Integrating BIM and Photogrammetry for Digital Twin Development: A Case Study in Road Infrastructure

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Abstract –

Building Information Modelling (BIM) has wide application in building construction; however, its adoption in road construction remains limited. Although some studies have investigated the integration of BIM and photogrammetry, this integration remains largely an under-explored and overlooked area in specific environment of road infrastructure construction, with significant gaps in research and application. The novelty of this study lies in bridging this research gap by exploring the practical integration of BIM and photogrammetry, leveraging commercial-grade drone technology to develop a BIM-enabled Digital Twin (DT) tailored to road infrastructure construction. In this study, a 3D BIM model of a 500-meter-long road project was developed using Autodesk InfraWorks 360. The modeling process was followed by the acquisition and processing of 816 high-resolution images, captured over four separate drone flights on different dates, using a DJI Mavic 3 Enterprise commercial drone. The photogrammetric data was processed in Agisoft Metashape, yielding a dense point cloud, a Digital Elevation Model (DEM), and ortho-mosaics. These ortho-mosaics were integrated into BIM model to create a DT. The synchronization of multimodal data demonstrated that a BIM-enabled DT powered by photogrammetry not only enhanced visualization but also proved to be a promising tool for reliable and efficient monitoring of road construction progress.

Keywords –

Digital Twin; BIM; Ortho mosaic; Drone; UAV

1 Introduction

The demand for road infrastructure has grown significantly because these initiatives are vital to a nation's competitiveness, economy, health, education, and quality of life [1]. Road projects frequently face challenges such as schedule delays, cost overruns, and inadequate construction monitoring. These issues compromise the projects' capacity to succeed [2]. Road infrastructure projects consistently perform behind project baseline, resulting in an estimated $82.6 billion in annual cost overruns worldwide [3]. To mitigate these issues, efficient monitoring of construction progress is essential. However, conventional manual tracking methods are often inefficient, time-consuming, and susceptible to errors [4, 5]. These traditional methods generally rely on checklists and daily reports, which are open to subjective interpretation and can fail to provide accurate physical measurements of on-site work, keeping progress monitoring largely a 2D process [6].

While Building Information Modelling (BIM) has been widely adopted in vertical construction, its application in road infrastructure remains limited, leading to missed opportunities for efficiency and cost-effectiveness. Global acceptance of BIM as a management approach and digital construction tool has grown, and it is increasingly becoming an important tool in project management [7]. The foundation of a Digital Twin (DT) lies in its digital representation, with BIM serving as the crucial technology to construct this representation. BIM can be integrated with advanced technologies such as laser scanning, photogrammetry, drones, and sensors to improve the accuracy, efficiency, and real-time updating of site information [8].

The most common data collection technologies include robotic total stations, the Global Navigation Satellite System (GNSS) receivers, Light Detection and Ranging (LiDAR) scanners, and aerial photogrammetry etc. However, the scale of most linear transportation projects requires methods that can efficiently survey large areas with sufficient accuracy and resolution [9]. Photogrammetry has emerged as a cost-effective, rapidly deployable data collection technology with numerous applications in different fields [9, 10].

Rapid advancements in drone technology have enabled wider and enhanced utilization of photogrammetry in construction projects. Drones are flying robots that fall under the category of Unmanned Aerial vehicles (UAVs). UAVs have become a popular and recognized technology in recent years because of their outstanding ability and flexibility [11]. They can be operated remotely by people or by software using pre-programmed flight plans [12]. UAVs have a range of applications, including aerial photography, and are utilized across many industries [13].

Using UAVs in combination with photogrammetry offers an efficient solution for digital mapping of projects [14]. By taking overlapping, georeferenced vertical and oblique photos, drone-based image acquisition makes large-scale surveys easier and quicker. These photos can then be utilized to produce precise, dense three-dimensional models. This approach is significantly more cost-effective than LiDAR and often achieves higher spatial resolution. Additionally, the portability of the hardware allows access to a greater variety of sites.

2 Related Work

Photogrammetry techniques can be used to generate a 3D model from data collected from drone pictures, while point clouds from 3D scanning of a construction site can also be used to create 3D models [8]. Then, during different phases of construction, this "drone model" can be compared with the Building Information Model to track and evaluate the status of the project [15]. Ortho-mosaic maps and 3D models produced through photogrammetry enhance visualization, providing clear and detailed visual representations of the site that support more informed decision-making. The shared model brings together engineers, contractors, and owners [16].

