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3D Reconstruction of a Precast Concrete Bridge for Damage Inspection Using Images from Low-Cost Unmanned Aerial Vehicle

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Abstract

Early damage detection in bridges is fundamental to their continued safety, and therefore of utmost importance to the bridge managers and policy makers. The traditional visual inspection which is the common practice for bridge inspection is inefficient, time-consuming, costly, risky, subjective and require the expertise of highly qualified inspectors. Consequently, the use of unmanned aerial systems (UASs) has gained significant attention in the area of bridge inspection. Most UAVs are quite expensive, ranging between $8000-$25000 for the best categories. It however requires the use of UAV equipped with high-cost sensors and longer battery duration, and adequate man power for real-time inspection. The expense of the UAV based inspection makes it unaffordable for many African countries. More recently, 3D models are increasingly deployed for image-based damage identification in bridges and other structures. The 3D models are constructed inform of a digital twin, and allow for computerized inspection using low-cost drones. This paper presents 3D Reconstruction approach for damage inspection and condition assessment of a bridge using images from low-cost unmanned aerial vehicle (UAV). The overall approach was illustrated in form of a case study on a precast concrete bridge. The 3D Reconstructed model of the bridge was virtually inspected to detect damages such as cracks, delamination, concrete deterioration, etc. The results showed that 3D reconstruction using low-cost UAV has great potential in its applications in bridge assessment.

Keywords: UAV, UAS, VI, 3D-Reconstruction, Bridge Assessment

Introduction

Bridges are fundamental to the transportation network of every nation, and their continued safety is of utmost importance to the bridge managers and policy makers. With the aim of maintaining safe operation, extending the useful life, and ensuring reliability through sustainable practices, bridge inspections have become a crucial component of infrastructure management [1].

Visual Inspection (VI) is one of the earliest methods of inspection and assessment of roadway bridges. This method, which is prevalent is conducted regularly by trained inspectors to examine bridge components for the presence of damages such as cracks, concrete spalling, rebar corrosion and efflorescence and thereafter, update the last inspection data related to the structure [2]. It provides an initial idea of the structural health of the bridge as well as a basis for further assessment if required.

Although visual inspection is relatively easy to undertake as it does not require sophisticated equipment, it however has a number of associated challenges. According to [3], visual inspection is highly subjective as different inspectors are reported to have presented different findings on the same structure. Furthermore, there could be difficult to reach areas on bridges like soffit over large water bodies. Consequently, inspecting such locations would require vehicles with lifts, or climbing while using ropes and harnesses. These activities can create potentially hazardous conditions for inspectors, increasing the risk of falls and other accidents [1,2].

These and other numerous limitations associated with VI has necessitated the need for technology driven method(s) to improve efficiency of the inspection process. One of which is the use of Unmanned Aircraft vehicle (UAV) for bridge inspection. The UAV is used to acquire high-resolution images, making it an innovative, simple, efficient, and safe choice for inspecting bridge [1]. By using UAS as platforms for observation and data collection, bridge inspections can be performed with greater accuracy and at a lower cost than traditional methods that require physical access to the bridge. This technology can also reduce the risks associated with bridge inspections, allowing for safer operations and more efficient use of resources. Unmanned aerial vehicles (UAVs) have gained significant interest in the application of bridge inspections as assistive, efficient, and cost-effective tools, offering great potential for inspection automation [1].

