A Review of Existing Evaluation Methods for Point Clouds Quality

Hector Fretes, Marcos Gomez-Redondo, Enrique Paiva, Jorge Rodas, and Raul Gregor

***Abstract*— One problem in 3D reconstruction from aerial photographs is the evaluation of the point clouds quality. For point clouds, in general, different authors evaluate their results in different ways. This paper analyzes the existing evaluation methods for the point cloud quality and a new discussion regarding their applicability to aerial photographs is opened. Some of these methods are chosen based on practical issues and applied to a pair of reconstructions. The principal conclusion is that objective methods are the most interesting in photogrammetry applications, particularly the comparison between two point clouds.**

***Index Terms*— Aerial Photogrammetry, Digital Photogrammetry, Review, Point Cloud, 3D Reconstruction.**

NOMENCLATURE

DEM	Digital Elevation Model.
DTM	Digital Terrain Model.
GCP	Ground Control Point.
MOS	Mean Objective Score.
ODM	OpenDroneMap.
PSNR	Peak Signal-to-Noise Ratio.
RMS	Root Mean Square.
RMSD	Root Mean Square Deviation.
SFM	Structure From Motion.
UAV	Unmanned Aerial Vehicle.

I. INTRODUCTION

NUMEROUS studies have been made with different reconstruction programs such as Pix4D, Agisoft, and OpenDroneMap, but they mainly compare the advantages and disadvantages of each one in terms of cost, accessibility to the source code, and other aspects rather than objective analysis [1]. For instance, in a study of the feasibility of using a smart camera as the payload for a UAV, a reconstruction with ODM is obtained but the point cloud analysis is not mentioned [2]. Although [3] mainly focus on the design of a low-cost tri rotor UAV, a reconstruction is performed and the results offered by Pix4D are presented with an estimated error that is calculated on the same software from some parameters such as the flight altitude and camera optics. Some authors describe an UAV mapping workflow and suggest some recommendations for the process, present initiatives that facilitate the gathering, hosting and sharing of user-contributed UAV imagery and also open software for digital photogrammetry [4] as well as open hardware [1]. This suggests that the number of 3D reconstructed scenes will be increased notably in the future, given that any user may share and access to data as well as open resources. It is also remarkable the number of works in the segmentation of point clouds, which attempt to extract information from 3D Point clouds, through artificial intelligence algorithms [5] or new descriptors [6]–[8].

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However, there is not yet a standard in the evaluation of 3D reconstructions in digital aerial photogrammetry, namely, point clouds. The main reason may be thought to be that the complete process is very extensive and authors generally evaluate only a part of the whole reconstruction procedure. For example, a factor involved into the process is the matching process, which is directly related with the number of points in the cloud, noise and affect the quality of the reconstruction, but it is a whole universe in computer science [9]. Taking that into account, this paper reviews point clouds quality evaluation methods in order to propose a standard to aerial reconstructions evaluation, namely, to researchers not very interiorized into computer science. In this way, researchers without too much knowledge could have a standardized method to determine the quality of the reconstruction and compare their results, without too much effort. In the following section, a variety of evaluation methods are presented and classified. In section III the most important evaluation methods for point clouds are summarized. In section IV there is an evaluation example and finally, some conclusions are presented.

II. BRIEF REVIEW OF THE EVALUATION PROCESS IN WORKS PRESENTED TO THE DATE

The evaluation methods can be classified into two major groups, subjective assessment methods and objective quality metrics.

A. Subjective assessment methods

These methods rely on qualitative analysis of the point clouds, based primarily on visual quality of the cloud and practical issues. For example, a sparse cloud is obtained in [10] and the evaluation is just a qualitative analysis of the DEM they have obtained. In another work, a 3D reconstruction system is proposed [11] and is verified through qualitative evaluation of experimental results for a variety of scenes. In [1] a comparison between commercial systems versus open-source systems is made. The author compares practical issues rather than the quality of the obtained reconstruction.

