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INTEGRATING 3D LASER SCANNING & UAV TECHNIQUES FOR ROAD BRIDGE INSPECTION

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Abstract. *The inspection of transportation structures is a necessary project for ensuring the public safety. Nevertheless, it is demanding and time-consuming procedure. Recent years, the evolution of measuring techniques and equipment allow faster data collection, minimal traffic disruption, and detailed detection of structural damage and the pathology of the constructions, e.g. microcracks as small as 0.1 mm. Given the number of the vehicles that cross road infrastructures annually, systematic monitoring is important to maintain their operational safety. This study presents the creation of a digital twin (DT) of a bridge, located on the Athens–Corinth highway, a major transportation axis of Greece. The methodology integrates terrestrial 3D laser scanning with aerial protogrammetry from a UAV. After processing the acquired data, a highly detailed digital twin of the bridge was produced, enabling thorough technical inspection and identification of structural pathologies. The field measurements, data processing, and generation of the final digital model are described thoroughly. The results show that combining terrestrial laser scanning and UAV photogrammetry, a reliable digital twin of a bridge can be produced and furthermore use it for its inspection. This, not only improves the accuracy of defect detection, but also this approach enhances long-term monitoring, facilitates condition assessment, and supports maintenance strategies.*

Keywords*: Laser Scaner, UAV, Digital Twin, Bridge inspection, Construction pathology, Crack detection*

INTRODUCTION

The technical inspection of structures, particularly road infrastructure, represent a requirement for guaranteeing public safety and maintaining the continuous operational capacity of these critical networks. Bridges and tunnels are exposed to continuous loads, weather conditions and material fatigue; their systematic monitoring ensures structural integrity and prevents catastrophic failures [0, 0].

Although essential, the conventional process of structural assessment is demanding, difficult and time-consuming. Bridge components subject to environmental exposure and traffic loads, which lead to material pathology such as concrete deterioration and cracking. Early and accurate detection of these defects is crucial for planning maintenance and preventing catastrophic failures. Until recently, inspections relied on manual visual methods performed by engineers using cranes or lifts (Figure 1), a process that is labour-intensive, costly, and sometimes hazardous [0]. The methods involved manually sketching and recording defects, such as cracks and concrete pathologies. This traditional methodology is characterized by several critical drawbacks: it is costly and hazardous to personnel; it mandates the partial or complete closure of traffic lanes, causing significant operational disruption. The resultant data lack the topographical precision required for exact diagnosis and subsequent intervention. Positional errors in locating defects using manual sketches can be substantial, greatly complicating efforts to relocate and repair the specific problem areas during maintenance cycles.

Figure 1. Bridge inspection with optical methods

In recent years, **advances in geomatic surveying technologies** have revolutionised structural inspection [0, 0, 0]. **Terrestrial Laser Scanning (TLS)** provides dense three-dimensional (3D) point clouds of structures, capturing millions of points with precision of mm. Meanwhile, **UAV photogrammetry** delivers complementary aerial imagery that enables the generation of orthophotos and 3D meshes of hard-to-reach areas [0, 0]. These techniques minimise traffic disruption and offer complete, repeatable datasets that support quantitative assessment of damage and deformation [0].

Across Europe and internationally, several transportation agencies have integrated **these techniques** into routine bridge inspection. For instance, the Highways England framework employs mobile and static LiDAR for monitoring highway bridges, while the Federal Highway Administration (FHWA) in the United States supports the use of UAVs for rapid post-disaster evaluations [0]. Comparable initiatives in Greece have begun to explore digital documentation and **digital-twin** workflows for bridges and tunnels, linking 3D survey data with structural health-monitoring information.

This paper presents a **case study** of a concrete bridge along the Athens–Corinth highway. The objective was to create a **digital twin (DT)** of the structure by integrating TLS and UAV photogrammetric data. The digital twin offers accurate assessment of the bridge's condition, detection of pathology and supports maintenance planning.

CASE STUDY

1.1. Location and Structural Characteristics

The bridge chosen for the inspection is Bridge A017 (Figure 2), which is located on the Olympia Odos (Athens - Corinth Național Highway), one of the country's most important transportation corridors, at kilometer position 45+550 (23.308927E, 37.974126N). The highway connects the capital city of Athens with the port of Patras, facilitating the movement of passengers and freight between mainland Greece and the western coastal ports. It is constructed primarily of reinforced concrete. Based on its dimensions, it is classified as a medium-span structure, featuring an opening of 41.4 m. It is situated approximately 60 km west of Athens, near the region of Megara, at a point where the motorway passes through a semi-urban environment characterised by moderate traffic and light surrounding vegetation. It consists of two simply supported spans, each approximately 20 m. long, with a total deck

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length of around 40 metres. The deck slab is constructed from reinforced concrete, supported by precast concrete beams and abutments founded on shallow concrete footings.

