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3-D RECONSTRUCTION OF A DIGITAL OUTCROP MODEL BASED ON MULTIPLE VIEW IMAGES AND TERRESTRIAL LASER SCANNING

Reconstrução 3D de Modelo Digital de Afloramento Baseado em Múltiplas Imagens e Laser Scanner Terrestre

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ABSTRACT

This paper presents a comparative study about of 3D reconstruction based on active and passive sensors, mainly LiDAR – Terrestrial Laser Scanner (TLS) and raster images (photography), respectively. An accuracy analysis was performed in regard to the positioning of outcrop point clouds obtained by both techniques. To make the comparison feasible, datasets were composed of point clouds generated from multiple images in different poses using a consumer digital camera and directly by a terrestrial laser scanner. After preprocessing stages to obtain these point clouds, both were compared using positional discrepancies and standard deviation. A preliminary analysis showed that the use of digital images for 3D reconstructions is a feasible method for digital outcrop modeling, with a low cost of data acquisition and without a significant loss of accuracy compared to LiDAR.

Keywords: LiDAR, 3D Reconstruction, Digital Outcrop Model, Terrestrial Laser Scanner, Digital Image.

RESUMO

Esse artigo apresenta um estudo comparativo sobre reconstrução 3D baseado em sensores ativos e passivos, principalmente LiDAR (Terrestrial Laser Scanner) e imagens raster, respectivamente. Uma análise de exatidão foi realizada para o posicionamento das nuvens de pontos para ambas as técnicas. Para tornar a comparação possível, nuvens de pontos foram geradas a partir de várias imagens tomadas de diferentes locais utilizando câmeras digitais de alta resolução. Após o pré-processamento para obter as nuvens de pontos, estas foram comparadas com as nuvens de pontos obtidas com o

Laser Scanner Terrestre por meio da análise de discrepâncias posicionais e desvio-padrão. Os resultados mostram que a utilização de imagens digitais para reconstruções 3D é adequada para a modelagem digital de afloramentos e tem como vantagens a rapidez e o baixo custo de aquisição dos dados sem perda de exatidão significante quando comparada com os modelos digitais resultantes da técnica LiDAR.

Palavras chaves: Reconstrução 3D, Modelo Digital de Afloramento, Laser Scanner Terrrestre, Imagem Digital.

1. INTRODUÇÃO

Increasing advances in new technologies have produced a couple of unexplored new opportunities in the field of technologies applied to geosciences. Thus it is important to test and evaluate the best way to use these technologies. Currently, in geology, we have efficient tools to obtain three-dimensional (3D) data that include color and intensity, allowing accurate measurements of layers thicknesses for inaccessible places, for example, outcrops. Three-dimensional digital models, especially those obtained from a 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 GNSS (Global Navigation Satellite System). This system has allowed more efficient integration, both in accuracy and in time gain, of the different products in a single geological reference system, ensuring greater reliability in the processes of generation three-dimensional geological models (PRINGLE *et al.*, 2004; THURMOND *et al.*, 2005; WHITE & JONES, 2008).

The use of digital mapping technologies has grown in the last ten years, in particular the use of terrestrial laser scanners and topography equipment, integrated systems with satellite navigation and geographic information (XU *et al.*, 2001; ALFARHAN *et al.*, 2008), thus replacing numerous photographic mosaics that are routinely used in the interpretation of large outcrops.

Terrestrial laser scanners are able to capture a few hundreds of millions of georeferenced points. This device, to define the 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 object is measured based on the time lag between the emission and return of the pulse. 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 is stimulated by the ability to quantify the data estimated or ignored due to the 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 has been used for this purpose for a decade (BELLIAN *et al.,* 2002), but only in recent years has the number of scientific articles 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), a 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 is a research topic that addresses the quick generation of three-dimensional calibrated models using a hand-held device (SE & JASIOBEDZKI, 2006). This technique allows for the creation of 3D models, both for visualization and measurements, based on multiple images. Several studies (LEUNG, 2006; ALIAGA *et al.*, 2006) have used this photogrammetry technique for the reconstruction of 3D models, and have analyzed the effects and methods for image-based modeling from multiple images (SZELISKI, 2010). In geology, our goal is that this technique will be able to applied to the analysis of outcrops in three dimensions in the laboratory at low cost compared with LiDAR. In addition to, it should be able to be used 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 positional error of outcrops mapped by an image-based modeling technique and by LiDAR, as well as 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. This is the reverse process of obtaining photographs from 3D scenes. When a 3D scene is projected a 2D plane depth is lost. A 3D point corresponding to a specific image point is constrained to be in the line of sight. From a single image, it is impossible to determine a point in 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 with the camera calibration process to relate the measuring range of the sensor to the real world quantity that it measures. It is necessary to first 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 the camera model in computer vision, since it is simple and accurate enough for most applications.

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

To understand multi-view geometry, we must first consider the relationship between two cameras (or sequentially moving one camera), which is actually called epipolar geometry. 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.