Mostafa Aliyari [4] demonstrated some of the developments UAV technology achieved in several civilian applications in the last 20 years. The study included two main functions of the UAV which are, the first being the most common, the 2D image data can be used to quickly establish a basic knowledge of the structure’s condition and the second reconstructs 3D models to provide a permanent record of the geometry for each bridge asset, which could be used for navigation and control purposes. Ghosh et al. [5] used UAV for a post-earthquake assessment of a bridge. The UAS was equipped with a thermal imaging camera, which allowed for the detection of heat signatures that could indicate damage to the bridge structure. The study found that the UAS provided an efficient and effective way to assess the damage, as it allowed for a comprehensive inspection to be conducted in a short amount of time. Gucunski et al. [6] used the UAV to inspect a bridge for rebar corrosion and concrete delamination. The UAS was equipped with ground penetrating radar, which allowed for the detection of subsurface damage to the bridge structure. The study found that the UAS provided an efficient and effective way to assess the damage, as it allowed for a comprehensive inspection to be conducted quickly, and without the need for personnel to physically access the bridge. Kocaman et al. [7] used a UAS to inspect a bridge for potential damage caused by a nearby construction project. The UAS was equipped with a laser scanner, which allowed for the detection of any deformation or displacement of the bridge structure. Yoon et al. [8] conducted a study comparing UAS-based bridge inspection results and human visual inspection results through three-dimensional image coordinates, and concentrated their analysis on comparing the spatial location of the detected damage.

Although the aforementioned studies correctly identified damages on the bridges, it however deployed the use of UAV equipped with high-cost sensors and longer battery duration, adequate man power for real-time inspection, long period time of inspection, and requires close range monitoring which increased the vulnerability of the UAS for obstacle collision. More recently, 3D models are increasing deployed for image-based damage identification of bridges and other structures. This method has more advantage to UAS based inspection, as it involves the construction of 3D models inform of a digital twin using images from a low-cost drone, and allow for computerized inspection which significantly reduced the number of inspectors and time of inspection.

3D reconstruction is the process of capturing the shape and appearance of real object in computer vision and computer graphics [14]. The process involves restoring scene depth from 2D images using line of sight and camera positions, resulting in the creation of accurate 3D models. The use of 3D models in bridge and infrastructure inspection offers significant potential, as it provides a record of condition and dimensions, facilitating comparison between inspections and aiding in navigation and control purposes. Dorafshan et al. [15] proposed a pioneering approach for semi-autonomous bridge inspections using 3D models generated through Unmanned Aerial Systems (UASs). The 3D models served as virtual maps, enabling UASs to navigate around the bridge effectively and avoid obstacles, thereby streamlining the inspection process. The study utilized Agisoft Photoscan for 3D model generation, yielding promising results. Meanwhile, the complex geometry of bridges posed a limitation, making the model generation process potentially laborious. Bartcezak et al. [13] proposed a time-effective framework for a UAS-based bridge inspection methodology that integrates 3D information from photogrammetry and machine learning based object detection to allow direct measurements in the images. The study deduced the use of a two-step flight planning to accurately reconstruct the bridge using limited manual effort. In addition, the study detects frequently occurring damages such as exposed rebars and concrete spalling on the inspection imagery. Hamza et al. [16] proposed a Building Information Modeling (BIM) and 3D reconstruction technique to acquire data for computerized inspection and generate a 3D finite element model for static or dynamic analysis. The result showed that 3D reconstruction has great potential in its application in civil engineering. The study generates an automated textured 3D model of a pedestrian concrete

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bridge across the lake in NUST H-12 campus in Pakistan to assess its viability for inspection and perform modal structural analysis using the generated geometric model.

Alexander Jiponor [17] describes the inspection and condition assessment of existing bridge over a railway line in Sofia, Bulgaria. The structure is part of important transport connection between two major residential areas proposed for expansion. The study includes the scanning with UAV and creating a digital twin of the structure. Registration of the damages and the identifying of maintenance problems is based on a computerized inspection, Non-Destructive Testing (NDT) tools and Building Information Model (BIM). The quality control assessment of the bridge is based on Performance Indicators (PI's) and Key Performance Indicators (KPI's) and two scenarios are elaborated for further action. Luhmann et al. [18] delved into 3D image reconstruction techniques for bridge inspection, leveraging Structure-From-Motion (SFM) and multi-view-stereo (MVS) approaches. Their study emphasized the importance of efficient feature detection algorithms, given the computational demands when processing numerous images in infrastructure inspection. Although SFM and MVS demonstrated good accuracy in creating 3D models, challenges in handling large datasets and occluded areas during reconstruction were recognized. Bechliolis et al. [19] developed a photogrammetric-based 3D image reconstruction method for bridge condition assessment. The study showcased the potential of 3D models in identifying surface defects, such as cracks and spalling. However, challenges in capturing fine details on large structures and the necessity of obtaining high-quality images to achieve precise 3D reconstructions were identified. Lin-Yao et al. [20] proposed a process using an imagery-based point cloud to inspect a bridge with the aid of data acquisition, 3D reconstruction, data quality evaluation and subsequent damage detection. He further proposed an evaluation mechanism through checking the data coverage, analyzing point distribution, assessing outlier noise, and measuring geometric accuracy. The study demonstrated that the UAV-SfM method can offer significant advantages in equipment cost, surveying time, point distribution and ultimate data coverage. Chai et al. [21] proposed a hybrid approach for 3D bridge reconstruction, combining terrestrial laser scanning (TLS) and photogrammetry. TLS provided highly accurate point cloud data, while photogrammetry complemented the process with texture and color information. Impressive results were achieved; however, limitations in computational resources for data processing and the need for careful calibration between TLS and photogrammetry were recognized.