The bottom side of the bridge is accessible for inspection, which made it easy for combined TLS and UAV photogrammetric documentation.

Figure 2. Location of the bridge A017 along the Athens–Corinth Motorway

1.2. Inspection Objectives

Main object of the study [0] was to produce a 3D digital model (digital twin) of the bridge, which would support the detailed inspection and long-term condition monitoring. Specific goals included:

- The accurate geometric documentation of the bridge.
- Detection of surface defects, including cracks, spalling and signs of corrosion.
- Integration of TLS and UAV datasets into a model with high metric accuracy.
- Preparation of deliverables such as orthophotos, cross-sections, and a textured 3D mesh suitable for engineering assessment.

Combining the above deliverables the corresponding engineers could identify both primary cracking mechanisms and various surface pathologies. Cracks can be broadly categorized as non-structural (e.g., plastic shrinkage or crazing, which are often hairline cracks mm) or structural (e.g., related to settlement, thermal expansion, or overloading). The DT methodology, with its high resolution, is essential for identifying microcracks that may signal early-stage degradation.

The accurate capture and quantitative dimensioning of these defects are prerequisites for determining their severity and timing the necessary maintenance actions, moving the inspection outcome toward predictive failure analysis rather than merely reporting visual degradation.

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2. Measurement Techniques: Methodology & Equipment

2.1. Equipment used

The successful creation of a high precision Digital Twin requires the integration of various equipment (Figure 3):

a) Terrestrial Laser Scanner: The FARO Focus Premium [0] was used. It high accuracy geometric output, which is essential for preparign a precise DT. It has a scanning range of 150 m. The measurement error is 2 mm at 10 m and 3.5 mm at 25 m, which makes it ideal for the required geometry. Moreover, it supports High Dynamic Range (HDR) imaging, providing realistic colorization for the point cloud.

b) UAV DJI Phantom 4 RTK [0]: It was deployed for peripheral and upper images. It has a camera of 20 Mpixel.

c) UAV DJI Mavic Air 3 [0]: A second drone was required to address specific viewing angle limitations inherent to photogrammetry, particularly for the bridge bottom part. It features a high resolution 48 Mpixel camera with both wide-angle and telephoto lenses. Crucially, its gimbal rotates +60° on the vertical axis, allowing the necessary high angle images of the bridge's underside, a traditionally difficult area to inspect.

d) Checkerboard Targets: Twenty numbered checkerboard targets (25 x 25cm) were evenly placed across the structure. These served as essential ground control points (GCPs), necessary for three purposes: ensuring highly accurate registration (alignment) of the 18 TLS scans, linking the aerial photogrammetric data to the TLS coordinate system and validating the final model's geometric integrity.

Figure 3. The equipment used during the measurements (a. Faro Focus Premium, b. DJI Phantom 4 RTK, c. DJI Mavic Air 3, d. Checkerboard Targets)

2.2. Terrestrial Measurement Procedure

The field work was designed to maximize data density while respecting the operational constraints of the live highway environment. The first step involved planning the optimal scanner positions to achieve complete coverage, ensuring that the targets were within the scanner's range. **Eighteen (18) total scan stations were defined**. Given that the highway operation could not be interrupted, all TLS activities were restricted to the areas surrounding the abutments of the bridge. The superior 150 m range of the TLS allowed the effective coverage despite these constraints.

A high density scanning profile was chosen. This setting yielded approximately 43.7 Mpts per scan, ensuring that fine details necessary for pathology detection were captured. With each scan taking approx. 4 minutes, the entire 18-station TLS campaign was completed in approximately 2 hours.

2.3. Aerial Measurement Procedure

The aerial campaign required precise maneuvering and utilized the strengths of the two specialized UAVs. The DJI Phantom 4 RTK was used for perimeter and upper bridge images. Flights were conducted manually rather than via automated flight plans to maintain optimal, close proximity to the structure and ensure high image quality. A necessary 80/80 image overlap (horizontal/vertical) was maintained to guarantee sufficient homologous points for robust photogrammetric alignment.