For effective progress monitoring, it is essential to integrate and visualize both as-planned and as-built information to gain a comprehensive overview of all construction processes. A visualization technique using BIM and Photogrammetry highlights progress deviations by superimposing an as-planned model onto real-time-lapsed photographs, resulting in a single, comprehensive visual representation [17].

While many studies have investigated the integration of BIM and photogrammetry for construction monitoring, they still have limitations and gaps that warrant further research. A review of 134 previous studies by Castañeda, Sánchez [8] aimed at identifying key complementary technologies to BIM in road projects found that photogrammetry was examined in merely eight (8) studies. This finding underscores that integration of photogrammetry with BIM remains a largely overlooked area in the specific context of road infrastructure projects.

Turkan, Bosche [4] developed a system that integrated spatial data collected from 3D laser scanning with schedule data for construction progress tracking; however, it was limited to vertical construction and it neither extended to linear projects like roads nor incorporated photogrammetry. Vick and Brilakis [9] and Lo, Zhang [5] conducted studies on utilization of aerial photogrammetry for road layer construction progress monitoring, but their studies did not integrate the point cloud data into a BIM model to create a DT, and they did not use a commercial-grade UAV. Puri and Turkan [18] proposed a framework using mobile LiDAR and 4D design models, but their study focused primarily on bridge construction only and lacked photogrammetry.

Jacob-Loyola, Muñoz-La Rivera [19] conducted a study on construction progress tracking by periodically recording physical site conditions using UAVs and generating point clouds through photogrammetry. The data was then integrated with 4D BIM for monitoring purposes. However, a key limitation of the study was its primary focus on vertical construction, limiting its applicability to linear infrastructure projects.

Foregoing in view, this study is aimed at addressing the limitations and gaps in previous research by focusing on the integration of BIM and aerial photogrammetry for road infrastructure using a commercial-level drone and the concept of DT—a novel approach that remains overlooked in existing literature.

3 Proposed Framework

This study aims to investigate the integration of BIM with photogrammetry in the specific context of road infrastructure construction using commercial-grade drone. This framework for BIM integration with road infrastructure is shown in Figure 1 and outlined as under:

- Selection of an under-construction road project, collection of relevant drawings, and development of a 3D BIM model using Autodesk InfraWorks 360.
- Acquisition of 816 images of the project through photogrammetry using DJI Mavic 3 Enterprise, spanned over four flights on different dates.
- Processing photogrammetric data using Agisoft Metashape to obtain high-resolution ortho-mosaic.
- Integration of ortho-mosaic with 3D BIM Model in Autodesk InfraWorks 360 to create a DT.
- Synchronization of data between actual project and DT.

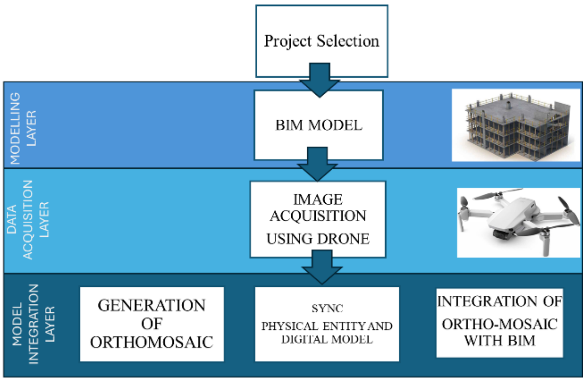

Figure 1. Proposed BIM-Photogrammetry framework for road construction monitoring.

3.1 Data Collection

The DJI Mavic 3 Enterprise was selected for capturing high-resolution images of the construction site due to its affordability, reliability, and capability to cover large areas efficiently. Specifically designed for high-precision surveying and mapping, this drone features a real-time kinematic (RTK) system, which uses satellite navigation to obtain accurate positional data. Other features include: a mechanical shutter, 56× zoom camera, 20MP sensor, and RTK module, all integrated into a compact and mobile platform. Additionally, the camera's ability to capture images at intervals of 0.7 seconds significantly enhances the efficiency of mapping operations, enabling faster data collection [20].

