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Structural health monitoring and inspection of dams based on Unmanned Aerial Vehicles photogrammetry with image 3D reconstruction

Surveillance de l'état structural et inspection des barrages basées sur la photogrammétrie par des véhicules aériens sans pilote avec reconstruction d'images en 3D

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ABSTRACT: The introduction of new technologies applied in unmanned aerial vehicles (UAV), to monitor civil engineering structures, substantially developed inspection techniques and deformation measurements in embankment dams. The use of UAV allows the acquisition of essential data on the behaviour of a structure, at a reduced cost. During a UAV flight, aerial photographs are recorded following a pre-defined route. They can be easily converted to orthophotos after processing. The quality of those orthophotos depends on many factors, namely, the photographs' quality (resolution, noise, distortion), their overlap, and the identification of enough control points, among other factors. To improve the accuracy of the orthophoto, and allow georeferencing, enough control points must be defined to allow for a high-quality orthophoto. Such control points, also called Ground Control Points (GCP), are positioned in situ with high-precision coordinates. Due to the great amount of aerial photographs recorded on each flight, it is essential to increase efficiency in GCPs identification in each photograph. This paper describes an open-source algorithm, developed by National Laboratory for Civil Engineering (LNEC) and NOVA University Lisbon, within the scope of a master's thesis, which automatically identifies GCPs and prepares data for processing in the WebODM platform.

RÉSUMÉ: L'introduction de nouvelles technologies appliquées aux véhicules aériens sans pilote (UAV) pour surveiller les structures de génie civil a considérablement développé les techniques d'inspection et de mesure de déformation dans les barrages en remblai. L'utilisation d'UAV permet d'acquérir des données essentielles sur le comportement d'une structure à moindre coût. Lors d'un vol d'UAV suivant un itinéraire prédéfini, des photographies aériennes sont enregistrées. Elles peuvent être facilement enregistrées avec des orthophotos après traitement. La qualité de ces orthophotos dépend de nombreux facteurs, notamment la qualité des photographies (résolution, bruit, distorsion), leur chevauchement, l'identification d'un nombre suffisant de points de contrôle, entre autres facteurs. Pour améliorer la précision de l'orthophoto et permettre la géoréférencement, un nombre suffisant de points de contrôle peut être défini pour permettre l'enregistrement, ainsi que le calcul de la proximité de l'ajustement obtenu dans le processus d'enregistrement. De tels points de contrôle, également appelés points de contrôle au sol (GCP), sont positionnés in situ avec des coordonnées de haute précision. En raison de la grande quantité de photographies aériennes enregistrées lors de chaque vol, il est essentiel d'augmenter l'efficacité de l'identification des GCP dans chaque photographie. Cet article décrit un algorithme open source, développé par le Laboratoire National de l'Ingénierie Civile (LNEC) et l'Université NOVA de Lisbonne, dans le cadre d'une thèse de maîtrise, qui identifie automatiquement les GCP et prépare les données pour le traitement dans la plateforme WebODM.

Keywords: UAV; dam; monitoring; safety; WebODM.

1 INTRODUCTION

The monitoring of civil engineering structures plays a fundamental role in analysing their behaviour and safety and predicting future performance. It also contributes to the development of new design methods. In the case of dams, given its high potential risk resulting from a dam failure, monitoring plays an increased role in safety control.

Monitoring essentially comprises two components: instrumental measurements and visual observations. Instrumental measurements involve collecting data from instruments installed inside or on the surface of the dam observing specific aspects of the structure. The combination and integration of these two components with conceptual, statistical, and mathematical models provide decision support for ensuring dam safety.

In the context of visual inspections, it is important to underscore that numerous anomalies may manifest on dams, such as cracks, settlements, and seepages, often eluding detection, particularly in their early stages. Nevertheless, early detection of these anomalies can prove pivotal for remedial measures, safeguarding the structural integrity and safety of dams.

In this context, the application of Unmanned Aerial Vehicles (UAVs) and laser scanning in monitoring dams has seen a notable increase, primarily due to reduced costs in acquisition, development, and dissemination (Leite et al., 2020). This cost-effectiveness allowed the development of new monitoring techniques and displacement measurements. However, the quality of the data collected by UAVs relies on factors, such as, the quantity and quality of ground control points (GCPs). GCPs play a crucial role in correcting the position of objects in the three-dimensional model during the post-processing process. This paper presents an algorithm developed to enhance the efficiency of GCP identification and data preparation for processing on the WebODM platform (Freire, 2022).