There is another evaluation method known as Mean Opinion Score (MOS), which consists of a subjective analysis of point clouds. The author in [12] present a codec that may be used for high rate transference of point clouds (data compression). In [13] is stated that current state-of-the-art objective metrics do not predict well visual quality, especially under typical distortions such as compression. The geometric distance, using RMS or Hausdorf distance, is applied to point-point, point-plane, and PSNR. Then the author shows the MOS and Point Cloud Quality Rating. In [14] another MOS evaluation is done. The author classifies the evaluation into objective, which is performed by a computer, and subjective, which is performed by the human. He also remarks about the importance of subjective evaluation to reaffirm the correctness of objective evaluation methods. After a brief review, he proposes a subjective evaluation model and some criteria for its application, finishing with an experiment. In [15] a correlation between the objective and subjective scores is assessed. As these works are centered to communication systems the MOS is useful, but when it comes to planialtimetric study, these studies do not seem to be applicable. Furthermore, subjective methods are time and cost expensive, and the reliability of the evaluations can be objectionable. For these reasons, a wide majority of scene reconstruction works use objective quality metrics in order to evaluate their results.

B. Objective quality metrics

Objective quality metrics rely on the definition of a parameter of the point cloud and obtaining a metric involving this parameter as the evaluation. Typically, these metrics involve measurements such as euclidean distances, angular distances, reprojection errors, ground control points location, number of points, and may involve the comparison between the evaluated point cloud and a reference model.

There exists some objective quality metrics that can be obtained exclusively from the evaluated point cloud. In [16] 3D point clouds are utilized for landslide scarp recognition. The quality of the 3D model is quantified in terms of point spacing in the cloud and point density, which gives a more complete evaluation of the model than the number of points in the cloud. In [17] a framework for 3D reconstruction from aerial images is presented and its results are compared against the ones of [18] in terms of the number of good-considered points, the mean error projection and execution time. But the more interesting could be the mean error projection [19], [20], because it gives an idea of the noise present in the point cloud.

Finally, the most common way to evaluate the quality seems to be the comparison against a reference [21], [22], [23], [24]. However, there are different kinds of references, depending on the case of study. We differentiate two major groups. The first, in which the exact model is known beforehand. The second, where you have a point cloud obtained by some other means.

1) Exact model:

a) Digital model: In some cases, the exact digital model is known, so you can generate a point cloud from it. That is the case of [25], where an evaluation of machining allowance of precision castings is made by comparing 2 point clouds, one of the model and one obtained by measurements. They analyse and compare these two taking into account some characteristics like plane angle, plane-plane distance, point-plane distance, shape ratio, size ratio. In [26] a simulation environment, FEATS, is presented. With this environment, the corresponding ground truth 3D point coordinate for each reconstructed 3D point is known, so that the error between these two points is easily calculated. In [27], a surface normal estimation for a set of unorganized points is revisited. They use available online data for their experiments. They propose measuring the average error per point in degrees' since their interest focus on surface normal estimation accuracy. This could be an interesting option for evaluating surface normals, rather than the cloud point. They test the algorithm rather than the point cloud. This kind of comparisons are really demonstrative but the need of the exact model in order to evaluate the reconstruction poses a problem for aerial photogrammetry, in which said model is not available.

b) Real model: The comparison could also be made against empirical measurements of the scene, which is not either a practical method when it comes to aerial photogrammetry, because of the time and cost demands of obtaining the model. In [28] they evaluate the quality of a commercial SFM Dense multi View 3D reconstruction software. In order to do this, a contrast against total station data and range scan data is performed. The author shows representative illustrations of the distance between different parts of the cloud points. Afterward, a table of Euclidean distances between different points is shown, comparing the results of the SFM-DMVR with the other data sources and then with the empirical measurements on the real monument. This last method was also used in [29]. In 2011, [30] compares different variants of the Hough transform regarding their reliability in detecting planes. They also introduce a new approach to design the accumulator. In concern with the evaluation, they made a quantitative as well as a qualitative evaluation of all the variants in five different scenes, taking into account the number of planes detected, angles and also the time consumed by every variant. In this paper, the evaluation is a comparison against a real model where the planes are known beforehand. So these characteristics are also representative in case of having two point clouds. They also conclude that Randomized Hough Transform is the method of choice when dealing with 3-dimensional data due to the time performance, but as far as it seems, the scene must be multiplanar rather than curve in order to use these evaluations. In [31] the analysis of the Super-Sauze landslide is performed. They compare two data sets and obtain a velocity profile of the land. They evaluate the quality of the DTM obtained so as to validate their results. The evaluation consists in quantifying the error by comparing 199 GCP locations to their measured locations giving a mean error and standard deviation in meters. In [32] the 3D models obtained are validated using field measurements of objects in the scene and 3D surfaces obtained by total stations as reference. The use of total stations allows obtaining a reference with a predefined accuracy and resolution to contrast the results.