The DJI Mavic Air 3 was utilized for the bottom part and internal abutment faces. Its enhanced gimbal range was critical for these high-angle shots.

Operational difficulty was significantly increased by severe high winds (reaching 7 Beaufort), which challenged flight stability and subsequently impacted the quality of the aerial data in certain critical areas.

2.4. Auxiliary Metrology and Crack Validation

In the final phase of field work, auxiliary measurements were conducted to ensure the metrological soundness of the digital data. Sample measurements were taken on representative cracks using a card-type crack gauge.

This step serves a critical function: to control the dimensional accuracy of the subsequent digital digitization performed in the office. Although the final orthomosaic pixel size was designed to be 0.8-1.0 mm, the process of visually digitizing a crack introduces a small error range, estimated at 0.2-0.3 mm. The field measurements validate the dimensional control, ensuring that the digital dimensions extracted from the Digital Twin are reliable and comparable to those obtained via physical contact, thereby confirming the quality of the digitization process.

3. Data processing, Analysis and Digital Twin production

3.1. Point Cloud Registration and Cleaning

The 18 raw scan files (FLS format) were imported into FARO Scene software for processing. Initial processing included computing normal vectors, balancing colors, and applying necessary filters. The subsequent unification of the individual scans (Registration) was performed using the Cloud to Cloud method. This manual approach was preferred over automated registration, as it allowed greater operator control and higher certainty in the alignment of the different point clouds, ensuring they converged into a single, cohesive geometry in a common arbitrary coordinate system.

The final registration report demonstrated the high geometric fidelity achieved across the large-scale capture, with a Maximum Point Error of 7.2 mm, a Mean Point Error of 4.7 mm and a Minimum Overlap of 76.3%.

The unified point cloud contained significant noise, primarily originating from transient elements (vehicles and trucks moving continuously on the highway during the scanning period). Although FARO Scene offers automated filters for moving objects, a manual

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cleaning approach was deemed more effective and efficient. The point cloud was exported as a standard .e57 file and imported into Autodesk Recap.

Autodesk Recap's user-friendly environment facilitates quick manipulation and visualization of the dense point cloud, making manual noise removal faster and more precise than relying solely on automated filtering. The final, clean point cloud was then converted to the native .rcp format for seamless integration with other Autodesk tools. The output of this stage is the final geometrically purified TLS point cloud, ready for fusion with the aerial data (Figure 4).

Figure 4. Instances of the final cleaned 3d point cloud

3.2. Photogrammetric Processing & Hybrid model generation

The 2038 UAV images (from the Phantom 4 RTK and Mavic Air 3) were processed in Agisoft Metashape (Figure 5). The subsequent critical step was the geometric synchronization of the photogrammetric data with the high-accuracy TLS data. The measured checkerboard markers were introduced into the project and assigned the coordinates defined by the TLS local system. The different clouds were transformed, bringing the aerial data into the stable, millimetrically accurate coordinate system established by the laser scanner. The two synchronized clouds were then combined.

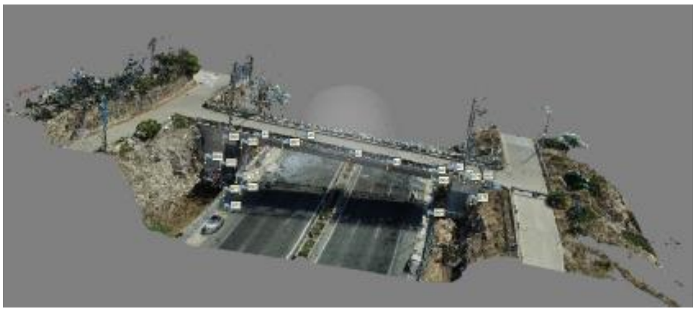

Figure 5. Point cloud from the photogrammetric procedure

The integrated methodology ensures that the geometric rigor of the DT relies on the TLS, while the visual realism is provided by the UAVs. This prevents the positional errors sometimes associated with purely photogrammetric models.

The final deliverable for crack analysis is the distortion-free Orthomosaic, defining the required projection planes based on the control markers. The resulting orthomosaic achieved a high pixel resolution of 1 mm. This resolution provides the necessary visual detail for the accurate identification of fine pathologies, which must be captured at a much higher resolution than that needed for general topographical mapping.

3.3. Identification and Quantitative digitization of concrete pathologies

The high resolution orthomosaics were used for the quantitative assessment. The orthomosaics were imported into the corresponding software, where we visually identified and digitized all visible defects and structural features (Figure 6).

