



## DIGITAL TWIN OF ZAGREB AIRPORT INFRASTRUCTURE USING UNMANNED AERIAL SYSTEMS

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### Abstract

Assessing and maintaining airport runways and infrastructure is essential for safe and efficient air transport. Traditional inspection methods, such as manual surveys or ground vehicles, are often time-consuming, costly, and disruptive. In recent years, Unmanned Aerial Systems (UAS) have become valuable tools for airport infrastructure condition assessment, offering rapid, accurate, and non-intrusive data collection. This article examines the use of UAS equipped with high-resolution cameras to create digital twins of runway surfaces and other airport infrastructure. Drones can capture detailed imagery that reveals cracks, potholes, contamination, foreign object debris (FOD), and more. Advanced image processing analyses the data, enabling classification and quantification of damage and changes over time. Compared with conventional methods, UAS inspections reduce downtime, limit human exposure to hazards, and support more frequent, real-time monitoring. They also access hard-to-reach or unsafe areas, improving the safety and reliability of inspections. Combining GIS with data collected by UAS enhances visualization and documentation, supporting predictive maintenance and informed decision-making. Although challenges such as regulatory restrictions, battery life, and weather constraints remain, ongoing improvements in drone autonomy, sensors, and analytics are expanding their potential. This paper outlines the procedures for aerial data acquisition, processing, analysis, and visualization of data collected at Zagreb Airport, as well as issues encountered during the workflow.

*Keywords: digital twin, UAS, airport, analysis, infrastructure*

### 1 Introduction

Airports are among the most critical nodes in modern transportation systems, where operational safety, efficiency, and reliability are among the most important factors. Runways and associated infrastructure are subject to continuous mechanical stress, environmental exposure, and operational wear. Defects such as surface cracking, rutting, potholes, contamination, and foreign object debris (FOD) pose serious risks to aircraft operations and must be detected and addressed promptly. Regular inspection and condition assessment of airport infrastructure are therefore essential components of airport safety management systems. Traditional inspection techniques, typically involving manual visual surveys or ground-based inspection vehicles, have long been the standard for monitoring runway conditions. While effective, these methods are often labor-intensive, costly, and disruptive to airport operations, frequently requiring runway closures or traffic restrictions [1]. Manual inspections are also subject to human error and may expose personnel to hazardous operating environments.

These limitations have prompted the search for alternative inspection technologies that can deliver accurate, repeatable, and efficient assessments while minimizing operational disruptions. In recent years, Unmanned Aerial Systems (UAS), commonly known as drones, have emerged as a promising solution for infrastructure inspection and monitoring. Equipped with high-resolution optical sensors and advanced navigation capabilities, UAS enable rapid, non-intrusive data acquisition over large and complex areas. In airport environments, drones can capture detailed surface imagery that reveals fine-scale defects, including cracks, surface deformation, material loss, contamination, and FOD. The collected data can be processed using photogrammetric and image analysis techniques to generate high accuracy orthomosaics, three-dimensional surface models, and digital twins of runway infrastructure [2].

Digital twin technology, integrated with UAS-based data collection, provides a powerful framework for airport infrastructure management. A digital twin is a dynamic, data-rich virtual representation of physical assets, enabling condition assessment, temporal change detection, and performance monitoring. When combined with Geographic Information Systems (GIS), these models enhance visualization, documentation, and spatial analysis, supporting predictive maintenance strategies and informed decision-making. Compared to conventional inspection methods, UAS-based approaches significantly reduce inspection time, limit human exposure to operational hazards, and allow for more frequent and near real-time monitoring [3, 4]. Despite their advantages, deploying UAS in airport environments presents challenges. Regulatory constraints related to airspace safety, limited battery endurance, weather sensitivity, and the need for robust data processing workflows remain key considerations. Nevertheless, ongoing advancements in drone autonomy, sensor technology, and analytical methods continue to expand the applicability and reliability of UAS for airport infrastructure assessment.

This paper presents a practical case study of UAS-based inspection conducted at Zagreb Airport. It outlines the complete workflow, including aerial data acquisition, data processing, damage analysis, and visualization. The study also discusses the technical and operational challenges encountered during implementation and evaluates the effectiveness of the approach for supporting runway condition assessment and infrastructure management.

