Use of Unmanned Aerial Vehicles (UAVs) for Transport Pavement Inspection

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Abstract Technological evolution has allowed the use of unmanned aerial vehicles (UAVs) in an easier and more diversified way, creating opportunities for its application in various fields of engineering, namely in the inspection of transport infrastructures. The present study begins with the analysis of the main practices that resort to the use of UAVs, in order to frame its application in the field of transport pavement inspection. A review of studies and other available literature served as a starting point to define the methodology adopted for the development of the case study presented. The methodology includes the collection of images of a flexible road pavement section, its processing, and the creation of an orthoimage and a 3D model from which it was possible to identify and characterize the distresses present on the pavement surface. The main results obtained point to planimetric and altimetric deviations of less than 2 and 10 mm, respectively, for the images collected by the Mavic 2 Pro drone at 3 and 20 m high. With the collected data, it was also possible to calculate the global quality index PCI for the inspected pavement section. Under these conditions, it is possible to conclude that the accuracy is very good and suitable for the intended purpose, allowing fast data collection at low cost. This new technological approach supports infrastructure managers in the design of maintenance programs and in the scheduling of interventions, thus contributing to the increase of the durability and safety levels of the inspected pavements.

Keywords Transport infrastructure · Pavement inspection · Unmanned aerial vehicles (UAVs) · 3D model · Evaluation of pavement surface distresses

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1 Introduction

1.1 Framework and Objectives

Sustainability is becoming a major goal for those responsible for the maintenance and management of transport structures. Pavement management systems (PMS) are key for improved cost efficiency and minimal user disturbance and additional costs [1]. Pavement condition information is a major component of such a system [2, 3].

For a system to have any meaningful impact on improving the sustainability of a pavement operation, the information on pavement surface status must be obtained in a timely manner. This information must meet specific quality targets [4, 5]. The data collection method also needs to be sufficiently expedited in order to be implemented with minimal additional training, as well as to improve the safety of personnel and users. Above all, it should be verifiable during all the PMS phases. Another major concern of data acquisition is its cost. On-foot inspection and specialized equipped vehicles are expensive and might have limitations on mingling and interacting with traffic, which can become a safety issue [6, 7].

A solution that produces verifiable data, while providing the inspection team with near real-life information, improving personal safety, allowing for a less stressful analysis of locations, and reducing the impact on users during data acquisition at a lower data cost, could have a major impact on increasing the frequency of surface inspection campaigns. Thus, improving the availability of timely information on surface degradation and potentially reducing maintenance costs, contributes to a proactive and sustainable approach.

The study presented in this paper assesses pavement surface analysis performed by trained collectors over computer-based photogrammetrically reconstituted virtual 3D surface models. Pavement distresses are analyzed in two different models obtained from two UAV flight heights (3 and 20 m).

1.2 Pavement Inspection Using Unmanned Aerial Vehicles (UAVs)

The technological development of UAVs has enabled the commercial availability of a multitude of platforms that incorporate a high-quality imaging and non-imaging sensors. Even low to moderate cost UAVs can produce final georeferenced images suitable for the complex processing that is necessary for photogrammetric techniques. Training of expert drone operators, even considering the stricter legislation recently introduced, is not economically significant and requires only short training programs.

UAVs are thus highly suited for collecting visual information from surfaces, such as pavements, that can be later processed into continuous image mosaics or used in photogrammetric tools in order to produce a 3D virtual reconstitution of the surface [8–10].

Pavement surface data collection can be executed without traffic disturbance, even when considering the limitations of overfly roads, due to the ability to collect images off-axis of the UAV flight path [11]. The georeferenced images can be stored and immediately processed after the survey campaign, not only allowing for fast processing times but also providing an archive for future reference of pavement condition at a specific time.

Flight height constrains the achievable ground resolution of the captured images, and, consequently, of the final product [11, 12]. Therefore, it is necessary to consider the survey flight level in order to achieve the detail that is necessary for operators to be able to identify meaningful details on the lowest severity levels of pavement distress. Lower flight heights will face added challenges such as the potential loss of GNSS signals and obstacles including buildings, traffic lights, street lamps and trees. Lower flight highs may also require manual flight, reducing speed and covered area per battery charge. Higher flight levels, although with reduced ground detail, might be flown under automatic conditions with permanent control of the pilot, allowing for larger pavement areas surveyed per battery charge.

