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As-is 3D geometric modeling of a railway tunnel in Caraguatatuba - SP, using aerial photogrammetry

Modelagem geométrica 3D "as-is" de túnel rodoviário em Caraguatatuba - SP com aerofotogrametria com drone

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ABSTRACT: Tunnels are underground structure with complex behavior that plays an important role in the transportation logistics of modern society, requiring attention in terms of monitoring and performance assessment. A collapse or interruption of these infrastructure may represent a significant social, economic, and ecological impact. Due to its importance, and the increasing utilization of transportation systems, maintaining this infrastructure safe and with adequate performance is a challenge for tunnel managers worldwide. Mostly time the inspection routine is time-consuming, expensive, and dependent on the subjectivity of the inspector evaluation. Numerous researchers are actively seeking expedited methodologies to address this issue, aiming to mitigate the inherent subjectivity in pathological evaluations. Facing this challenge, this study introduces a methodology for creating a 3D "as-is" geometric model utilizing drone-based photogrammetric techniques. The methodology is applied in a highway tunnel in Caraguatatuba - São Paulo State, Brazil. The results show that the methodology was able to measure a variation of 7.58% in the cross-section in comparison with the project design, showing that the use of advanced technologies, such as drone-based photogrammetry with computer vision, may contribute to improve the accuracy and the efficiency of tunnels inspections and maintenance.

KEYWORDS: Inspection, Tunnel, 3D as-is, drone.

1 INTRODUCTION

The infrastructure around the world demands a considerable investment in inspection and repairs to maintain its integrity. As example, the ASCE reported that only for bridges in the United Kingdon and United States would be necessary 315000 inspections and an investment of $123 billions in repairs (ASCE,2017). For tunnels the reality isn't different, according to FHWA – Federal Highway Administration (NTIS, 2015), the US has about 350 rail tunnels, which 40% are less than 50 years old, and about 5% are more than 100 years old.

The infrastructure assets are aging, and inspection and monitoring campaigns are still unable to meet existing demands to guarantee global standards of safety in tunnels. A more effective inspection and monitoring system may help in the maintenance decision of infrastructures. As example, the integration of the lifecycle of an infrastructure asset through a digital twin, enables inspection campaigns that are integrated in all their "as-designed", "as-built" and "as-is" phases, allowing more effective analysis and solutions for anomalies (Futai et al, 2022).

Industry 4.0 has established a high technological level, especially in the digitalization of the management of infrastructure assets. The use of drone enables ease access and higher speed in inspection campaigns by using RGB, thermal, multispectral imager sensors, profilometers, LiDAR system, which generate a geometric model from a point cloud and connect to strategic platforms, helping is the challenge to implement the digital transformation of cities infrastructure. Those technological advancements are already transforming the tunnel inspection as seen in Sjölander et al. (2023) and Balaguer et al (2014).

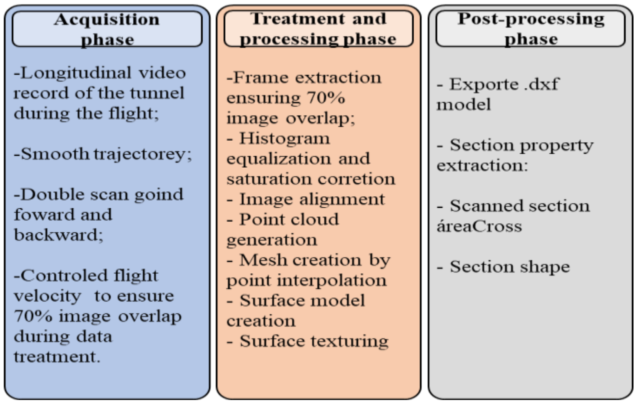
On this context, the application of drones in aerial photogrammetry has been shown to be highly effective in the inspection of urban infrastructure assets (Jing et al. 2019), and also for as-is modeling by photogrammetry techniques, with allow modeling of assets quickly and effectively (Aber et al, 2010), making the employment of drones useful to improve inspections procedures of tunnels.

Faced with the challenge of making inspections less complex and costly, this work suggests a methodology to develop current 3D models of tunnels using drone aerial photogrammetry techniques. The procedure still under development presented in this article showed good results, being able to reconstruct the tunnel as-is with sufficient precision to extract measurements to quantify and classify pathology through its surface properties.

2 METHODOLOGY

The planning of image acquisition is crucial for the 3D model result. Before the field exploitation is necessary to consider the environmental conditions, flight obstacles, restricted areas, necessary licenses, lightening and local access. After considering all necessary issues the described methodology may be followed.