## 2 Study area and methodology

### 2.1 Study area

The study was conducted at Zagreb Airport, a major international airport with extensive airside infrastructure, including runways, taxiways, aprons, and surrounding operational areas. Due to the safety-critical nature of airport environments, all UAS activities were conducted in compliance with airport operational requirements and under specific authorization for aerial mapping activities.

### 2.2 Regulatory approval and operational constraints

Before data acquisition, formal consent for aerial mapping was obtained from airport authorities. The approval specified the spatial scope, operational timeframe, and safety conditions for UAS flights. The authorization was valid from 1 February to 1 July 2025, after which operations were not permitted. In addition to regulatory approval, strict airport movement requirements were enforced to ensure flight safety and prevent interference with ongoing airport operations. These constraints affected mission scheduling, flight altitudes, and zone segmentation.

## 2.3 Ground control points

Accurate georeferencing was achieved using a network of Ground Control Points (GCPs) and Check Points (CPs), with a total of 92 points distributed across the study area (figure 1). Due to safety and operational constraints, no GCPs were placed directly on the runway surface. Instead, runway GCPs were derived from the model generated for the entire airport concession area, enabling absolute geolocation and accurate alignment of all datasets. This approach ensured geometric stability while maintaining compliance with airside safety regulations.



**Figure 1** Distribution of Ground Control Points (GCPs) and Check Points (CPs) across the airport area

## 2.4 Mission planning

Mission planning involved subdividing the airport concession area into six main zones covering approximately 330 ha, as shown in figure 2a, each surveyed at a target ground sampling distance (GSD) of 1 cm. A Digital Surface Model (DSM) was also created, enabling terrain follow flights and maintaining consistent image overlaps, as shown in Figure 2b, so the targeted GSD could be achieved.



**Figure 2** a) Mapping zones, b) DSM used for terrain follow flights

## 2.5 High-resolution survey areas

In addition to mapping the entire airport concession area, selected subareas – runway, taxiway, and apron – were surveyed at significantly higher resolution. These areas, covering approximately 48 ha in total, as shown in figure 3, were captured with a ground sampling distance (GSD) of 4 mm to enable detailed inspection of critical infrastructure elements.

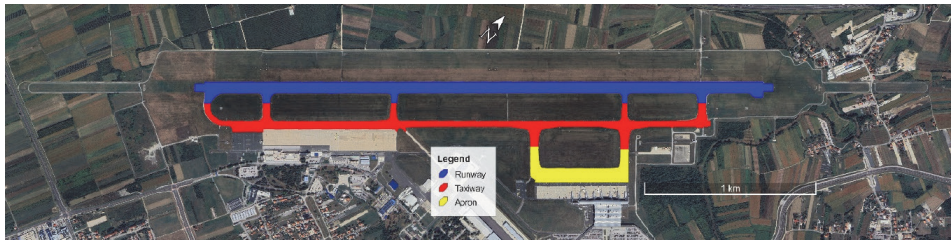


Figure 3 Runway, taxiway, and apron areas surveyed at high resolution

### 3 Aerial data acquisition

To ensure high positional accuracy, operational reliability, and data quality, aerial data acquisition was conducted using the DJI Matrice 300 RTK unmanned aerial platform [5] shown at figure 4a. This platform was chosen for its robust flight stability, extended endurance, and integrated real-time kinematic (RTK) positioning capabilities, which are particularly important for operations in complex and restricted airport environments. The RTK functionality improved the geolocation accuracy of the captured imagery, reducing reliance on ground control points in operationally sensitive areas. The UAS was equipped with a DJI Zenmuse P1 full-frame camera [6] shown at figure 4b, featuring a high-resolution CMOS sensor and a mechanically stabilized gimbal. The full-frame sensor, combined with a global shutter, enabled the acquisition of sharp, distortion-free images suitable for high-precision photogrammetric processing. Camera parameters, including flight altitude, image overlap, and acquisition intervals, were optimized to achieve the target ground sampling distances of 1 cm and 4 mm, depending on the surveyed zone.