Image mosaic stitching has been used in order to produce a continuous record of the surface of large structures, but this method does not present the 3D information required for the analysis of several distress types that are essential for pavement surface characterization. Using a photogrammetric reconstituted 3D tilled surface allows for virtual visual inspection, identification, and measurement of 3D characteristics of the surface, allowing a much more precise and safer evaluation in a less stressful environment.

2 Method

Drone surveys require careful preparation for the mission. Details depend on the flight level chosen for the task. Higher heights usually encounter fewer obstacles, but those that exist can be harder to detect, visually or by the drone sensors, which is the case with utility poles and power lines. Higher flight level automated missions should be specially prepared, using auto-pilot applications that compensate for terrain level changes, namely on long flights. In lower-level missions, where roads must be investigated, traffic needs to be conditioned on the surveyed section, the obstacle density increases, and manual flight is required. Common to both types of mission, weather conditions should be evaluated not only for rain, snow, and strong winds but also for illumination patterns such as strong direct light and shadows, which can disturb image processing.

Georeferenced images from the surveyed target are then processed in order to obtain a detailed virtual tilled 3D model of the pavement surface using commercial software or freeware. Usually, the processing of targets with a very long dimension in one direction, when compared with the transversal dimension, originates a gentle upward curving surface, even when using georeferenced images. To limit these artefacts, ground control points are established and used either as constraints or as quality control indicators. These ground control points are georeferenced on high visibility targets on the ground or, as it usually happens, using data from previous topographic surveys on the road pavement and lateral structures, thus reducing survey costs.

Different outputs can be generated during the several steps of the software processing. Dense cloud points can be used as reference for future 3D comparations of surface deformations or changes, but usually are not of interest for a visual inspection. They are, however, useful for the processing of the 3D model, and later tilled 3D model, which provides a more familiar analysis to the operator.

Using virtual tools provided by 3D model visualizer software, pavement distress dimensions can be measured, registered, and used to determine a pavement condition index, such as the ASTM's PCI (Pavement Condition Index) [4, 5]. It is also possible to digitize shapes, areas and volumes that can later be transferred to a geographic information system (GIS) environment for further analysis, processing, or archive for future reference.

3 Case Study

This section aims to assess the possibility of collecting pavement distress data using UAVs for subsequent processing to obtain a pavement quality index. The section is divided into 4 parts. In the first part, the characterization of the road section to be inspected and the features to be measured are performed. This is followed by the presentation of the conditions and resources used in the inspection. Then, the description of the collecting operation and processing of images for surface distress identification and pavement condition index determination (PCI) is performed. The last part involves the analyses of the obtained results for validation of the inspection approach.

3.1 Characterization of the Road Section Under Study

The road section under study is located in a semi-rural environment, at kilometer 49.8 on National Road 18 (N18), between the cities of Fundão and Covilhã, in Portugal. The cross section consists of 2 carriageways divided by a median of 1.0 m width, with 2 lanes of 3.2 m width in each direction, no shoulders, and a drainage system consisting of a buried collector fed by trench drains.

The collection of images using a UAV was conducted on the right lane in the SE-NW direction, covering a pavement extension of approximately 52 m and an area of 183 m^3, as depicted in Fig. 1a. The road pavement exhibits severe damage: cracks, alligator cracking, localized deformations, potholes, and repairs are clearly visible. The aim of this operation is to gather information about the pavement distresses according to the measurement requirements of the Portuguese Catalog of Road Pavement Distresses [13] and the ASTM D6433-23 Standard Practice for Roads

a b

Fig. 1 **a** Study area delimitation (extracted from Google Earth), **b** UAV inspection with traffic restrictions on the inspected road section

and Parking Lots Pavement Condition Index Surveys [5]. Therefore, the measured characteristics and the required precision should encompass the various types and severity levels of distress considered in these catalogs: a planimetric precision of 2 mm (low severity crack) and an altimetric precision of 10 mm (low severity deformation). To achieve this, resolutions of 0.3–0.5 mm in planimetry and 5 mm in depth must be ensured.