The methodology is separated into three phases. The image acquisition, data treatment and processing, and the post processing phase, Figure 1.



Acquisition phase	Treatment and processing phase	Post-processing phase
-Longitudinal video record of the tunnel during the flight; -Smooth trajectorey; -Double scan goind foward and backward; -Controled flight velocity to ensure 70% image overlap during data treatment.	-Frame extraction ensuring 70% image overlap; - Histogram equalization and saturation corretion - Image alignment - Point cloud generation - Mesh creation by point interpolation - Surface model creation - Surface texturing	- Exporte .dxf model - Section property extraction: - Scanned section áreaCross - Section shape

Figure 1 – Photogrammetry methodology workflow

The image acquisition by drone needs to be done with a smooth trajectory to avoid abrupt variation in pixel likelihood and the image need to be recorded on the longitudinal direction of the tunnel on a forward and backward trajectory to reduce occlusion points and improve the model quality. To decide the best trajectory and scanning speed, it is necessary to know the characteristics of the sensor to decide the best position relative to the target and the appropriate speed to guarantee 70% image overlap. This overlap is the minimum necessary so that there is a correspondence between different image points, used to calculate depth (stereoscopy).

For the treatment phase is recommended to process the images in software's for frame extraction and brightness adjustment. The frame extraction should have a compatible rate to ensure 70% overlap. Furthermore, brightness adjustment should be done carefully to avoid the decorrelation between homologous points in the images.

The processing is done applying a method known as Structure from Motion (SfM) for three-dimensional reconstruction. This process involves the analysis of a set of images acquired from different viewpoints, allowing the camera position determination and each image's position through epipolar geometry, followed by the reconstruction of the scene in the order flow 1) image alignment, 2) point cloud, 3) Mesh model, 4) surface model e 5) surface texturized.

The post-processing is related to the accuracy and precision metrics of the models, to verify their level of reliability.

3 CASE STUDY

The methodology is tested with a drone DJI P4 PRO® in a highway tunnel, close to Caraguatatuba city, São Paulo State. (Figure 2). This road tunnel was built using the NATM method, with shotcrete lining, is approximately 3.7 km in length, although only 200 meters were surveyed with a drone (Figure 3).

Figure 2 – Tunnel location.

Figure 3 – Tunnel inner condition.

For the sensor with 30FPS used on the Drone, the flight velocity was kept close to 6 m/s to ensure the 70% image overlap.

The data treatment is initially done by the FreeVideo® Software to extract 46 frames guaranteeing the 70% image overlapping. Then a histogram equalization and brightness adjustment are done to the images. The image treatment shall be done carefully to preserve its originality and reduce homologous points among images. After the data treatment a processing is done using the Argisoft Metashape® Software to align images and generate the point cloud based on the scanned surface's complexity, create the mesh surface, and finally create an 3D texturized model.

The mesh quality during the surface construction depends on the available computational resources. For data treatment, processing and post-processing was used a computer with Intel i5®, 4MB RAM, GPU Intel Iris® 4GB.

Finally, for the post-processing, a .dxf format model is generated and analyzed with the AutoDesk AutoCAD® Software. The geometry section properties were extracted and compared with the original project.

4 RESULTS AND DISCUSSIONS

Figure 4 shows the drone route into the tunnel. The variation on its trajectory is because of a drift caused by the need of manual control due to the low GNSS signal into the tunnel. An alternative to improve the quality of the images and reduce the drift effect keeping a smooth trajectory is to fly preferably with the area as unobstructed as possible, and reducing the flight speed, 6 m/s in this case, to maintain a straighter trajectory to maintain a smooth variation among pixels.

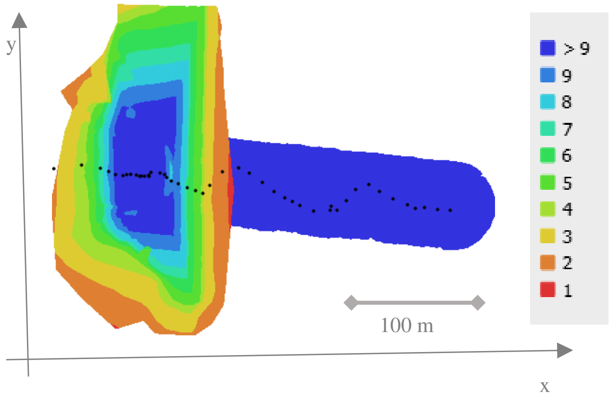


Figure 4 – Floor plan of the drone route inside the tunnel and image overlap level.