2) Point cloud obtained by other methods: Another approach consists in the comparison of point clouds obtained by different methods, software or technologies. This is the more easily applicable method regarding aerial photogrammetry. In [31] they also compare 2 DTMs of the same scene and give the RMS and maximum deviations for this validation. In [33] an open-source-based process pipeline to develop a 3D model is described. An analysis of popular feature detectors is made, comparing a maximum number of robust feature keypoints detected, average computation time and even distribution of keypoints. The suitability of feature detectors for different scenes is also studied, based on repeatability and a high number of correspondences for each detector in a given scene. The relative accuracy of the 3D point clouds obtained is then analyzed by comparison with the Pix4D output using the Euclidean distances between pairs of clouds. In 2018, GRAPHOS has been introduced [34]. It is another open-source software that can process the imagery up to the dense point cloud. It is missing only the georeferencing for the full reconstruction. It mainly has an educational purpose but it also presents a metric for the point cloud evaluation, the median absolute deviation (MAD). In [35] a rapid 3D reconstruction method based in image queue, considering continuity and relevance of UAV camera images is presented. The method is first evaluated using the DTU Robot Image Data Sets [36] by comparison of the clouds obtained with the proposed method and the clouds provided by the dataset. Then is tested with aerial images taken from UAV's flights, the results of these tests are analyzed in terms of the number of points in the final clouds.

III. Interesting evaluation methods for planialtimetric aplications

A. Objective evaluation metrics

These methods seem to be the most appropriate in aerial photogrammetry. The most popular are P2Point and P2Plane. These two evaluate mostly the noise present in the cloud point. For any of these methods, the definition of a distance function is needed. There are two standard distances: RMSD and Hausdorff metric.

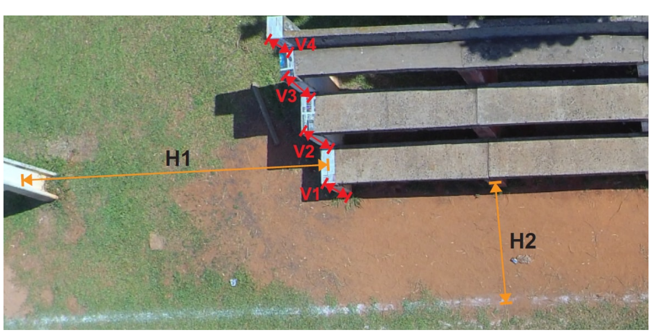

Fig. 1. Measured distances in the scene.

TABLE I
EMPIRICAL MEASUREMETS IN THE SCENE. RESULTS FOR THE EUCLIDEAN NORM OF SOME SEGMENTS IN THE CLOUD OBTAINED BY WEBODM.

Segment	Point cloud distance [cm]	Measured distance [cm]	Error [cm]	Percentage error (%)
H1	497	487	-10	2.05
H2	194.2	180	-14	7.77
V1	69	69	0	0
V2	51	56	5	8.93
V3	49	56	7	12.5
V4	47	30	17	56.67

B. Direct comparison of some metric.

Another existing method employed into the cloud point evaluation, however, its simplicity, is to take measurements on the real scene and then contrast some distances and angles with the obtained on the reconstruction. This method is useful when the empiric measurement does not represent an obstacle, namely, small scenes and regular geometric shapes (planes, circles) so as to obtain all the information needed without too much effort. Another aspect of this analysis is that you only need one point cloud, given that you compare the reconstruction directly with the scene. One problem this method has is that a dense point cloud is needed, otherwise, the determination of points may be difficult to achieve. This kind of analysis could be applied in photogrammetry of urban areas or wherever the model could be considered as multiplanar, maybe with the help of some segmentation method for obtaining the different planes in the scene.

IV. Results and discussion

For the evaluation, a set of 13 aerial images from an altitude of 20 meters were used. Photographs were taken with the Autel X-Star Premium drone. These photographs were used for the reconstruction of two point clouds. One point cloud with WebODM and the other with Regard3d.