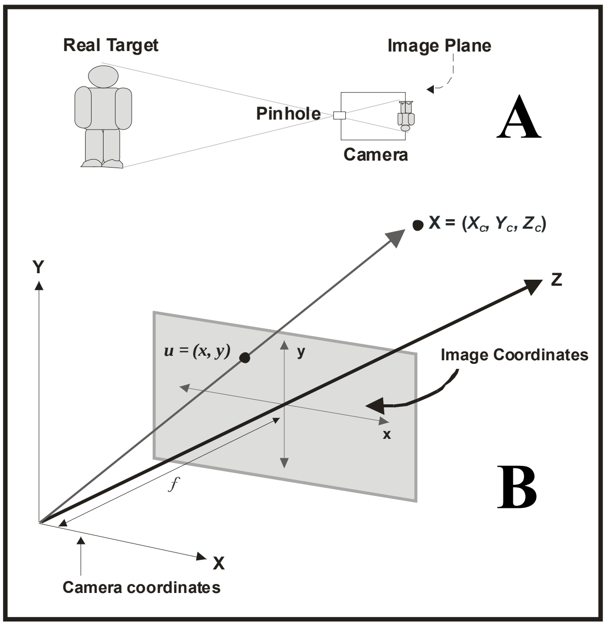

Fig. 1 – Pinhole camera (A), Model (B).

We have shown 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).

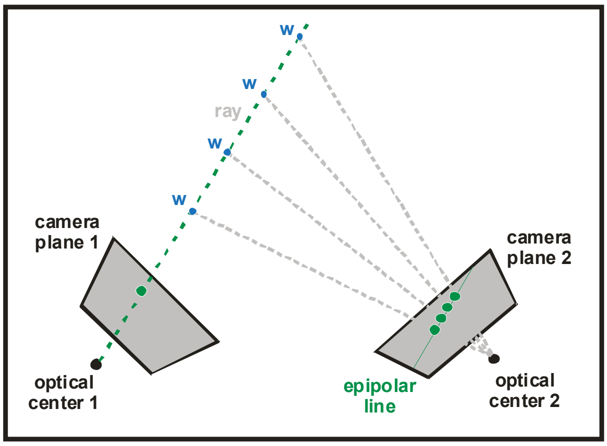

Fig. 2 – Two cameras with epipolar constraints.

Consider a single camera viewing a 3D point w in the world passing through x1 and optical center c1. 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 an epipolar constraint. The constraint on corresponding points is a function of the intrinsic and extrinsic parameters. If intrinsic parameters are given, then the extrinsic ones can be determined as well as the geometric relationship between the cameras. Another advantage is that, given the intrinsic and extrinsic parameters of the cameras, the 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 the corresponding points x1 and x2 in two normalized cameras can be obtained by an essential matrix (note that either camera calibration or a different matrix – fundamental matrix – is required). Details about the 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 the camera pose estimation, which utilizes the 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, therefore 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 purpose of computation, we 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.

3. MATERIALS AND METHODS

The following subitems describe the materials and and methods used in the development of this work.

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 coordinate, latitudes 30°18'10"S and 30°18'40"S and between longitudes 51°38'40"W and 51°38'30"W in the datum SIRGAS2000. The area is an abandoned quarry that was 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.

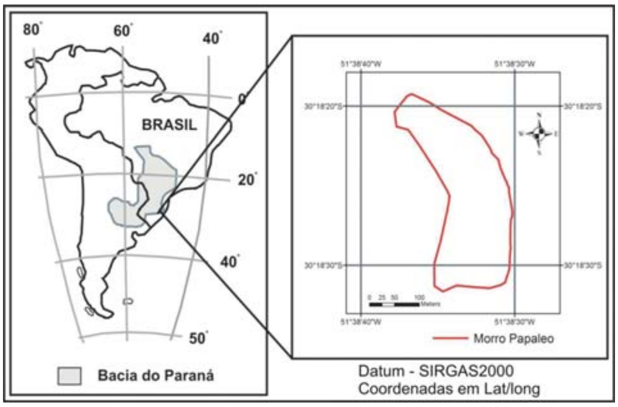

Fig. 3 - Location map of the study area.

We implemented points that server as a support for the georeferencing of the point clouds obtained by LiDAR and the image-based modeling technique. The georeferenced points were tracked with Hyper-RTK GNSS equipment and were supported by geodetic points layered 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

[1]https://code.google.com/p/ceres-solver/
[2]http://eigen.tuxfamily.org

outcrop, which were subsequently 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:

Table 1: Plane coordinates in the utm projection of the points of support for surveying via the central meridian at 51° sirgas2000 reference system (geocentric reference system for the Americas).

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

To obtain the coordinates on the surface of the outcrop we used a total station (Leica Viva TS15, Fig. 4 - Tracking of points P1 and P2 with the use of GNSS-RTK (A). The points of the surface outcrop were measured with Total Station (B).