2 THE USE OF UAVS FOR VISUAL OBSERVATIONS

The importance of visual observations in dam security is paramount, and UAVs can play a crucial role in the development and implementation of innovative visual observation methodologies. By collecting data from UAVs, it is possible to generate a dam model from a point cloud and subsequently reconstruct its geometric representation. Point clouds result from processing georeferenced images captured during the flight. These three-dimensional models exhibit geometric precision and enable the comprehensive modelling of the entire object to a certain extent. They provide the unique advantage of analysing perspectives of the dam that are typically inaccessible, such as views from above and upstream.

Beyond the evident benefit of capturing the entire geometry during the flight survey, these models, in an ideal scenario, promote a more thorough and phased inspection over time. Moreover, the data derived from the geometric model closely resembles that obtained through instrumental monitoring, offering a numerical representation stored in a database, devoid of subjectivity. The approach is not limited to the visible spectrum; alternative systems capturing data outside this range (thermal, infrared or ultraviolet) can also be employed. While the current study focuses on visible spectrum data, the developed technique can be applied for any sensor, as long as the maps obtained refer to the same positions in the image.

2.1 Developed technique

Regardless of the type of sensor, ensuring high geometric accuracy is essential to enhance the quality and efficiency of the model. To achieve this, in each data collection survey, points with known coordinates (GCPs) are used. These points, visible in a large number of photographs, provide each photograph with a set of GCP coordinates in pixels, aligning them accurately with the real-world coordinates. This procedure significantly enhances the model's quality. These points are used in object reconstruction algorithms that use photographs to correct the geometry.

In this study, an Open-Source Software (OSS) was used to apply UAV technologies in dam observation, since it allows for the development of applications avoiding dependencies on a specific supplier. The Open Drone Map (ODM) software was used in its version with a web interface (WebODM). WebODM serves as an GUI application interface for ODM, which, in itself, comprises a collection of open-source tools designed to process and convert aerial images captured by drones into various georeferenced outputs, including maps, point clouds, digital elevation models, and 3D textured models. When processing images, ODM performs a sequence of six operations: Structure from Motion (SFM), Multi View Stereo (Point Cloud Densification), Meshing, Texturing, Georeferencing, Orthophoto Processing, and Generation.

2.2 GCP finder

In SFM, when photographs are georeferenced, ODM uses this information to determine the camera’s position at the time of capture. In the absence of this metadata, the camera’s position can still be deduced approximately, albeit with some errors. However, even with georeferencing, factors such as image size, granularity, optical quality, or minor variations during the UAV's flight can induce considerable errors. This is where GCPs come into play. An effective GCP should be easily identifiable from a high altitude, possess shapes or colours that distinguish it from the surrounding environment, and feature a well-defined point for convenient GPS placement. Regardless of the GCP format, a matte non-reflective target is essential to prevent light reflection, ensuring ease of identification in the photographs (Freire, 2022).

Creating a manual list of coordinates is a relatively straightforward task for a small number of photographs, but it becomes highly time-consuming and prone to errors when dealing with a large volume of images, as often encountered in real surveys. Thus, the developed algorithm is essential for the SFM phase, as it enables the automatic and high-quality generation of a comprehensive list of GCP coordinates in each image (Marcelino et al., 2022). The algorithm is freely accessible on the GitHub (t.ly/EhGIQ - in the console version) and on the web interface for server installations, found at (t.ly/quv7U). The platform provides the source code, installation instructions, and a practical application example.

3 CASE STUDY

3.1 Description of Lapa Dam

Lapa is an embankment dam with a maximum height of 24 m and a crest level at 174.0 m, as presented in Figure 1. The full reservoir level (FRL) is set at 170.0 m, while the Maximum Flood level (MFL) is positioned at 171.92 m and the dead storage level (dSl) is located at 162.2 m. The reservoir has a relatively modest volume (0.64 hm^3), and a flooded area of 9.5 ha. The upstream and downstream slopes exhibit ratios of 1:3.25 (V:H) and 1:2.5 (V:H), respectively. Additionally, the downstream slope incorporates a 2.5 m wide bench, positioned at 164.0 m.

3.2 UAV surveys carried out

Two UAV surveys of the Lapa dam were conducted in 2021 (Figure 1) and in 2022 (Figure 2). GCP were employed in both surveys, and in 2022, the GCP finder algorithm was used for their automatic detection.

Figure 1. Textured model of the Lapa dam, survey of 2021.

Figure 2. Textured model of Lapa dam and UAV positions, survey of 2022.