For the comparison against the real model, measurements of a set of six segments were taken in the scene as they are shown in Fig. 1 and tabulated in TABLE I and TABLE II.

The problem found with this method is that human error might be introduced during measurement, from both the scene and the cloud, especially when a segment is not easily

TABLE II
EMPIRICAL MEASUREMETS IN THE SCENE. RESULTS FOR THE EUCLIDEAN NORM OF SOME SEGMENTS IN THE CLOUD OBTAINED BY REGARD3D.

Segment	Point cloud distance [cm]	Measured distance [cm]	Error [cm]	Percentage error (%)
H1	497	487	-4.41	2.05
H2	176	180	4.2	2.22
V1	69	69	-6.69	0
V2	58	56	1.19	3.57
V3	56	56	-2.7	0
V4	34	30	0.2	13.33

TABLE III

DISTANCES BETWEEN CLOUDS

Method	Mean	Std. deviation
Point-point	0.629	0.540
Point-plane	0.0.552	0.454

identifiable in the cloud, as in the case of the segment V4 in TABLE I. Low point density and noise in the region of interest are factors that increase the probability of human error.

Afterwards, both cloud points were compared using point-point and point-plane distance and the results are presented in TABLE III.

Fig. 2 shows the distribution of the distances along with the scene and in Fig. 3 a histogram of this distribution is presented, in which the number of points against the distance is plotted.

It can be seen that the highest distances between the clouds appear at the edges of the scene, where the radial distortion existing in the cloud reconstructed with ODM is maximum, while in the center of the models obtained the distances between them are low, which shows a high correspondence between the two models in that area.

The results of the point-plane distance measurement are given by Fig. 4 and Fig. 5. It can be seen that the mean distance is lower than the one obtained for the point-point distance, and even in the regions where the cloud obtained with WebODM presents high distortion, the distance is lower for the point-plane distance. This indicates that even though distortion and the error for individual points of the scene are high, the model can still be representative of the scene, particularly for applications such as obtaining a Digital Elevation Model of the scene.

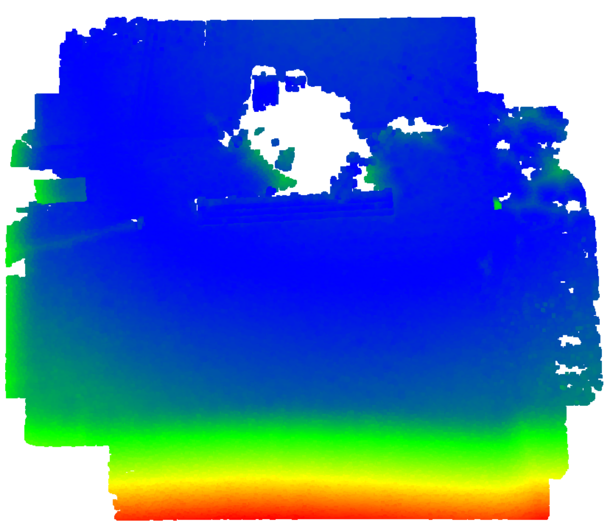

Fig. 2. Point to point distances between clouds.

V. CONCLUSIONS AND FUTURE OF POINT CLOUD EVALUATION

Although subjective methods could provide a preliminary evaluation of a point cloud, they are not of interest for aerial photogrammetry, in which accuracy and precision are required by most applications, because in order to provide a reliable result require evaluation by various subjects, which impacts in time and monetary costs.

Direct measurement in the scene for comparison against the point cloud should be the ideal evaluation method, but

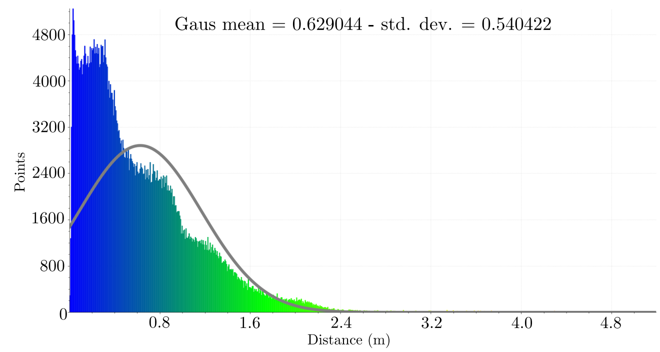

Fig. 3. Point to point distances histogram.

