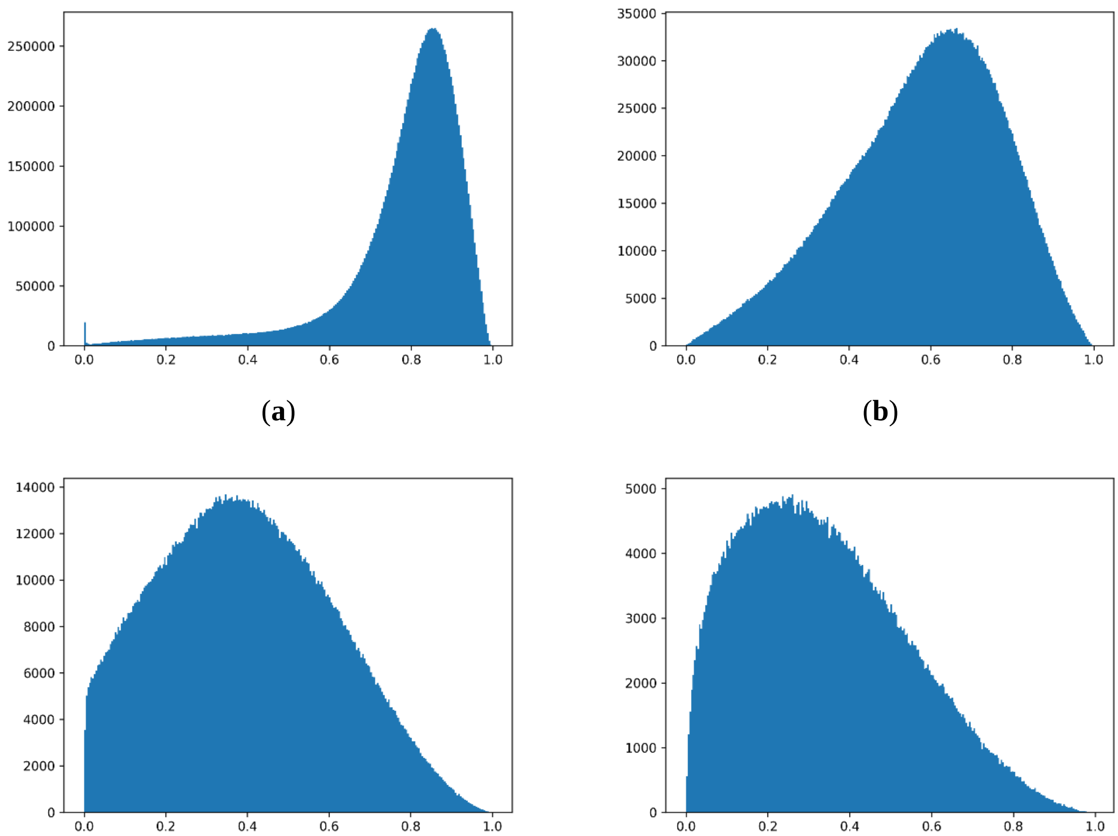
(a) (b)




(c) (d)

**Figure 5.** Histograms of planarity parameter values for points forming reference planes generated from: (a) Agisoft Metashape, (b) Pix4D,(c) OpenMVS-PM ,and (d) OpenMVS-SGM for Test Site II.

As for Test Site II, the smallest spread of values and the best planarity was found for OpenMVS-PM (Fig. 5c). It should be noted that similar results were also obtained for OpenMVS-SGM, and slightly worse for Agisoft Metashape (Fig. 5a). As for Test Site I, increasing the number of points (Fig. 5a), did not significantly improve planarity determination. The histogram obtained for the planarity values for Pix4D (Fig. 5b) is flat, with values between 0.2 and 0.9. This indicates a poor representation of planarity and, in comparison with other solutions, an incorrect shape representation.




(a) (b)

(c) (d)

**Figure 6.** Histograms of planarity parameter values for points forming reference planes generated from: (a) Agisoft Metashape, (b) Pix4D,(c) OpenMVS-PM ,and (d) OpenMVS-SGM for Test Site III.

In contrast to the previous two Test Sites, the smallest spread of planarity values was obtained for Agisoft Metashape (Fig. 6a). Heterogeneity in the density of detected points using OpenMVS algorithms (Fig. 6c and d) contributed to the poor determination of planarity in comparison with Agisoft. A similar discrepancy is also noticeable for the point cloud from Pix4D (Fig. 6b), but the influence of erroneous planarity is not as significant as for the results from OpenMVS. A solution to improve this could be not to use the minimum detection points in 2 images but to include more indentation, both for Pix4D and OpenMVS-PM and SGM.