3.2 Constrains and Resources

The specific site constraints were checked, and the flight plan was set within the applicable legal restrictions. The existence of obstacles such as trees, lighting poles, or overhead wires was also checked, and it was concluded that those did not interfere with the outlined flight plan. It was considered that the planned inspection flights would be conducted under the "open category", i.e., using low-weight UAVs (under 25 kg) at low altitudes (up to 120 m height), operated within visual line of sight, outside restricted spaces, and at a safe distance from people and obstacles. Since no additional limitations were found, the flight was planned with the concern of minimizing risks to people and property. Therefore, the inspection was scheduled for the daytime during a day with less traffic (Saturday, May 15, 2022, in the morning). Local weather conditions were checked (sunny and low wind speed) to ensure the stability of the UAV during flight and, due to regulations, the traffic flow on the investigated road lane was restricted (see Fig. 1b).

To conduct the inspection, the following human and equipment resources were mobilized: 1 UAV operator, 1 support technician, 1 traffic diversion team (3 workers from Fundão Municipality), 1 Drone DJI Mavic 2 Pro (weight: 907 g), 2 levelling staffs, 1 measuring tape, a total station and topographic tripods and prisms.

3.3 Image Capture and Data Processing

Flights were conducted at two heights using different piloting methods. This study analyzes images captured from manually operated flights at 3 m height and images obtained through automatic flight and captured at 20 m height. The spatial resolution per pixel, which depends on the flight height and the focal length of the lens, affecting the amount of image detail, was:

- For 3 m height flights: 3.97 m by 2.65 m of ground area captured in each image and pixel resolution of 0.73 mm (pixel side).
- For 20 m height flights: 26.47 m by 17.64 m of ground area captured in each image and pixel resolution of 4.84 mm (pixel side).

The achieved resolution is sufficient to assess pavement distress. However, considering the measurement requirements presented in Sect. 3.1, dimensions on the order of 2 mm can be measured only in the images captured at 3 m height. Images were imported into the Agisoft Metashape processing software, where stereoscopic and photogrammetric processing was executed, resulting in point clouds, orthomosaics, and 3D models. To correctly georeference all the data, a prior topographic survey was conducted to obtain a set of control points. Using the processed images, a 3D model was created and the geometric characteristics of the pavement distresses were manually measured with the set of tools available in Agisoft Viewer (see Fig. 2). For verification of dimensional accuracy, elements of known sizes were measured in the 3D models (Fig. 2a). The set of performed measurements revealed a maximum planimetric and depth deviation of 3 mm from the actual dimension for measurements under 5 cm in the 3D—3 m model, and 4 mm in planimetric and 8 mm in depth in the 3D—20 m model for measurements under 10 cm. Table 1 presents the measured distress quantities in both models for the identified pavement distresses and the PCI values determined from this information, according to the standard ASTM D6433-23.

3.4 Discussion of Results

The results obtained from the pavement surface distress measurements in the 3D models constructed using images captured at 3 and 20 m heights, together with the PCI values, were compared and analyzed to assess the feasibility of conducting inspections using UAVs at a height of 20 m. While analyzing the measurements