Figure 4 also shows the influence of the image acquisition position to guarantee the image overlay. The images in the center (in blue) coincide with the direction of the image acquisition and are obtained with highest overlapping, more than 9 overlapping images. However, approaching too the edges of the tunnel scanning the overlapping gradually decreases until the red color where there is only one image overlapping.

Figure 5 shows the point cloud with approximately 60000 points classified as its interaction with other images. The colors closest to red indicate points with lower interaction, while points close to blue color has better interaction with other images. In general, the points on the tunnel roof and floor had the lowest interaction, it may be explained by two factors:

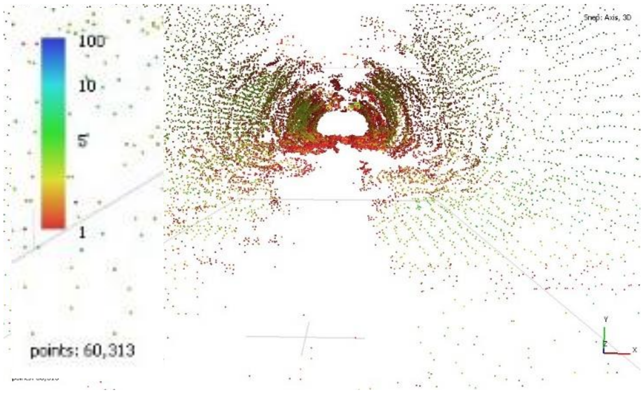


Figure 5 – Cloud of points with confidence scale.

Firstly, the excessive saturation of the lighting in the tunnel roof, caused by the position of the lighting system, may disrupt the SIFT algorithm (Scale Invariant Feature Transform) from Argisoft® Software. With a poor or excessive lighting, the SIFT software wasn't able to find the stereo correlation between the homologous points in different images, ignoring the points that don't fit with the local scale invariance criterion.

The lowest interaction on the floor may be explained by the field of view image capture angle (FOV), that was 84º for the camera used. The FOV defines the maximum reach of the image edges as a function of the distance from the target. Therefore, the drone proximity to the tunnel roof may impaired the reliability of points on the floor.

Using a computer with Intel i5®, 4MB RAM, GPU Intel Iris® 4GB the mesh generated from the point cloud has approximately 1.5 million faces, Figure 6. As showed in Figure 6, there is a deformed interpolation on the floor in the mesh model. It may be caused due to a filter applied to clear unwanted objects from the scene. This effect emphasized the importance of using appropriate processing to not impair the desired data on the 3D model. After the points cloud, the surface model maybe created with mesh surface Figure 6 and solidly filled Figure 7 for a better visualization of the tunnel contours.

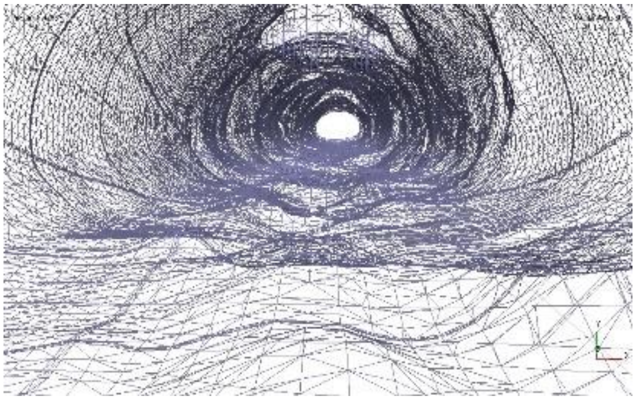


Figure 6 – Mesh model.

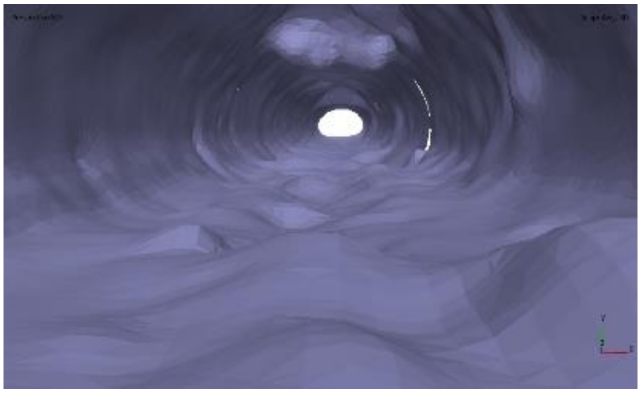


Figure 7 – Solid model.