3.1.1 Flight Planning

Flight planning is performed to ensure that manual input is not necessary for acquisition of data, ensure reproducibility of results and limiting the effect of data on the skill of operator. A flight plan outlines the specific route and procedures that the UAV will adhere to during its flight. First, the mission was planned through DJI Remote Control by logging into DJI application. Subsequently, a spacious, obstacle-free launch area was carefully selected. The equipment was meticulously assembled, with all propellers securely fastened. The batteries for both the drone and the remote control were thoroughly inspected to ensure they were fully charged. Once the remote control and the drone were powered on, their connection was verified to confirm proper functionality.

Prior to take-off, the system validated the availability of an adequate number of satellites to ensure a stable and reliable flight. Figure 2 shows a snapshot of flight planning. All necessary permissions required for operation of done were acquired before the conduct of flight and a professional drone pilot was tasked to overview safe operation of the drone.

Figure 2. UAV flight planning for photogrammetry-based monitoring

3.1.2 Image Acquisition

UAV flights were conducted over the study area on four separate dates: 26th August, 6th September, 30th September and 15th October 2024. Each flight was executed with a consistent flying altitude of 60 meters to ensure uniform data collection across all sessions. A total of 816 images (204 images per flight) were captured at a resolution of 1.87cm/pixel, providing high-detail visuals necessary for precise analysis of the project’s development over time.

Figure 3 presents a series of high-resolution images captured over the study area from a 90-degree angle. Each image contained detailed geospatial data reflecting the current state of the site, highlighting key features such as access routes, construction modules, and the terrain's topography. Additionally, these images provided essential georeferencing information, facilitating the integration of data for creating a precise point cloud model.

Figure 3. High Resolution images acquired using UAV

3.2 Image Processing

The process of generating ortho-mosaics from the high-resolution drone images was carried out in multiple steps using Agisoft Metashape, which is a robust photogrammetry tool commonly used for 3D reconstruction from 2D images [21].

4 Case Study

The study area selected for this research is a 500-meter linear stretch of the service road located parallel to the Islamabad Expressway in Islamabad, Pakistan. Figure 4 shows the study area. The site is part of an interchange project at Islamabad Highway. The images were taken on site for further processing and integration with BIM for progress monitoring. The coordinates marking the boundaries of the study area are 33°33'19.01"N, 73°10'0.23"E at one end, and 33°33'3.62"N, 73°10'11.52"E at the other end.

Figure 4. Geographic representation of the 500-meter study area along the Islamabad Expressway.

The process of generating ortho-mosaics from the high-resolution drone images was carried out in multiple steps elaborated as follows.

4.1.1 Data Import

The data processing began by importing the captured images into Metashape, ensuring that all high-resolution images, captured at a consistent altitude with a side overlap ratio of 70% and a frontal overlap ratio of 80%, were prepared for further processing.

4.1.2 Image Alignment

The next step involved image alignment, where Structure-from-Motion (SfM) algorithms were utilized to reconstruct the relative positions of the images based on their overlapping features. These algorithms detect matching key points across multiple images, allowing the software to calculate their spatial relationships and reconstruct the 3D geometry of the scene. This process relies on bundle adjustment, an optimization technique that refines the camera positions and orientations to minimize errors and ensure alignment accuracy [22]. Incorporation of RTK positioning data significantly enhanced this process by providing precise geospatial information. The RTK module embedded in the drone ensured centimetre-level accuracy for the positional data of each image, eliminating the need for a large number of Ground Control Points (GCPs).

4.1.3 Point Cloud Data

After image alignment, a dense point cloud was generated for three-dimensional representation of the scanned area. This process first produced a sparse point cloud, containing fewer points spread across the scene, which was used for initial alignment. Once the alignment was complete, the point cloud was refined into a dense point cloud, containing a higher density of points that more accurately reflected the physical environment. These dense point clouds provided finer details of the site, crucial for accurate modeling and progress monitoring.

The data obtained from the point cloud included essential information about the terrain and site structures, offering a foundation for further steps in the workflow. Following the generation of the point cloud, a Digital Elevation Model (DEM) was created to represent the terrain's surface without any objects, such as buildings or vegetation, and was used to understand the topographical aspects of the study area.

4.2 Development of Ortho-Mosaics

Finally, the ortho-mosaics were created from the images. These high-resolution, geometrically corrected images provided a comprehensive view of the entire site, ensuring that every pixel was aligned with its true ground position. Figure 5 shows the DEM and corresponding ortho-mosaics for two out of the four data collection intervals.