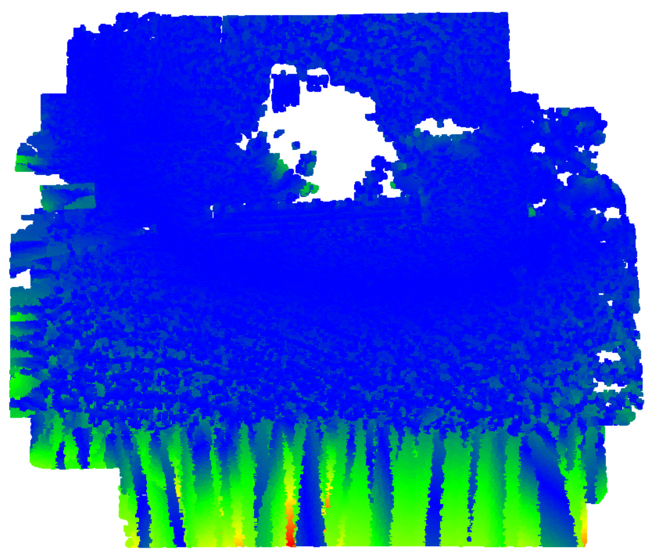

Fig. 4. Point to plane distances between clouds.

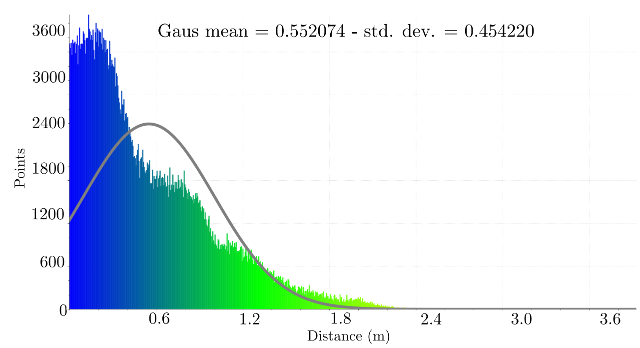

Fig. 5. Point to plane distances histogram.

becomes impractical when it comes to digital photogrammetry applied to aerial photographies, because of the size of the scenes and the potential measurement errors introduced by low point density and noise in the clouds.

The most interesting evaluation method for this case seems to be the comparison between two point clouds obtained by different means, which reduces human interference and guarantees less error in the evaluation of the cloud obtained. The comparison method between the clouds depends highly on the application of the point cloud. If the main application is the utilization of the cloud for planialtimetric studies and DEMs, the point-plane comparison method provides a better evaluation of the cloud, because points with high individual error can still be representative of the surfaces studied. It is noted that for a complete evaluation of a cloud, evaluation by two or more methods should be realized, as an unique objective metric does not necessarily correlate to good visual quality, and a particular method could fit better for a certain application, such as the aforementioned point-plane distance for DEMs.

Future challenges in evaluation methods include the characterization of surfaces in the model, as current evaluation methods, such as the comparison of GCP location and point-point distance, provide metrics for individual points but ignore the regions of the cloud between those points. Techniques such as point cloud segmentation [7], [37] could be explored for this purpose, as the could provide boundaries information which could help in the characterization of surfaces in the scene, while eliminating disparities between different data sets of the same scene produced over time (such as vegetation growth, constructions, among others).

Another challenge is the correlation between the given metrics and the visual quality of the point cloud. In this aspect, segmentation could also provide new metrics in the form of object classification and identification [5], where the number of objects detected could give a metric that correlates to the visual quality of the point cloud.

This correlation between the metrics and visual quality, the surface characterization, and the development of an objective metric that comprises the existing metrics are the main goals of research on evaluation methods, in order to simplify the evaluation process into a unique metric for every possible application of the point cloud.

Acknowledgment

This publication was made in the framework of the project PINV15-0136 called “Vehículos aéreos no tripulados (UAV) en aplicaciones de fotogrametría para el análisis planialtimétrico y cálculo de volumen” funded by Consejo Nacional de Ciencia y Tecnología (CONACYT) from Paraguay.

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