### *3.4. The roughness of point clouds analysis*

Surface roughness analysis in point cloud data is fundamental for understanding the intricacies of spatial textures. This study leverages CloudCompare, a widely used open-source software for point cloud processing, to quantitatively assess surface roughness. In order to calculate the roughness, the distance between this point and the best fitting plane computed on its nearest neighbours is computed for each point.

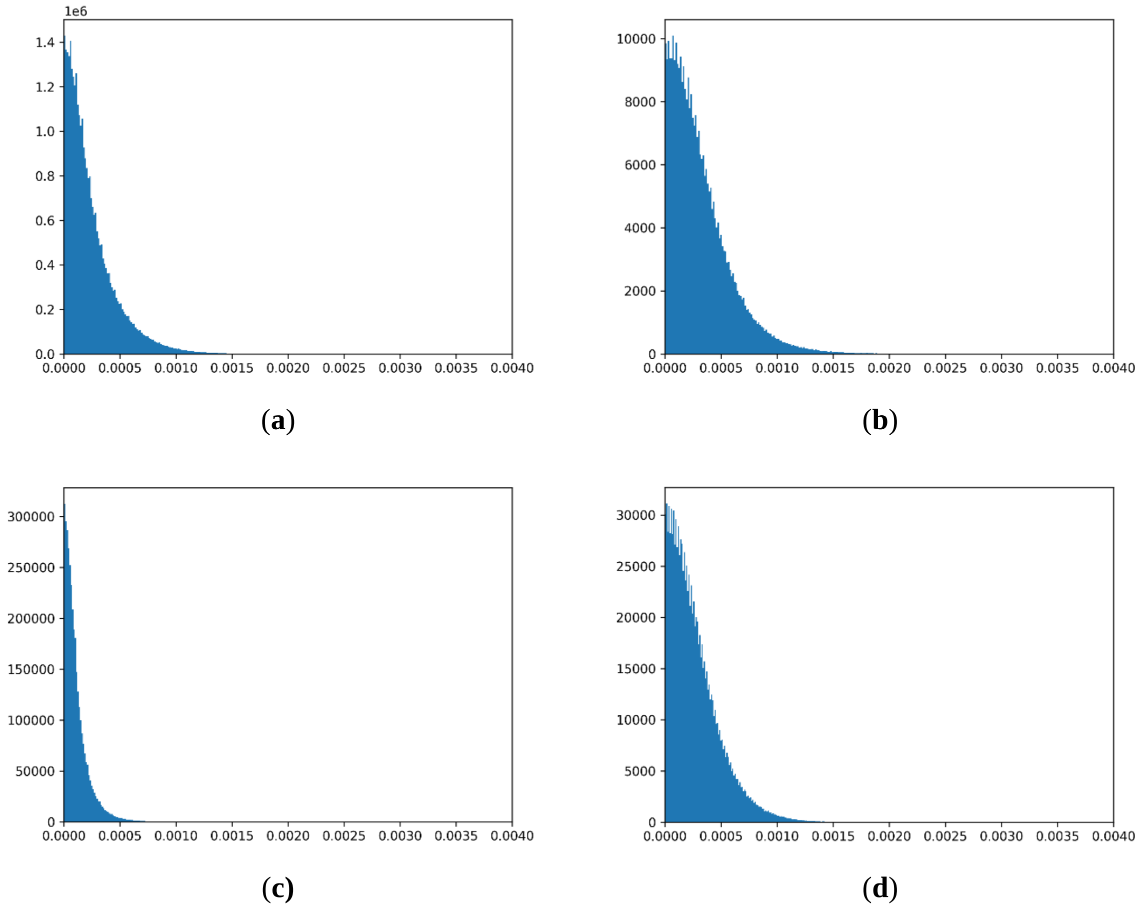



**Figure 7.** Histograms of roughness parameter values for points forming reference planes generated from: (a) Agisoft Metashape, (b) Pix4D,(c) OpenMVS-PM ,and (d) OpenMVS-SGM for Test Site I.

Similar to the planarity analysis for Test Site I, it was decided not to scale the y-axis values to show the distribution of values without considering the number of detected points. Evaluating the roughness for the fresco mapped on Test Site I (Fig. 7), the best results were obtained for the solution based on OpenMVS-PM and successively for Agisoft Metashape, OpenMVS-SGM and Pix4D. It should be noted that the results obtained for all solutions are correct. As for the planarity analyses, the higher number of detected points using Agisoft Metashape did not significantly improve roughness.