Figure 3 presents an image derived from the 2022 orthophoto, showcasing two different types of GCP: one traditional and one with a QR Code (Aruco marker). These GCPs are automatically identified by the GCP Finder and immediately classified, as the pattern of each GCP corresponds to its assigned number. For example, in the figure, the visible GCPs are numbered 3 and 11 (https://chev.me/arucogen/).

Figure 3. View of GCP – Aruco marker nº 3 and nº 11.

The disparity in the crest between the two surveys was assessed using point cloud visualization tools and algorithms (Figure 5). According to the figure, settlements occur at the base of the dam downstream and in the spillway channel.

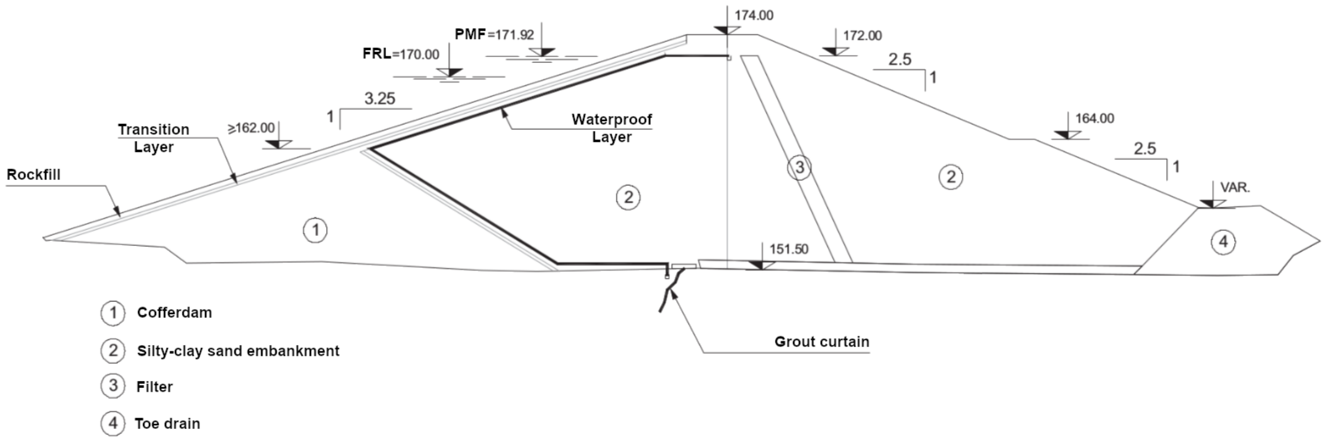

Figure 4. Cross-section of the Lapa dam.

Occasionally, there are also some movements on the downstream face, but these cases may correspond to errors due to deforestation (partial in 2021 and total in 2022). In the case of settlements in the spillway channel, it is necessary to take into account that the visualization of this area is less precise due to its geometry, so the displacement values obtained from the survey will be less accurate.

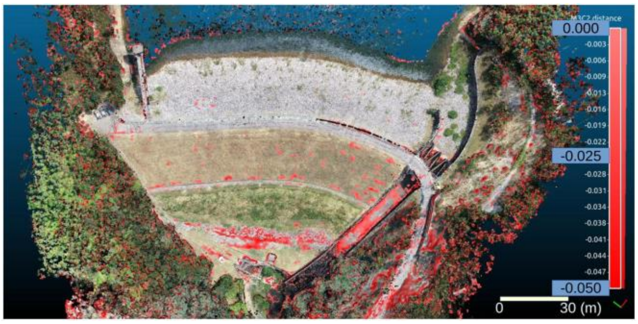

Figure 5. Settlements increments (2021-2022) in Lapa dam obtained by photogrammetric processing of high-resolution UAV images

4 CONCLUSIONS

The use of UAVs to support visual inspections of geotechnical structures has been increasingly significant, driven either by cost reduction or the development of more efficient post-processing software.

The quality of surveys and models obtained through post-processing depends heavily on various factors, such as the quality of the optics, image resolution, ambient light during photography, and also the existence of reference points with known coordinates that allow correction of the reconstructed model.

This paper outlines the development of an important tool designed to automate the identification of GCP in photographs derived from photogrammetric surveys. This tool was developed as part of a master's thesis at Universidade Nova de Lisboa, under the guidance of LNEC, is now accessible to any user under an open-source license, allowing unrestricted use.

In further developments, GCPs could incorporate GPS positioning modules, eliminating the necessity for individual position determination. Instead, these targets could communicate with each other, transmitting their positions to a centralized server for data consolidation.

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