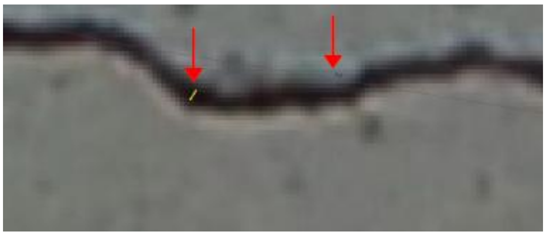

Figure 6. Manual crack identification and digitization

The crack features are digitized and then dimensioned using the software's measuring tool. The measurement of the crack width is taken antidiametrically across the widest point, focusing on the dark pixel border to delineate the crack edges. This stage leads in the preparation of accurate drawings of the bridge's pathology distribution (Figure 7).

The final inspection documentation includes highly accurate representations of all structural faces (Abutment Views, Cross Sections, North and South Elevation Views, Bottom View). The orthomosaics clearly show the location, the extent and measured dimensions of the digitized pathologies across the structural elements of the bridge.

Figure 7. Digitized cracks and pathology on the orthomosaic of the bridge

RESULTS AND DISCUSSIONS

The high value of the Digital Twin methodology is evident when comparing the resultant As-Built plans against those derived from a prior inspection conducted using conventional visual methods (dating to 2022).

The DT analysis showed significantly more findings regarding concrete pathologies and cracks, primarily because the 1 mm resolution orthomosaics allowed the identification and precise measurement of subtle defects missed by direct human observation.

Furthermore, the DT method generates reports based on millimetric geometry and topographical accuracy. In contrast, the older reports produced findings that were largely schematically recorded, leading to significant deviations in the actual position and size of the pathology. For example, images detailing the North and South faces of the prior visual inspection show only broad, conceptual representations of damage, while the DT output shows specific vectors and dimensions. The enhanced geometric fidelity of the DT ensures that maintenance crews can relocate and repair defects with certainty.

A recognized obstacle was observed for the bridge bottom view. Due to the high winds during aerial data acquisition, the UAV images of this section were less stable, making the identification of cracks difficult to distinguish compared to the stable side elevations.

CONCLUSIONS

The integration of TLS and UAV techniques for bridge inspection, indicates the necessity of adopting Digital Twins in structural assessment. The proposed methodology transforms the technical inspection of large structures into an efficient, safe and accurate task.

The advantages of the DT approach are presented below:

- **Geometric Accuracy**: The fusion method offers high accuaracy.
- **Increased Findings**: The DT consistently reveal a significantly higher number of defects and provides certainty for their position and dimension, surpassing the subjective and imprecise results of manual visual inspections.
- **Operational Safety and Efficiency**: The use of the aforementioned or similar equipment minimizes the risks to personnel and allows the continuous flow of highway traffic, an undeniable advantage over conventional methods.
- **Data Permanence**: The resulting data set is available every time in the future for potential re-examination or for comparison with a previous or next inspection. This permanence supports long-term structural health monitoring, allowing engineers to quantitatively track the evolution of defects (e.g., crack propagation rates) over time, enabling proactive and predictive maintenance planning.

Based on the results and operational problems faced, the following proposals are made for future work in order to optimize the inspection method:

Accelerating Field Acquisition with SLAM Technology: The current reliance on static TLS setups, while highly accurate, remains time-consuming, particularly in busy environments. Future research should prioritize the integration of SLAM (Simultaneous Localization and Mapping) 3D scanners. These systems, when combined with a high accuracy geodetic control network, can minimize the time needed for the field measurements, which further minimizes the time exposed to traffic and the vulnerability of the acquisition process to weather conditions.

Automation of Analysis using Artificial Intelligence (AI): The most time consuming step was the manual creation of the drawings. It is proposed the integration of an Artificial Intelligence (AI) platform for automated data analysis. While data acquisition is now rapid, the office work (e.g. the process of manually identifying, digitizing, dimensioning, and categorizing thousands of crack features on the orthomosaics) remains a bottleneck. An AI platform trained on the high-resolution DT data could assume this analytical role, drastically reducing the human capital and time required for post-processing. This automation would fully establish bridge inspection as a simple, high volume routine procedure, significantly limiting the duration and cost required to complete the final engineering drawings and assessments.

Standardisation and Guidelines: The development of national or European guidelines for the application of the methodology in bridge inspection would ensure consistent data quality, interoperability and adoption by public authorities.

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