Although UAV equipped with sensors have been largely successful for various inspection, a significant challenge remains cost. Table 1 shows the cost of some UAVs discussed. The high expenses associated with UAV-based inspection is primarily due to the sophisticated sensors and other accessories attached to this system. Bearing in mind the prohibitive cost of UAV deployments which is from $5000-$25,000 for the most expensive class, and with scarcity of funds for constructing new bridges, the traditional method of VI is more likely to be in use for the foreseeable future especially in developing countries. Besides, even the most sophisticated UAV systems and however successful, would at some point require human assistance for assessing the severity of the damages identified in the 3D reconstructed models. Therefore, while the benefits of utilizing UAVs for bridge inspection are numerous, it has become imperative to lower/minimize cost while trying to achieve as much as possible.

This study presents a 3D reconstruction approach for damage inspection and condition assessment of a bridge using digital images captured with a DJI Mavic 2 Air drone, which cost less than $1000. The 3D reconstruction allows for computerized inspection and provides a record of the bridge's condition and dimensions, aiding in the assessment of structural health over time. Overall, the aim of the research is to present a low-cost UAV-based methodology that incorporates 3D reconstruction techniques for damage Inspection and condition assessment of a bridge infrastructure.

Table 1. Cost comparison of UAV and sensor configurations for bridge inspection

Ref.	Year	Method	Drone	Sensor Type	Cost ($)
-	Proposed 2024	3D Reconstruction	DJI Mavic Air 2	48Mp Camera, 4K Video Resolution	560
[16]	2023	BIM and 3D Reconstruction	UAV	4k Smartphone Camera	800-1,500
[13]	2023	3D Reconstruction	DJI Mavic Pro	12Mp Camera	2,199
[22]	2021	Model-based Inspection	DJI Matrice 300 RTK	Zenmuse H20 T Camera	13,700
[21]	2018	3D Reconstruction	UAV	TLS Sensor	25,000
[12]	2018	Deep Learning Convolutional Neural Networks	12Mp DJI Mavic	12Mp Nikon GoProHero 4	906
[11]	2017	Fuzzy C-means Clustering	UAV	4K Camera	1,000
[10]	2017	Restricted Boltzmann Machine	UAV	4K Nikon D7000	20,000
[9]	2017	Review	UAV	Visual, Thermal, Ultrasonic, Laser	5,000 - 25,000

Materials and Methods

Materials

The materials used for this study is categorized into hardware and software.

Hardware

UAS platform

The DJI Mavic Air 2 UAV drone (Figures 1 and 2) paired with the high-resolution 48-megapixel digital camera and 4K video resolution was used for the study (Table 2). This is essential due to its exceptional combination of accuracy, stability, and image quality.

Table 2. Details of UAV available for inspection

Details	Specification
Name	DJI Mavic Air 2
Weight	590g
Rotors/Size	4 rotors
Flight time	30 minutes

Computer specification

A robust and capable computer system is an essential component in the successful execution of the study. The computer would serve as the central processing unit for data management, analysis, and visualization. A 7-core Intel® Dell CPU @ 2.60GHz was used for this project. Table 3 describes specifications that were considered when selecting the appropriate computer for this project.