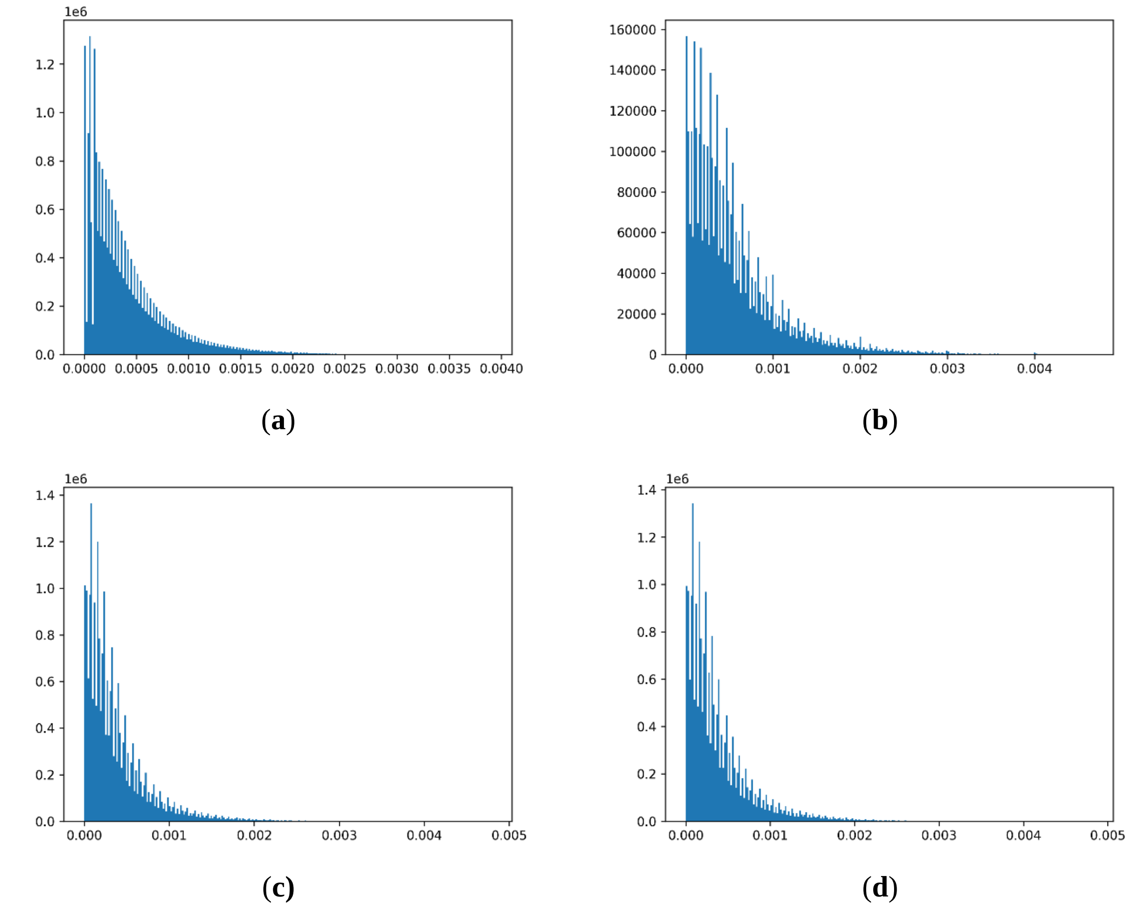
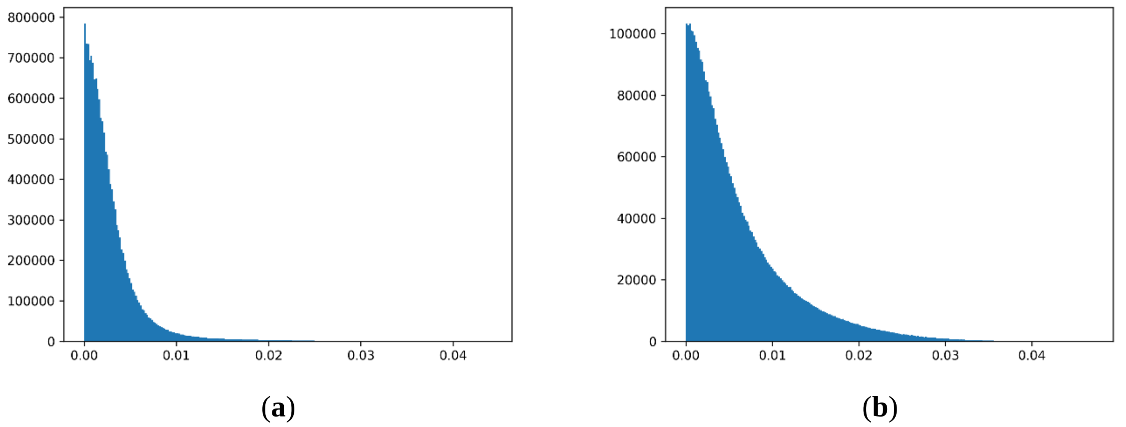
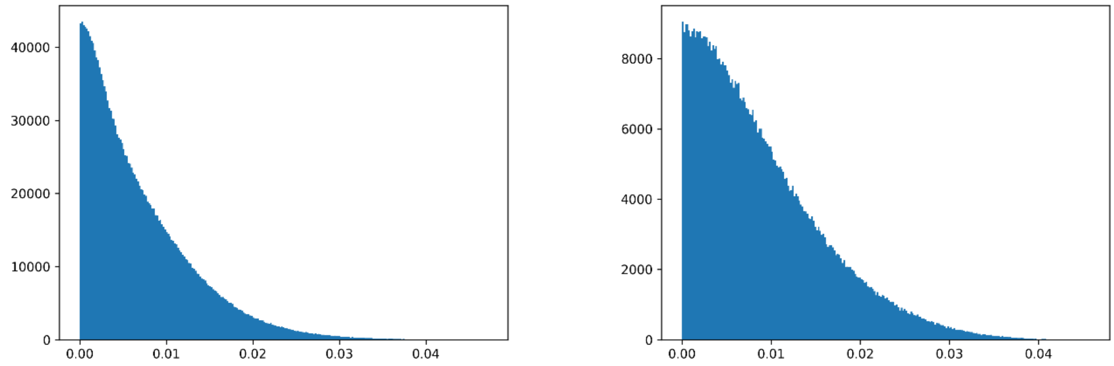