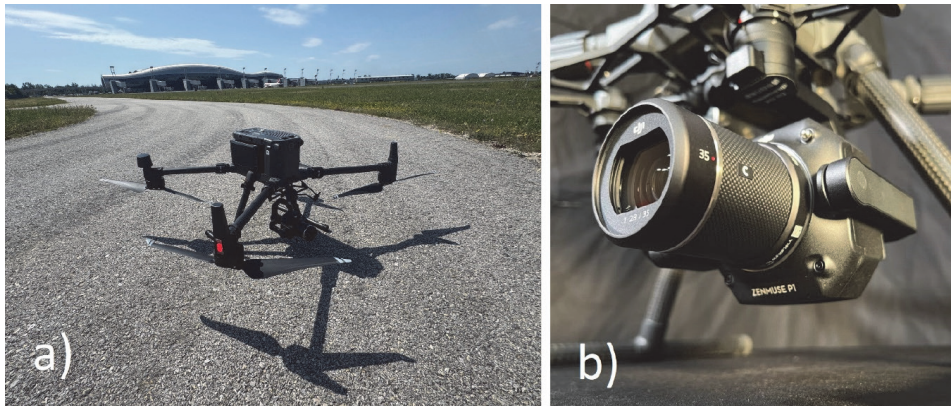


Figure 4 a) UAS DJI Matrice 300 RTK, b) DJI Zenmuse P1 full-frame camera

Flight missions were executed autonomously along predefined flight paths, with continuous monitoring by the flight crew to ensure compliance with airport safety procedures. Operations were coordinated with airport authorities to minimize interference with aircraft movements. The selected UAS configuration effectively balanced high-resolution data capture with operational safety, efficiency, and regulatory compliance, making it well suited to large-scale airport infrastructure mapping and detailed surface inspection, as demonstrated in previous studies [7]. After all flight missions were completed, a brief statistical summary of flight operations was produced, showing a total flight distance of approximately 231.2 km, an air time of 11:02 h, and 28, 500 geolocated photos taken. Figure 5 shows an example of First Person View (FPV), illustrating how the UAS “sees” the area around it.

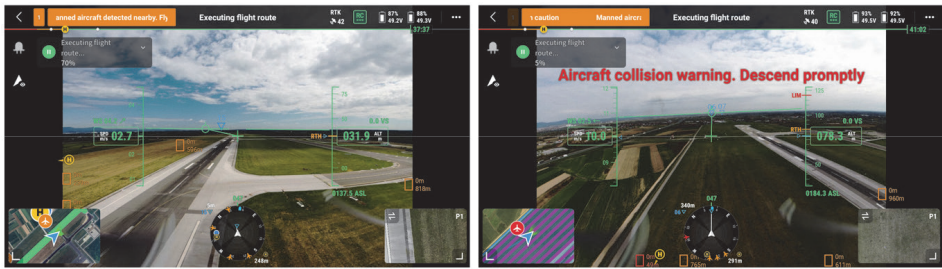


Figure 5 Field operations FPV during UAS-based aerial mapping at the airport

### 3.1 Data processing

Photogrammetric data processing was conducted using professional photogrammetric software, following a standardized and repeatable workflow designed for large-scale, high-resolution aerial surveys [8]. Due to the size of the surveyed airport area and the varying spatial resolutions of the datasets, processing was conducted separately for each flight zone to ensure optimal performance and data consistency. The six main airport zones produced approximately 823 GB of spatial data, while the high-resolution selected subareas – runway, taxiway, and apron – datasets contributed a further 949 GB, resulting in a total processed data volume of approximately 1.77 TB. The processing workflow included initial image quality assessment, aerial triangulation, and camera self-calibration. Ground Control Points (GCPs) and Check Points (CPs) were incorporated to strengthen the photogrammetric block geometry and improve absolute positional accuracy. After successful image alignment, dense point clouds were generated, providing detailed three-dimensional representations of the runway surfaces and surrounding infrastructure [9]. These point clouds as shown in figure 6 were then used to derive Digital Surface Models (DSMs) and high-resolution digital orthophotos.