Table 3. Computer hardware specification

Item	Specification	Area of Application
Processor	Minimum of 2.5 GHz	Handling the computational demands of data processing and analysis software
RAM	Minimum of 12 GB RAM	Handling large datasets and running memory-intensive applications
Graphics Card	Maximum of 4GB VRAM	Accelerating graphical computations
Storage	Minimum of 500 GB	Storing and managing the large volumes of data collected during the UAS flights

Software

The DJI Terra Software was selected for this study among many other software. It has an excellent user interface and could be obtained at the website [23]. A limited free student version was used for the purpose of this study. DJI Fly software was used to control and design the optimal flight path for drone. It is a free version software and can be obtained at their website [24].

Figure 1. DJI Mavic Air 2 UAV drone

(a) (b)

Figure 2. DJI Mavic Air 2 UAV drone during image acquisition

Table 4. Software Applications used in the Project

Software	Application
DJI Fly	Optimal flight path design
DJI Terra	Image alignment and 3D reconstruction

Bridge description

The bridge selected for this study was a concrete bridge at Gada-Biu along Kwakonka-Tudun Wada Road, Jos, Plateau state, North central, Nigeria. The bridge as shown in Figure 3 consist of 3No span, each 18m long, with a total length of 54m. The superstructure consists of 8 precast T-beams on each span of the twin bridge. The carriageway is 6m with a precast parapet wall on both sides. The substructure consists of 2 piers connected by a pier cap at 4 different locations. The abutment, which is of the bank seat type, occupies the extremities of the flyover. The bridge was constructed in 2010 and has an estimated annual average daily traffic (AADT) of 5,000.

Figure 3. Real image of the bridge

METHODOLOGY

The 3D model was created using DJI Terra software to assess the viability of 3D reconstruction for visual inspection (Figure 4). The software was able to convert the images to a 3D point cloud, and are aligned to formed a sparse point cloud by aero-triangulation which had more than 390,358 projections and 105,107 tie points, each with x,y,z coordinates, which enables to automatically build the dense cloud, mesh, texture, digital elevation model (DEM), and orthomosaic for a successful 3D reconstruction model. A detailed methodology adopted in this study consist of nine (9) macro-processes as shown in Figure 5. A brief on each of the process is presented.

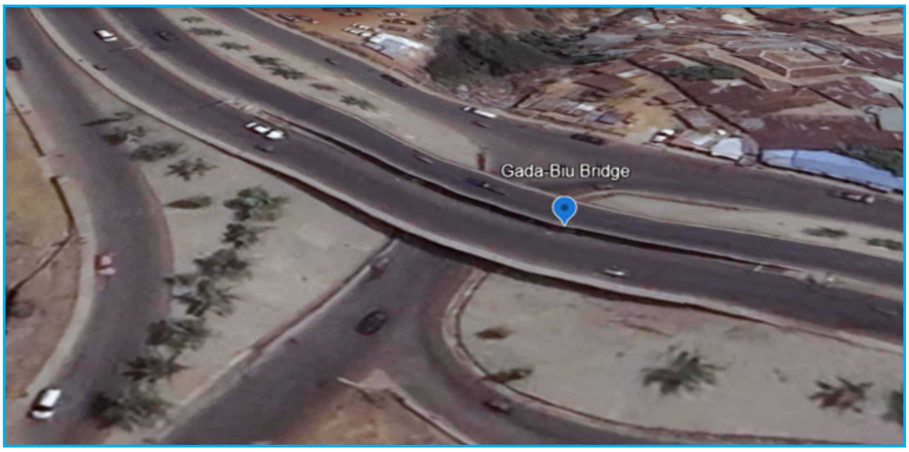

Figure 4. 3D view of Gada-Biu bridge along Kwakonka-Tudun wada road. source: Google Earth

TASK DEFINITION

This project aims to utilize unmanned aerial systems (UAS) for damage inspection and condition assessment of bridge infrastructure. The primary tasks include capturing images using a drone, processing the data to create a digital twin of the bridge in form a 3D.

