3-D Reconstruction Of Digital Outcrop Model Based On Multiple View Images And Terrestrial Laser Scanning

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Abstract

This paper presents a comparative study about 3D reconstruction based on active and passive sensors, mainly LiDAR – Terrestrial Laser Scanner (TLS) and raster images (photography), respectively. An accuracy analysis has been performed in the positioning of outcrop point clouds obtained by both techniques. To make the comparison feasible, datasets are composed by point clouds generated from multiple images in different poses using a consumer digital camera and directly by terrestrial laser scanner. After preprocessing stages to obtain these point clouds, both are compared, through the positional discrepancies and standard deviation. A preliminary analysis has been shown the feasible employment of digital image jointly 3D reconstruction method for digital outcrop modeling, concerning with data acquisition at low cost without significantly lost of accuracy when compared with LiDAR.

Key words: *LiDAR, 3D Reconstruction, Digital Outcrop Model, Structure From Motion, Terrestrial Laser Scanner (TLS), Multiple View Geometry, Digital Image.*

1. INTRODUCTION

The increasing advances in new technologies have emerged a couple of unexplored new opportunities in the field of technologies applied to geosciences. Thus it is required to test and evaluate the best path to use these technologies. Nowadays in geology, we have efficient tools to obtain three-dimensional (3D) data that include color and intensity, allowing accurate measurements layers thickness for inaccessible places, for example, outcrops. Three-dimensional digital models, especially those are obtained from terrestrial laser scanner and more recently from multiples digital images have been intensively employed.

One technique that has quickly evolved is georeferenced geological information by the System GNSS (Global Navigation Satellite System). This system has allowed more efficient, both in accuracy and in time gain, integration of the different products in a single geological reference system, ensuring greater reliability in the processes of generation of three-dimensional geological models (Pringle *et al*, 2004; Thurmond *et al*, 2005; White & Jones, 2008).

The use of digital mapping technologies have grown in the last ten years, in particular the use of terrestrial laser scanner and topography equipment's, integrated systems with satellite navigation and geographic information (Xu *et al*., 2001; Alfarhan *et al*., 2008), thus replacing numerous photographic mosaics routinely used in the interpretation of large outcrops.

Terrestrial laser scanners are able to capture few hundreds of millions of georeferenced points. This device, to define three-dimensional coordinates of points on a surface, emits laser pulses with the aid of a scanning mirror. When a pulse hits an object a portion of the energy returns back to the equipment. The distance between the sensor and the object is measured based on the time lag between emission and return of the pulse. The calculation of the coordinates of each point, obtained by the laser scanner, is possible from a point with known coordinates in the source pulse. Thus, the study of outcrops gets a new impulse by the ability to quantify the data estimated or ignored due to lack of access.

The use of LiDAR technology, especially terrestrial laser scanner, in studies of outcrops is expanding due to the ease of acquisition of precise, fast and automated georeferenced data.

This technology is being used for this purpose from a decade (Bellian *et al*., 2002), but only in recent years the number of scientific articles have increased significantly. However, the topics of interest are quite diverse, and include: methodological approaches (Bellian et al., 2005; Abellan et al. 2006; Enge et al., 2007; Buckley et al., 2008; Ferrari et al., 2012), reservoirs (Pringle et al., 2004; Phelps & Kerans, 2007; Kurtzman et al., 2009; Rotevatn et al., 2009; Enge & Howell, 2010; Fabuel-Perez et al, 2009,2010), fractured rocks (Bellian et al., 2007; Olariu et al., 2008; Jones et al., 2009; Zahm & Hennings, 2009), erosion rates (Wawrzyniec et al., 2007), synthetic seismic model (Janson et al., 2007), orientation of basaltic lava flows (Nelson et al., 2011) and classification of spectral patterns (Inocencio et al., 2014).

Photo-realistic 3D modeling has been a research topic, which addresses the quick generation of three-dimensional calibrated models using a hand-held device (Se & Jasiobedzki, 2006). This technique allows the creation of 3D models, both for visualization and measurements, based on multiple images. Several studies (Leung, 2006; and Aliaga *et al*., 2006) have used this photogrammetry technique for reconstruction of 3D models, and have analyzed the effects and methods for image-based modeling from multiple images (Szeliski, 2010). In geology, we aim this technique can be applied in analysis of outcrop in three dimensions in the laboratory at low cost when compared with LiDAR. Besides, it can to improve and facilitate virtual interpretations (Baltsavias *et al*, 2001; Enge *et al*, 2007).

Thus the aim of this study is to quantify, through control points, the error positional of outcrops mapped by image based modeling technique and by LiDAR, and to perform a comparison of the positional errors.