Figure 8 shows a continuous classification map indicating the position where there is a greater number of interactions (green color), and regions with smaller interaction of homologous points between images (red color). It helps to understand how the image quality affects the model reconstruction process. Since the interaction made by the SIFT algorithm seeks the likelihood among neighbor pixels the reconstruction presents several challenges such as the occlusion of recessed regions, the abrupt variation of image scale related to the distance between the camera and the target, and the angle of view and lightening intensity. Those problems justify the importance of forward and backward scan.

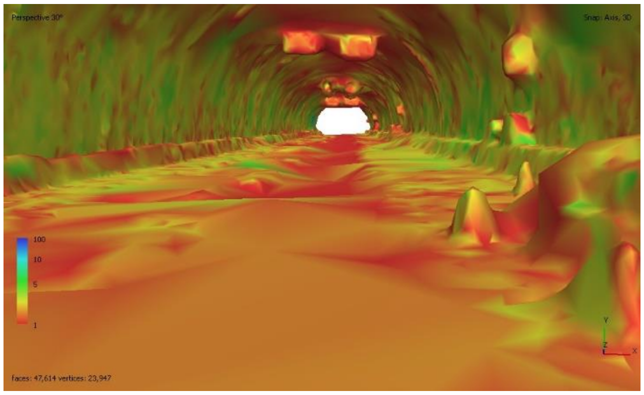
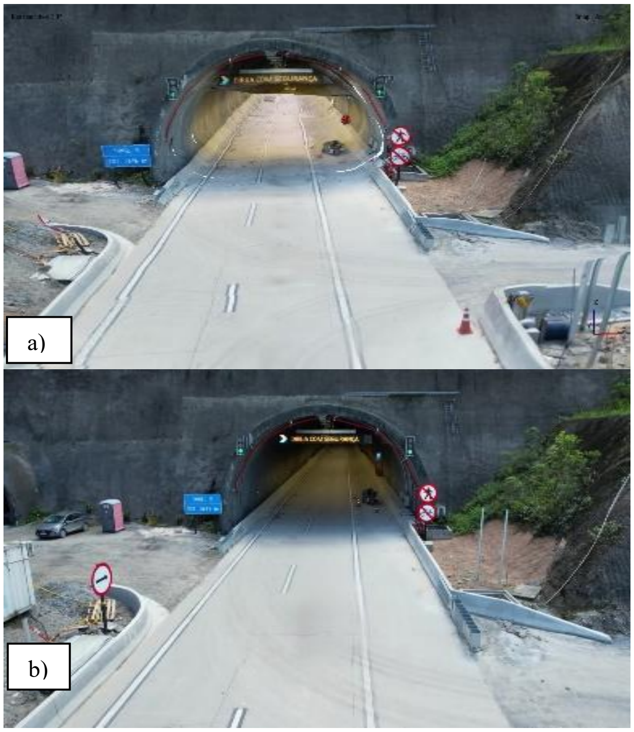


Figure 8 – Interaction map of homologous point.

Figure 9 and Figure 10 shows the real picture of the tunnel and As-is 3D model constructed after the conclusion of the methodology procedures with all the geometry and texture that is useful for tunnel inspection and documentation.



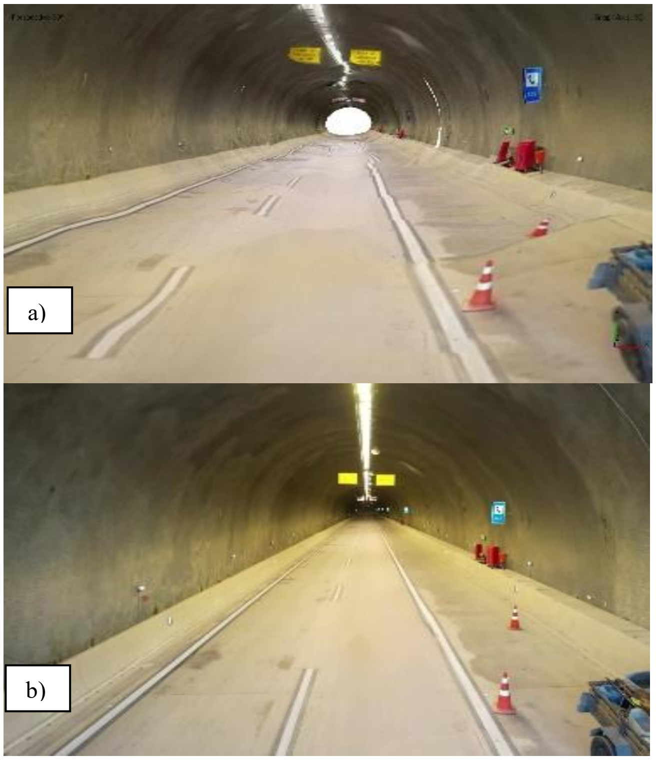


Figure 10 – a) 3D model and b) Real picture inner of tunnel.