Mission preparation and criteria assessment

Prior to conducting UAS flights, comprehensive mission planning is carried out. This involves selecting suitable UAS equipment, defining flight parameters, and adhering to safety regulations. Relevant literatures were reviewed to assess the performance of the UAS-based damage detection and condition assessment.

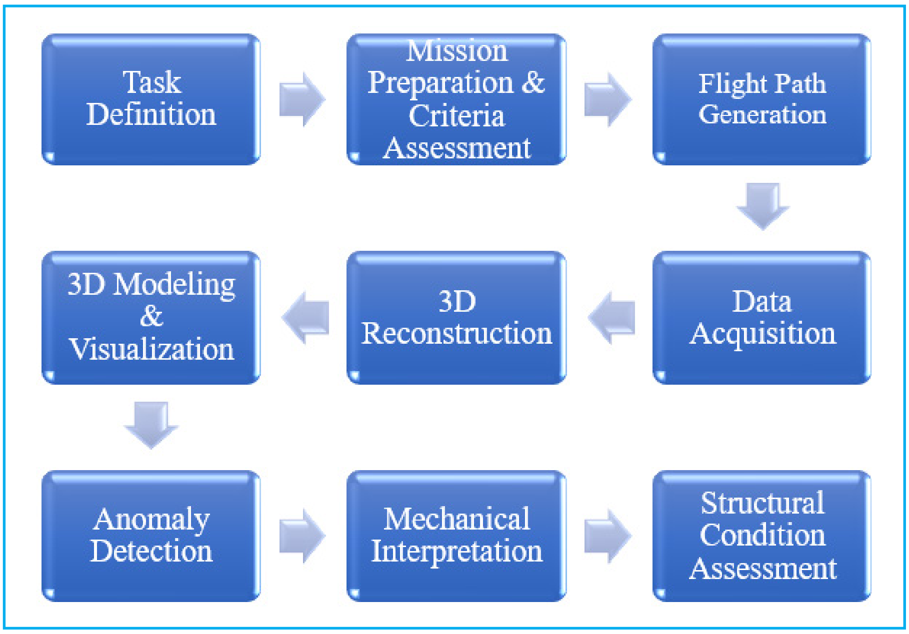

Figure 5. 3A detailed methodology for UAV-based damage inspection & condition assessment

Flight path generation

DJI Fly software is utilized to control and manually generate flight paths for the UAS. Flight paths were designed to cover the entire bridge infrastructure, ensuring proper overlap between images to facilitate accurate 3D reconstruction. The mapping paths for the sub-structure and super-structure are as shown in Figure 6 and Figures 7 respectively. These are a straight-line trajectories and flights routes on the bridge at different heights and camera inclinations.

Data acquisition

DJI Mavic Air 2 drone is deployed for digital image capture of the bridge following the planned flight paths. The data was synchronized with geolocation information to enable precise 3D reconstruction.

3D-reconstruction

Advanced photogrammetry techniques were applied to process the collected imagery and generate a 3D point cloud of the bridge. DJI Terra software tools specialized in 3D reconstruction was used to create 3D models of the bridge. The workflow on the 3D reconstruction is further explained on Figure 8.