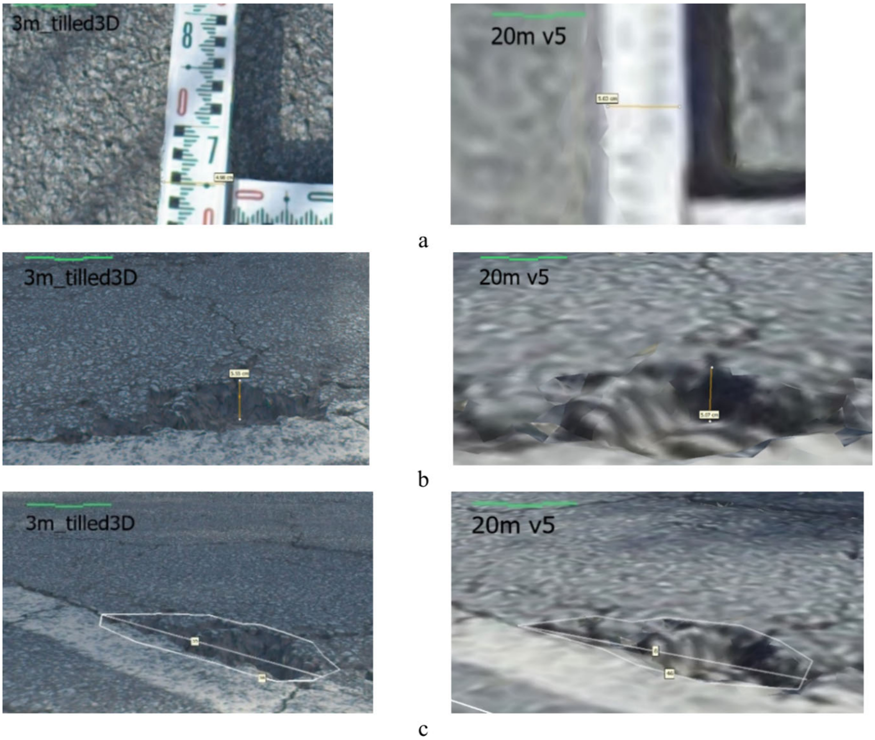

Fig. 2 Examples of measurements performed using the tools available in Agisoft Viewer: Element with known dimensions **a** Depth **b** and planimetric **c** measurements of a pothole

Table 1 Types and quantities of pavement distresses

Pavement distress	Severity level	3D—3 m model	3D—20 m model	Absolute variation	Relative error (%)
Cracks (m)	Low	0.000	0.000	0.000	0
	Medium	5.220	3.090	2.130	–41
	Hight	7.400	6.070	1.330	–18
Alligator craking (m^2)	Low	0.000	0.000	0.000	0
	Medium	35.473	34.192	–1.281	–4
	Hight	96.000	94.000	–2.000	–2
Paching (m^2)	Low	0.000	0.000	0.000	0
	Medium	0.000	0.000	0.000	0
	Hight	0.574	0.569	–0.006	–1
Potholes (n.°)	Low	3	3	0	0
	Medium	1	1	0	0
	Hight	3	3	0	0
PCI (scale: 0–100)		5	6	1	1

and calculations, it is possible to notice a significant difference in the measurements of cracking obtained from images captured at 3 and 20 m height, especially for the medium severity level. This evidence may be related to the fact that images captured at 3 m height have better spatial resolution than those captured at 20 m height, which influences the assessment. Lower severity cracks are more closed, making their identification more difficult in images captured at greater heights. As the more severe pavement distresses are larger and more visible targets, there is a smaller difference between the measurements taken from images obtained at heights of 3 and 20 m for high severity level. Overall, images captured at a height of 20 m pose greater difficulty in visually identifying lower severity distresses. However, these differences, for the analyzed section, result in a low variation in the PCI value, specifically around 1%. The two PCI values indicate that the studied pavement is in structural failure and requires reconstruction.

4 Conclusion

UAVs will significantly transform pavement inspection practices, as they offer a more efficient, accurate, safer, and cost–effective approach to assess road surface conditions. Their ability to capture detailed data and provide valuable insights plays a pivotal role in ensuring the safety, durability, and optimal performance of roadways, ultimately contributing to enhanced transportation infrastructure management.

Considering the analysis conducted, variations between the PCI values obtained from data captured at 3 and 20 m in UAV-based pavement inspections are minimal. Therefore, it is concluded that despite the 3-m survey being more dimensionally precise and detailed, data collection at 20 m can be considered a more reasonable approach for assessing road pavement conditions using UAVs. The validation of this approach presents the following advantages:

- Automatic flights at 20 m over 3 m manually flights.
- Reduced inspection time.
- Larger inspected area per UAV battery charge.
- Inspection without interrupting traffic, as image capture can be performed from the roadside, using near-vertical photography.
- Enhanced safety during inspection operations (due to fewer obstacles at 20 m height).

As an extension of this work, it is suggested to expand the study encompassing a larger inspection area to include multiple road sections with varying levels of pavement condition. Furthermore, artificial intelligence techniques can be researched for automatic detection of pavement surface distresses.

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