2. 3D RECONSTRUCTION MODEL FROM MULTIPLE IMAGES

Using multiples images (photographs), we can (re)construct three-dimensional models. It is the reverse process of obtaining photographs from 3D scenes. When a 3D scene is projected in 2Dcplane and depth is lost. A 3D point corresponding to a specific image point is constrained to be on the line of sight. From a single image, it is impossible to determine a point on the line of sight that corresponds to the image point. However if two images are available, then the position of a 3D point can be found at the intersection of the two projection rays. This process is called triangulation. Therefore, this process requires the multiple pass approach, that begins from camera calibration process to relate measuring range of the sensor with the real world quantity that it measures. It is necessary first to understand the mathematical model of a camera to calibrate it. For this purpose, we have adopted a *projective camera* model (pinhole camera), which has been widely adopted as camera model in computer vision, since it is simple and enough accurate enough for most applications.

The pinhole camera is illustrated in Figure 1 (a), while a slightly different model, where image plane is on front of the center of projection, is expressed in Figure 1 (b).

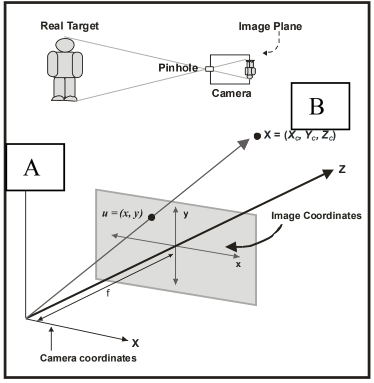

Figure 1 – Pinhole camera (A), Model (B)

To understand multi-view geometry, first of all we have considered relationship between two cameras (or sequentially moving one camera), which is actually called **epipolar geometry**. The epipolar geometry is the geometry of intersecting planes of images. Using the common points between the images, along with the intersection of planes, it is possible to calculate the 3D position of objects in the scene.

We have show that there is a geometric relationship between corresponding points in two images of the same scene. This relationship depends only on the intrinsic parameters of the two cameras and their relative translation and rotation Figure 2.

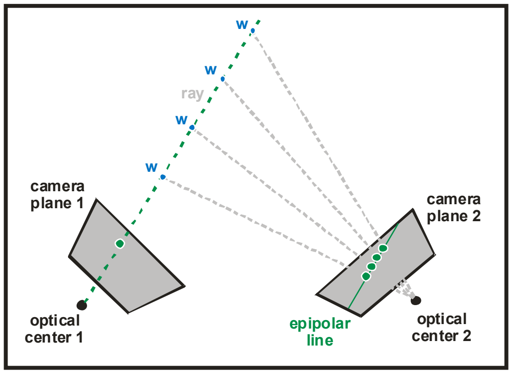

Figure 2 – Two cameras with epipolar constraints

Consider a single camera viewing a 3D point **w** in the world, passing through $\mathbf{x}_1$ and optical center $\mathbf{c}_1$. From one camera, it is impossible to identify the point in the ray. The projection of the ray in image plane 2 defines an *epipolar line*. Therefore, the point in the first image plane (Camera 1) corresponds to a constrained line in the second image plane (Camera 2). This relationship is called as *epipolar constraint*. The constraint on corresponding points is a function of the intrinsic and extrinsic parameters. If intrinsic parameters area given, then the extrinsic ones can be determined, and so the geometric relationship between the cameras. Another advantage is that, given the intrinsic and extrinsic parameters of the cameras, corresponding point of one image can be found easily through a 1D search along the *epipolar line* in the other image.

A mathematical model can capture the relationship between two cameras (two images) and can provide 3D point determination. In a general context, the mathematical constraint between the positions of corresponding points $\mathbf{x}_1$ and $\mathbf{x}_2$ in two normalized cameras can be obtained by *essential matrix* (note that either camera calibration or a different matrix – fundamental matrix – is required). Details about essential matrix can be obtained from any good computer vision literature (Harttley R. & Zisserman, 2004). This matrix can provide the above described parameters, mainly the camera matrices (*resectioning process)* and their parameters. Using a series of 3D-2D image plane correspondences it is possible to compute camera pose estimation. It utilizes camera parameters of the right camera that minimize the residual error of the 3D-point reprojections.

In another approach three or more cameras, instead of two can be considered. In three views, there are six measurements and so three degrees of freedom. However, it is for lines that there is the more significant gain. In two-views the number of measurements equals the number of degrees of freedom of the line in 3D-space, i.e., four. Consequently, there is no possibility of removing the effects of measurement errors. However, in three views there are six measurements on four degrees of freedom, therefore a scene line is over-determined and can be estimated by a suitable minimization over measurement errors.

For the computing purpose, we have implemented this sequence of concepts in an in-house computer vision library, using OpenCV (Brahmbhatt , 2013) – for computer vision and image processing support, Google Ceres-Solver library[1] – for modeling and solving large complicated nonlinear least squares problems and Eigen library[2] – a high-level C++ library of template headers for linear algebra, matrix and vector operations, and numerical solvers.