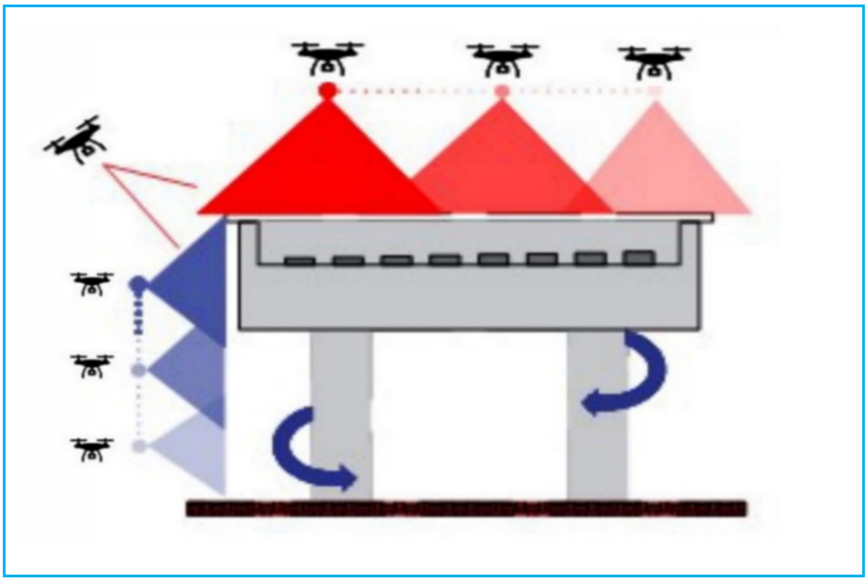

Figure 6. Mapping path for sub-structure

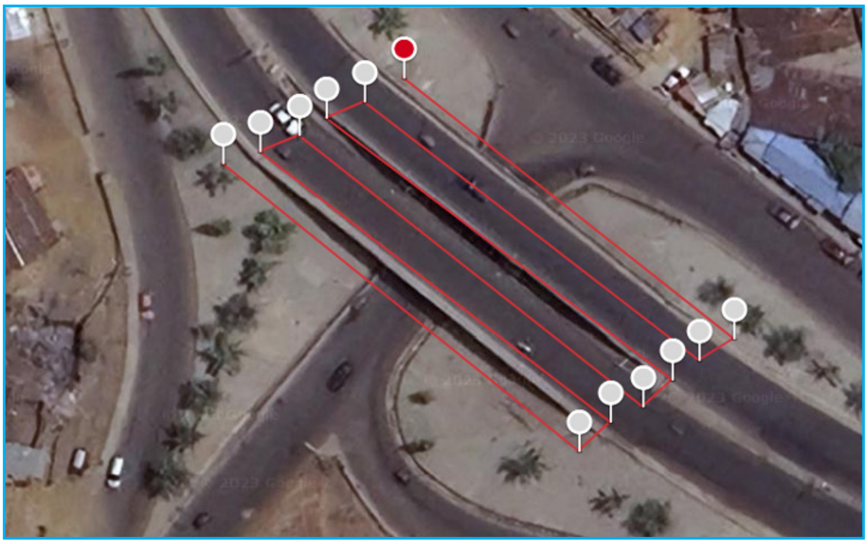

Figure 7. Mapping path for super-structure

Anomaly detection

The 3D reconstructed model undergoes a comprehensive computerized visualization to identify and highlight potential structural damages or anomalies. The digital twin of the bridge is inspected for the presence of damages. The 3D point cloud data, coupled with the high-resolution UAV-captured images, plays a pivotal role in this inspection process. Additional inspection of the bridge was carried out using videos recorded by the UAV to validate the anomalies detected from the 3D model.

Mechanical interpretation

The detected anomalies were interpreted based on engineering expertise and analysis. Their severity and potential implications will be assessed. As such a holistic understanding of the bridge's health was attained.

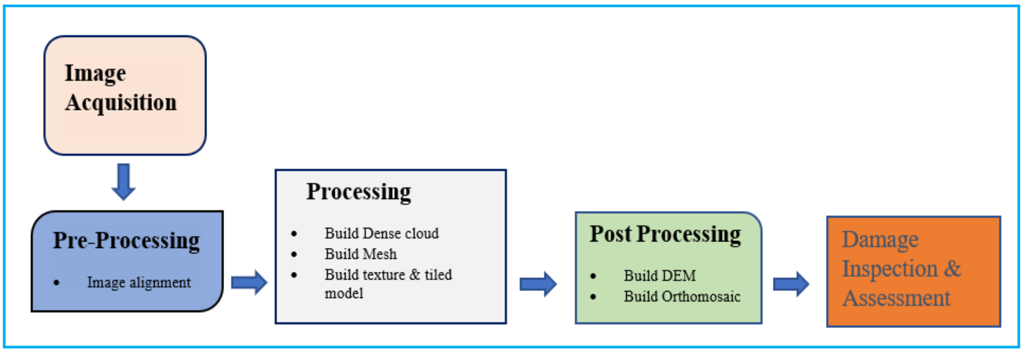

Figure 8. Workflow for 3D reconstruction

Structural condition assessment

By piercing together information from the mechanical interpretation and anomaly detection, a holistic understanding of the bridge's condition was emerged. As a result, the overall structural health of the bridge was understood.