**Figure 8.** Histograms of roughness parameter values for points forming reference planes generated from: (a) Agisoft Metashape, (b) Pix4D,(c) OpenMVS-PM ,and (d) OpenMVS-SGM for Test Site II.

The presented histograms of roughness values in Figure 8 show slight deviations from 0, indicating the correctness of the generated dense point clouds. Only significantly small deviations are noticeable for Pix4D.






(c) (d)

**Figure 9.** Histograms of roughness parameter values for points forming reference planes generated from: (a) Agisoft Metashape, (b) Pix4D,(c) OpenMVS-PM ,and (d) OpenMVS-SGM for Test Site III.

As with the previous two Test Sites, histograms indicate small surface irregularities or variations in a three-dimensional point cloud dataset. The smallest irregularity was obtained for Agisoft Metashape (Fig. 9a), and the largest for OpenMVS-SGM (Fig. 9d). Similar results were obtained for results with Pix4D and OpenMVS-PM.

## 4. Conclusions

The article aimed to show the possibilities and critically evaluate the use of commercial solutions for generating dense point clouds implemented in the software Pix4D and Agisoft Metashape and in the open-source solution OpenMVS2.0 based on Multi-View Stereo algorithms. The analysis used images acquired from a Hasselblad h6d-100 medium-format camera (Test Site I), from low-cost sensors (Test Site II), and a Canon 5D Mark II full-frame camera. The following conclusions could be drawn from the analyses:

- The use of both commercial and open-source solutions allows for correct shape reproduction. For this reason, it is worth considering whether using a solution based on the OpenMVS library is justified due to the possibility of selecting the parameters for generating dense point clouds, i.e. (1) Semi-Global Matching vs point detection algorithm. Patch-based, (2) selection of the number of photos necessary to generate dense point clouds, (3) the number of iterations of "thickening" point clouds and (4) the level of the pyramid used for point detection. This solves the black-box problems of commercial software but requires programming knowledge.
- Selecting input parameters for algorithms in OpenMVS requires specialised knowledge in image processing and photogrammetry. There is no single set of the same parameters for different Test Sites, which requires consideration on a case-by-case basis. In the article, the proposed data processing parameters presented in Table 1 enabled correct shape mapping for fragments of flat frescoes (Test Site I) and a flat wall of bricks and stones (Test Site II). The results obtained for fragments of a brick wall (Test Site III) indicate that it is necessary to modify them, e.g. by using a larger number of photos to determine points, to improve the geometric quality and obtain a similar data density.
- The analyses show that a larger number of points detected using the Agisoft Metashape software (compared to OpenMVS-PM) does not significantly improve the accuracy of shape mapping. For this reason, it is reasonable to consider whether

additional point filtration should be used, considering additional dependencies such as planarity or roughness.

**Authors Contributions:** Conceptualisation, J.M., A.M. and K.K; methodology, investigation, J.M and K.K.; writing—original draft preparation, A.M. and J.M. All authors have read and agreed to the published version of the manuscript.

**Conflicts of Interest** The authors declare no conflict of interest.

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