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[1] https://code.google.com/p/ceres-solver/

[2] http://eigen.tuxfamily.org

3. MATERIALS AND METHODS

3.1 Materials

The study area is an outcrop of the Rio Bonito Formation, Lower Permian of the Paraná Basin, called Morro Papaléo and located at Mariana Pimentel, Rio Grande do Sul state, southern Brazil (Figure 3), between the geodetic coordinates, latitudes 30°18’10”S and 30°18’40”S and longitudes 51°38’40”W and 51°38’30”W in the datum SIRGAS2000. The mentioned area is an abandoned quarry originally exploited for kaolin. It is a three-dimensional outcrop with a good exposure of rocks such as fossiliferous siltstone, carbonaceous siltstone, pebbly mudstone and sandstone.

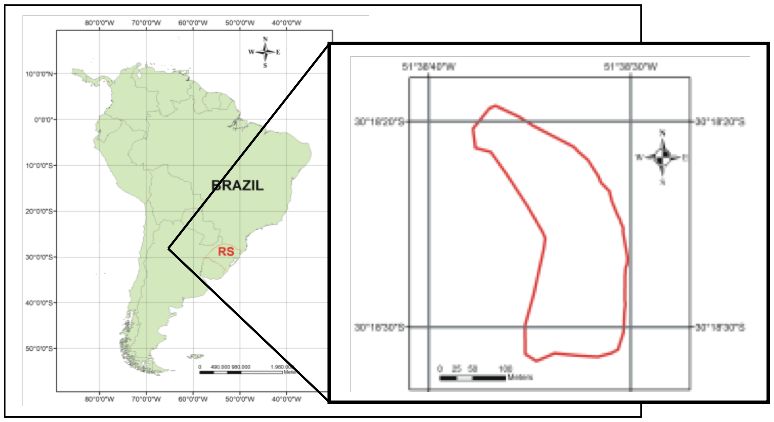

Figure 3 - Location map of the study area.

We implemented points serving as support for the georeferencing of the point clouds obtained by LiDAR as image-based modeling technique. The georeferenced points were tracked with Hyper-RTK GNSS equipment and were supported by geodetic point, implanted on top of the outcrop. These georeferenced points (P1 and P2, Table 1) were used as a support for measuring coordinates of points on the surface outcrop, which subsequently, were used to analyze the positional error. As a result tracking points (P1 and P2) were obtained in the system coordinates (Figure 3, & Table 1) UTM:

UTM COORDINATES			
POINTS	**E (m)**	**N (m)**	**Ellipsoidal height – h (m)**
P1	438125,808	6646812,115	136,775
P2	438135,602	6646873,338	137,468

Table 1 - Plane coordinates in UTM projection of the points of support for Surveying, Central Meridian at 51° SIRGAS2000 Reference System (Geocentric Reference System for the Americas).

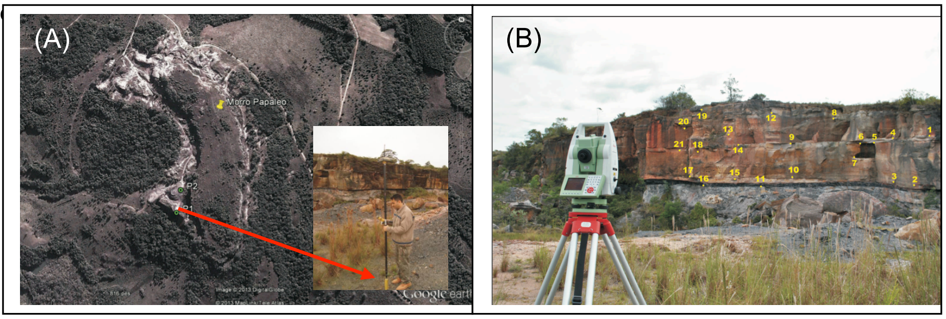

Figure 4 - Tracking of points P1 and P2 with the use of GNSS-RTK (A). Points of the surface outcrop measured with total station (B).

To obtain the coordinates on the surface of the outcrop we used a total station (Leica Viva TS15, Figure 4B), supported at points (P1 and P2) with GNSS-RTK. It was adopted as a criterion for selection of local points emphasizing on the contrast of colors and other well-defined characteristics. This facilitated the identification of the point cloud, both in terrestrial laser scanner and image-based modeling. With the total station, 21 points at the surface of the outcrop were measured, as illustrated in Figure 4B. These coordinates were used as parameters to determine the positional quality of the outcrop study.

For imaging the outcrop was used Leica Scanner Station C10, was used with resolution point cloud ranging between 2mm to 4cm.

The point cloud was processed to eliminate unnecessary information such as, vegetation and fallen rocks in front of the outcrop. In outcrop, sandstone predominates in *Morro Papaléo* and these rocks are in the point cloud in Figure 5.