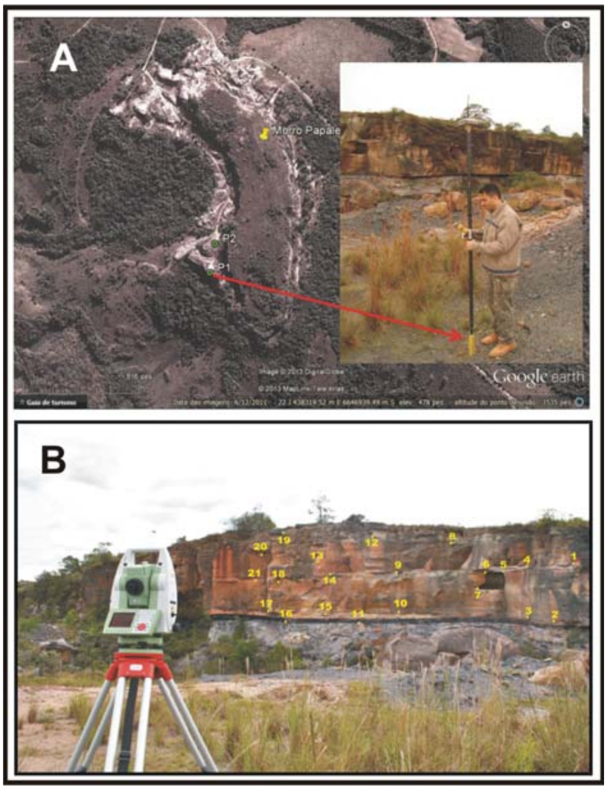

Fig. 4 - Tracking of points P1 and P2 with the use of GNSS-RTK (A). Points on the surface outcrop measured with Total Station (B).

This was adopted as a criterion for the 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 a terrestrial laser scanner and image-based modeling. With the total station, 21 points on 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, we used a Leica Scanner Station C10, with a resolution point cloud ranging between 2mm and 4cm.

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

Fig. 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 maintain approximately the same distance between the camera and 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 to obtain approximately 60% overlap between the images.

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

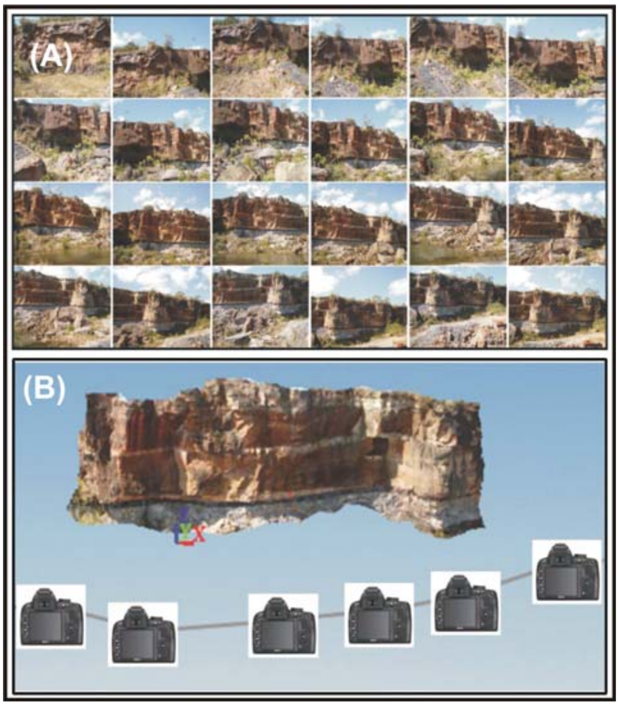

Fig. 6 – Pictures obtained with the camera (A). Positions of the camera (B).

4.RESULTS AND DISCUSSION

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

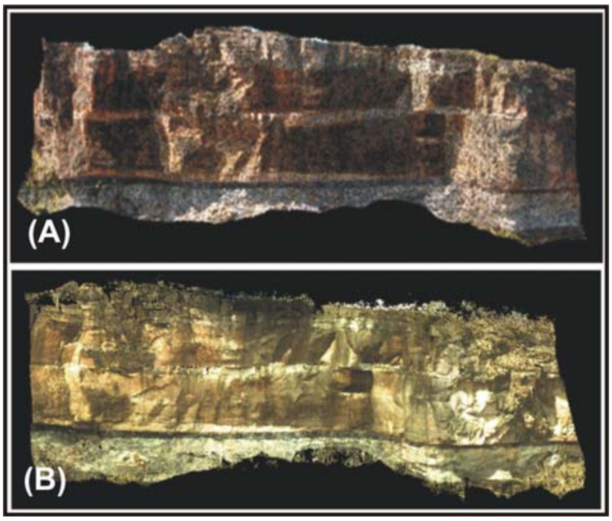

Fig. 7 – 3D Reconstruction from photos (A) and the terrestrial laser scanner (B).

Assembling the image-based modeling and terrestrial laser scanner point cloud, the Chi-Square test indicated a 95% confidence level for georeferencing the differences, indicating that there was no significant difference between the control data and techniques evaluated. In the comparison of the relative error models of the techniques used, we 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 the large size and height of an outcropping, or for security reasons. This paper’s results have shown that the image-based modeling techniques can be feasible in this application instead of LiDAR because the average linear error is under 40 cm. The cost of LiDAR equipment is much higher than that of a digital camera; hence, image-based modeling can provide good quality results at a lower cost as well.

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

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

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

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