Results and Discussion

The total of 254 high-resolution images were collected using the drone during the data capture phase of the study with a minimum of 70% overlap between adjacent images. The 3D model was successfully reconstructed and included a high-quality texture which allows for visualization of damages in the 3D digital twin of the bridge. Some of the re-constructed digital twin of the bridge as shown in Figures 9-10.

Figure 9. 3D model of the bridge generated by DJI Terra

Figure 9 and Figure 10 shows the 3D model which was used to visualize the bridge for the presence of damages like cracks, corrosion, delamination, concrete deterioration, etc. The identified damages include rebar exposure, algal delamination and deterioration caused by water as shown in Figure 11, Figure 12 and Figure 13 respectively.

The bridge was virtually inspected to detect damages such as cracks, corrosion, delamination, concrete deterioration, etc. The identified damages include rebar exposure, algal delamination and deterioration caused by water as shown in Figure 11, Figure 12 and Figure 13 respectively.

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(a) (b)

Figure 10. 3D model generated by DJI Terra

(a) (b)

Figure 11. Identified damage due to rebar exposure: 3D reconstructed model (left) and the real image (right)

This part is located at the bridge's superstructure, particularly on the precast parapet wall. The rebar exposure specifically indicates the visibility of the reinforcement bars (rebars) within the parapet wall. The detected rebar exposure poses a potential threat to the bridge's structural integrity, particularly in load-bearing components. This damage was identified on the 3D model in 3 different locations at the superstructure. The damage is clearly visible on the 3D reconstructed model as seen in Fig.11 (a) which shows that the automated 3D reconstructed model by DJI Terra is effective for computerized damage identification. Exposed rebar is susceptible to corrosion, which can lead to a loss of structural capacity and integrity.

(a) (b)

Figure 12. Identified damage due to algae: 3D reconstructed model (left) and the real image (right)

As shown in Figure 12, sections of the bridge's surface exhibited pronounced algae growth, particularly on the pier cap. This greenish discoloration was prevalent on horizontal surfaces and areas with reduced sunlight exposure. This damage was identified on the 3D model in 4 different locations at the substructure and may have a long-term effect on the structural integrity of the bridge. The damage is clearly visible on the 3D reconstructed model as seen in Figure 12 (a) which also shows that the automated 3D reconstructed model by DJI Terra is effective for computerized damage identification. Algae can accelerate the deterioration of concrete by promoting the growth of microorganisms and facilitating the penetration of water into the concrete matrix.

(a) (b)

Figure 13. Identified deterioration caused by water: 3D reconstructed model (left) and the real image (right)

As shown in Figure 13, the 3D model revealed instances of surface deterioration attributable to prolonged water exposure. Noteworthy areas included the underside of the bridge deck and support structures directly in contact with water. Water-induced deterioration, if left unaddressed, may compromise the long-term durability of affected structures. This damage was identified on the 3D model in 18 different locations at the superstructure, particularly on the beam girders and may have a long-term effect on the structural integrity of the bridge. This is as a result of water leakage through potholes on the bridge deck. Water ingress can lead to the corrosion of reinforcing steel, compromising the overall structural stability.