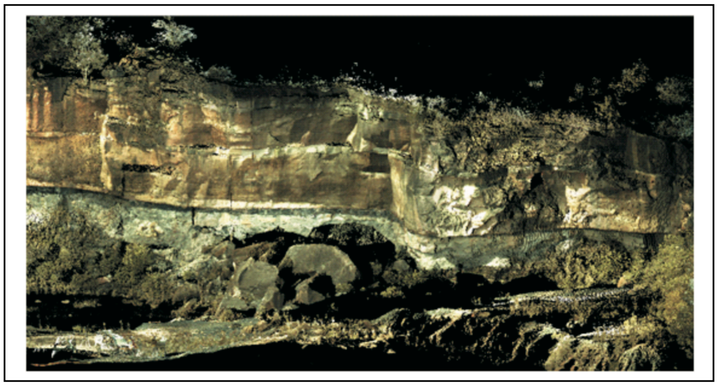

Figure 5 - Point cloud obtained with the terrestrial laser scanner

The same outcrop was photographed with a Nikon D3000 digital camera at a resolution of 7 Megapixels. The procedure for the collection of photos in the field was adopted to keep approximately the same distance between the camera and the outcrop (Figure 6). Another procedure was adopted to consider the top and bottom of the outcrop in the same photo. The photos were taken from different positions in order to obtain approximately 60% overlap between images.

Figure 6 – Pictures obtained with the camera (A). Positions of camera (B).

The processing of digital photos and reconstruction of the outcrop were based on image-base modeling technique. We have reconstructed the 3D outcrop and generated a cloud of points and georreference following the same procedures used in the generation of Digital Outcrop Model (DOM) obtained with the TLS.

4. RESULTS AND DISCUSSION

By comparing the results for the generation of DOMs, based on LiDAR technique and reconstruction of 3D objects from photos, it became evident that the image based modeling (Figure 7A) for photos allowed a visual resolution of better quality. However, the model generated by terrestrial laser scanner (Figure 7B) allowed control of spacing (resolution) of the points in the point cloud, whereas, there is no such control in image-based modeling from photos.

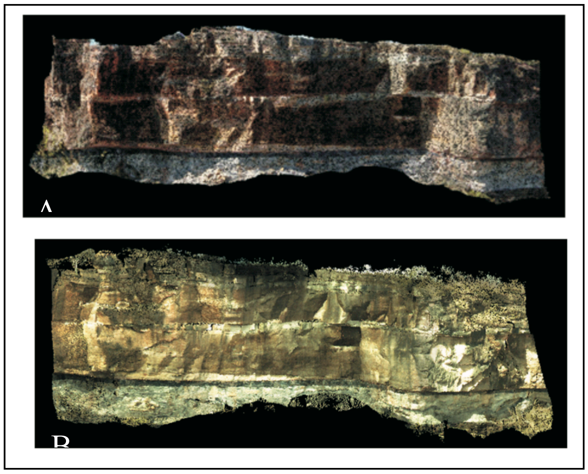

Figure 7 - 3D Reconstruction from photos (A) and terrestrial laser scanner (B).

Putting the image-based modeling and terrestrial laser scanner point cloud together, the Chi-Square test indicated 95% confidence level for georeferencing the differences were not significant between the control data and the techniques evaluated. In the comparison of the relative error models of the techniques used. It was observed that the difference became smaller than 5 cm as shown in Table 2.

Table 2 - Difference between linear measurements obtained from the models generated

Lines	**Terrestrial Laser Scanner (meters)**	**Image-Based Modeling (meters)**	**Difference (meters)**
1	1.6134	1.6375	-0.0241
2	2.3313	2.3451	-0.0138
3	1.8380	1.7960	0.0420
4	1.7010	1.6892	0.0118
5	2.8580	2.8669	-0.0089

5. CONCLUSION

The digital outcrop modeling technique can assist in outcrop interpretation, mainly for places that are hard to reach, due to large size and height of the outcropping or for security reasons. The paper results have shown the image-based modeling techniques can be feasible in this context of application instead of LiDAR, due the average linear error is under 40 cm. The cost of LiDAR equipment is much higher than a digital camera; hence the image-based modeling can provide good quality results at a lower cost,too.

The relative precision measurements performed from the point cloud obtained from image-based modeling had an error below 5 cm (Table 2) than that for the point cloud obtained from terrestrial laser scanner, which allows analysis of geological features for data modeling.

This study argue that image-based modeling techniques can to assist in getting the point cloud in places with occlusions by shading or obstructions around the object of the study, which is not possible using LiDAR technique.

The georeferencing of the point clouds from the image-based modeling technique allowed overlapping of point cloud from the LiDAR technique; it proves that the model generated from photos can be associated to a reference system. This, in turn, allows integration of other information obtained from other data sources.

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