Figure 11, 12 and 13 shows the similarity of a section of the generated point cloud with the designed section. The model was exported to a *.dxf format and compared using the AutoDesk AutoCAD® software.

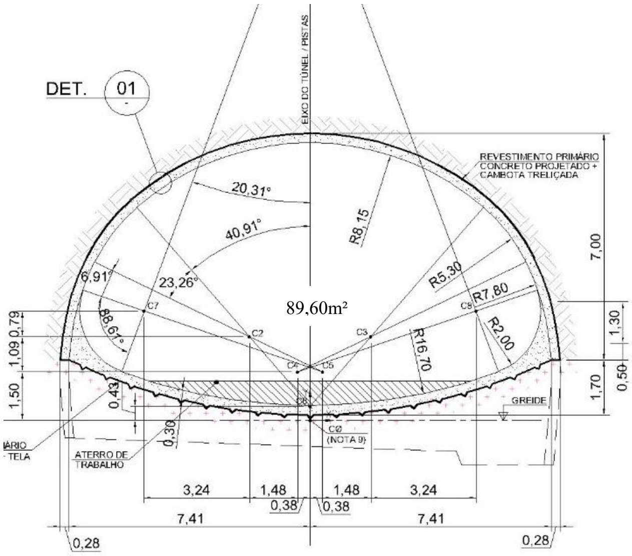


Figure 11 –Designed cross section.

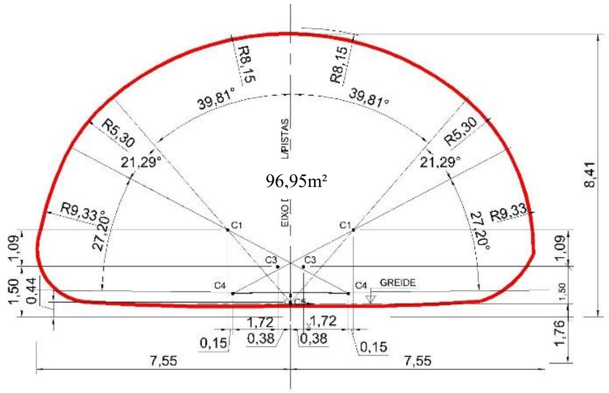


Figure 12 –Red line is 3D model cross section.

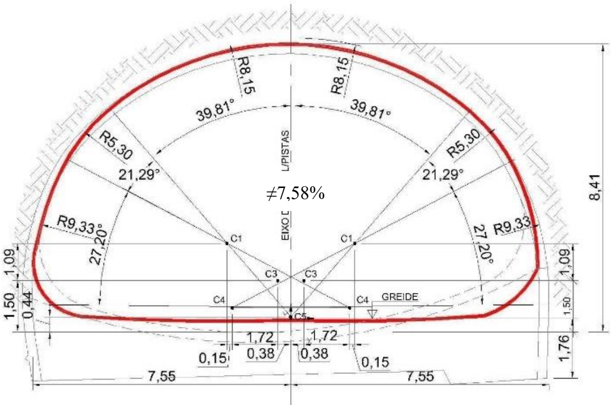


Figure 13 – Cross section overlayer 3D model in red x designed in gray.

The measured area and geometry of the designed cross-section is 89.60 m², and 96.95 m² for the cross-section area of the 3D model made with photogrammetry, resulting in only 7.58% variation. Furthermore, there was a good fitting between both geometry sections, showing confidence in the methodology.

5 CONCLUSION

This paper presents the methodology for inspecting tunnel geometry using drone-based photogrammetry, an innovative technique since this practice was not commonly applied due to the unavailability of GNSS signals in underground environments.

This methodology was tested in a real tunnel and yielded promising results with a difference of just 7.58% in the cross-section area. Furthermore, there was a good fit between sections, demonstrating confidence in the methodology.

The need for good flight planning is crucial to the success of the 3D model, maintaining a smooth trajectory without resulting in large variations in probability, as well as ensuring an overlap of at least 70% between images. Furthermore, to avoid occluded surfaces, a distribution of light saturation in the environment is necessary.

This work has shown promising results regarding the longitudinal trajectory, but maintaining ideal flight characteristics is very difficult when piloting manually. There is a gap in research on autonomous drones for inspection missions. This will be the next step of this work.

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