Table 4. Inspected damages

Damage type	Identified in the 3D model	Available in Real Bridge
Cracks	No	Yes
Corrosion	No	No
Delamination	Yes	Yes
Rebar Exposure	Yes	Yes
Spalling	No	No
Water leakage	Yes	Yes

Table 5. Identified damages from the 3D models

Damage type	No. of damages	Location	Effect on structural health
Delamination	18	Beam girders	Reduces bond strength between layers which may compromise the integrity of the bridge structure over time
Rebar Exposure	3	Parapet wall	Heightens the risk of corrosion
Deterioration caused by water	4	Pier cap	Leads to corrosion of steel and causes structural vulnerability of the bridge

The model-based inspection performed satisfactorily; it enables the identification of damages that could have negative impacts towards structural safety. Table 4 shows the inspected damages which are identified in the 3D reconstructed model upon visualization. Table 5 shows the number, location and the structural effect of the identified damages on the model. Figure 14 shows bar chat extent of the identified damages on the 3D model.

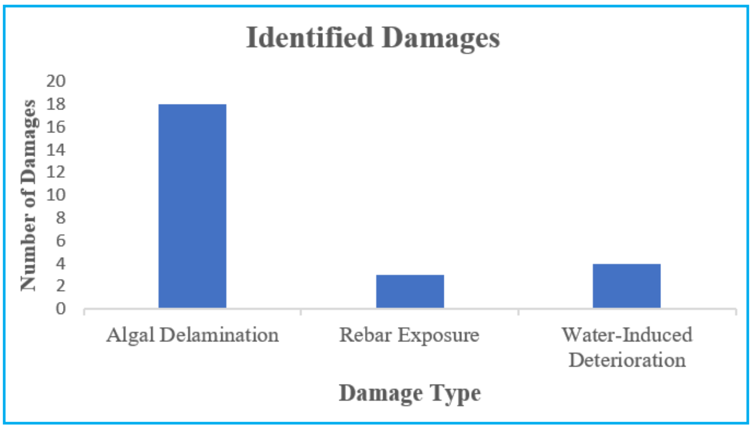

Figure 14. Inspected damages

Conclusion and Limitations

Conclusion

This study utilizes DJI Terra, a low-cost UAV to capture digital images for 3D reconstruction of a 54m-long bridge for damage inspection and condition assessment. The 3D reconstructed model was employed in identifying damages on the bridge with the aim of assessing the ability of the 3D model to correctly identify damages. Using the 3D model, damages such as cracks, delamination, rebar exposure, alga delamination and deterioration caused by water, were correctly identified, and a good comparison was found between the damages on the real bridge and its 3D reconstructed digital twin.

The following achievements have been reached through this study:

1. The 3D model was successfully reconstructed based on digital images captured using a low-cost drone, thereby eliminating the exorbitant of using advanced UAVs.
2. The 3D reconstructed digital twin of the bridge allows for computerized inspection to identify damages such as cracks, corrosion, delamination, concrete deterioration, etc., and provide a permanent record of the bridge's condition, aiding in the assessment of structural health over time.
3. The 3D reconstruction-based assessment showed that 3D reconstruction using low-cost UAV has great potential in its applications in bridge assessment.

Limitations

1. Low-cost UAVs often produce lower-resolution images, which may compromise the accuracy of the 3D model and limit the detection of small-scale damages like micro-cracks.
2. Structural complexity and environmental obstacles can cause occlusions and blind spots, leading to incomplete 3D reconstructions and missed critical damages. A multi-angle imaging approach, combining UAVs with ground-based photography or LiDAR scanning, can improve the data collection process.
3. 3D reconstruction is a post-processing technique that does not provide real-time monitoring, making it unsuitable for continuous damage tracking. Periodic UAV inspections combined with embedded sensor-based monitoring can enable both detailed visual assessment and real-time structural health insights.

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Conflicts of Interest

The authors declare that they have no competing interests.

Author Contributions

Bala Ismail Muhammad: data curation, methodology, software, investigation, visualization, writing-original draft preparation. **Omoniyi Tope Moses:** conceptualization, supervision, writing – reviewing and editing. **Omoebamije Oluwaseun:** data curation, software. **Abba-Gana Mohammed:** validation, writing – reviewing. **Duna Samson:** writing – reviewing.

Data Availability Statement

The dataset that supports the findings of this study is available from the corresponding authors upon request.

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