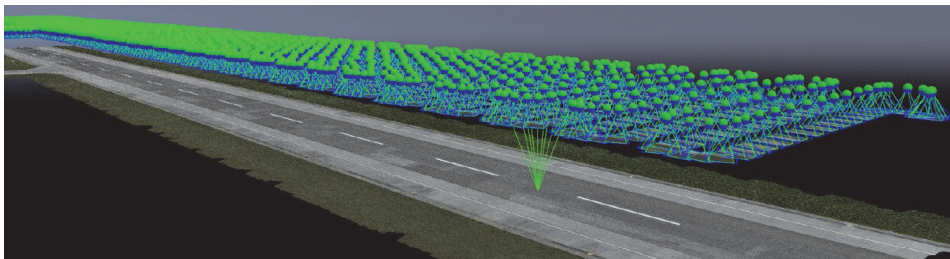


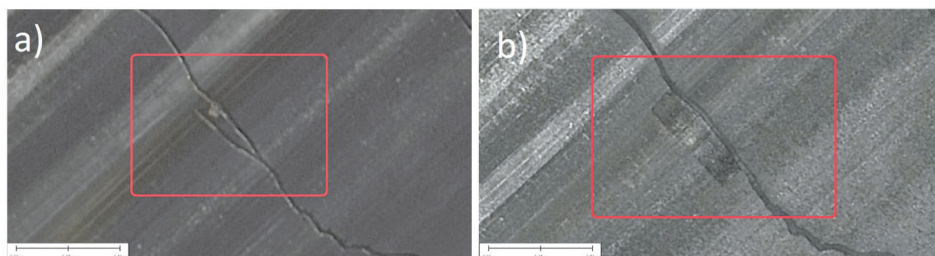
Figure 6 View of the runway point cloud

Orthophotos were produced at a spatial resolution of 1 cm per pixel for the main airport area and 4 mm per pixel for selected high-priority zones. Due to the size and complexity of the datasets, processing required substantial computational resources and careful data management. The resulting geospatial products provide a reliable basis for detailed surface inspection, damage detection, and further analysis, including point cloud classification, vectorization, and multi-temporal change detection to support airport infrastructure monitoring and maintenance planning.

### 3.2 Change detection and monitoring

High-resolution orthomosaics and point clouds generated from UAS imagery are key outputs of the photogrammetric workflow and form the foundation for advanced monitoring and analytical applications.

The resulting orthomosaics provide geometrically accurate, seamless representations of runway surfaces and airport infrastructure, enabling detailed visual inspection and precise spatial measurements. With spatial resolutions of 1 cm and up to 4 mm per pixel, small-scale surface defects, contamination, and foreign object debris can be clearly identified and documented.



**Figure 7** Comparison between the orthomosaic a) generated in 2023 and b) from 2025 reveals changes in surface condition and infrastructure features over the two-year interval

Beyond single-epoch analysis, orthomosaics and point clouds enable multi-temporal monitoring and change detection. By comparing datasets acquired at different times, as shown in figure 7a and figure 7b, geometric and surface-related differences can be identified, enabling the detection of surface degradation, newly formed cracks, material displacement, or changes in object presence. This capability is particularly valuable for proactive runway maintenance and safety management. When integrated within a GIS environment, orthomosaic-based change detection improves visualization, documentation, and decision-making, supporting predictive maintenance strategies and contributing to the development of dynamic digital twins for airport infrastructure management.

## 4 Conclusion

This study demonstrated the applicability of Unmanned Aerial Systems (UAS) for high-resolution inspection and the development of a digital twin of airport infrastructure, using Zagreb Airport as a case study. The results confirm that UAS-based aerial mapping provides an efficient, accurate, and non-intrusive alternative to conventional runway and airside inspection methods. By combining carefully planned flight missions, a dense ground control network, and photogrammetric processing, high-quality orthophotos and three-dimensional surface models were generated for both large areas and selected high-priority zones. The geometric accuracy of the photogrammetric model was evaluated using independent check points, confirming that the achieved positional accuracy meets requirements for infrastructure assessment and monitoring. The multi-resolution approach enabled both large-scale mapping and detailed inspection, while ensuring operational safety and minimizing disruption to airport activities. The resulting datasets form a key component of a digital twin framework, providing accurate spatial information that can be integrated within GIS environments for visualization, documentation, and analysis. In practice, the models support infrastructure management through condition assessment, defect identification, and spatial analysis of runway and airside assets. This approach reduces inspection time, limits personnel exposure to hazardous conditions, and allows more frequent monitoring than traditional methods. Despite challenges such as regulatory constraints, weather dependency, and large data volumes, UAS technology proves to be a reliable tool for data acquisition within a digital twin concept. Future work will focus on automated point cloud classification, feature extraction, and multi-temporal change detection, enabling predictive maintenance and long-term asset management while improving operational efficiency, safety, and infrastructure planning.

## Acknowledgments

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