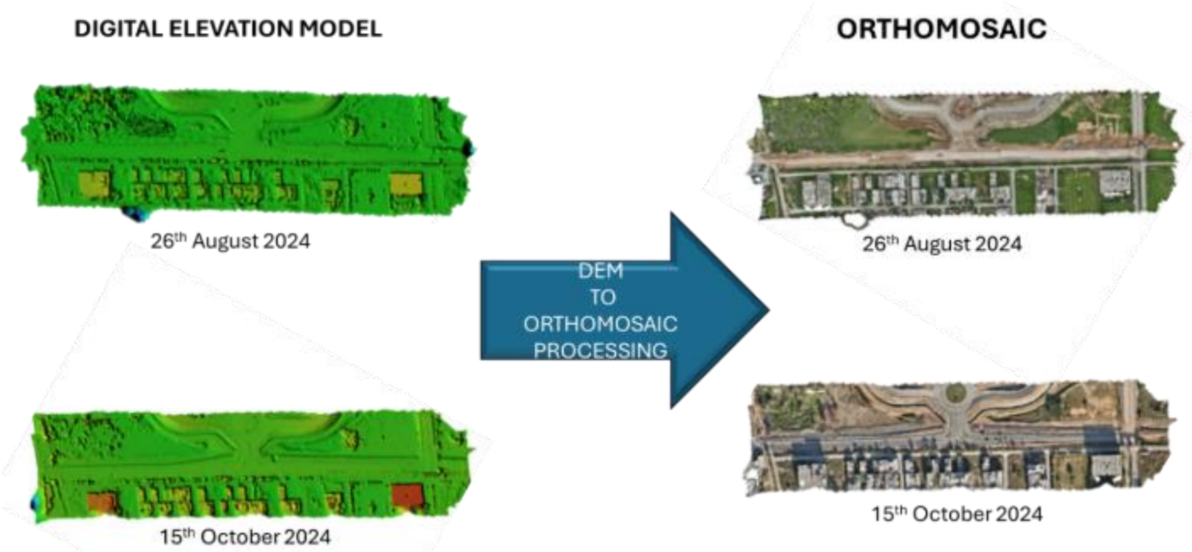

Figure 5. DEM and Ortho mosaic of data acquired on 26th August and 15th October

4.3 Integration with BIM

The processed ortho-mosaic data was exported in formats compatible with various BIM software applications to ensure seamless integration with project workflows. One of the primary formats used for export was TIFF (.tiff), which is widely supported across many Geographic Information System (GIS) and BIM platforms due to its high-resolution capabilities and geospatial referencing attributes. This export process enabled the ortho-mosaic to be incorporated into BIM environments for enhanced visualization, design, and analysis. By exporting the data in such formats, it allowed precise geospatial data into BIM models, improving the accuracy of site planning, progress monitoring, and decision-making throughout the project's lifecycle.

The processed photogrammetry data was integrated into the 3D BIM model using Autodesk InfraWorks 360. This process involved overlaying the high-resolution ortho-mosaic onto the 3D BIM model of the road, enabling precise mapping of the current site conditions. The ortho-mosaic was imported and georeferenced within the InfraWorks environment, creating a comprehensive DTof the construction site.

The creation of layers in the BIM model enabled effective monitoring of the progress of the project. The road layers, such as the base course, sub-base course, and surface course were carefully mapped and tracked to assess their completion status. This integration facilitated a visual comparison of the planned design with the actual progress on-site, enabling accurate and reliable progress monitoring. The combination of photogrammetry data and the BIM model enhanced and ensured the alignment between the planned design and evolving site conditions.

4.3.1 Data Synchronization

Regular updates to the BIM model were conducted by integrating the latest photogrammetry data after each drone flight. This was pivotal in enabling the DT of the project, ensuring that the BIM model accurately reflected the current state of the construction site. By continually synchronizing the model with multimodal real-time data, it provided an up-to-date visualization that enabled effective monitoring of progress and site conditions. Table 1 depicts construction progress on the dates of data acquisition, and Figure 6 shows the digital representation.

Table 1. Construction progress of pavement computed through Digital Twin

Date	Layer	Area (m^2)	Volume (m^3)
26th August 2024	Sub-base	2,461	492
	Base	6,171	1,234
6th September 2024	Base	8,632	1,726
30th September 2024	Base	3,953	791
	Surface	4,726	945
15th October 2024	Surface	8,632	1,726

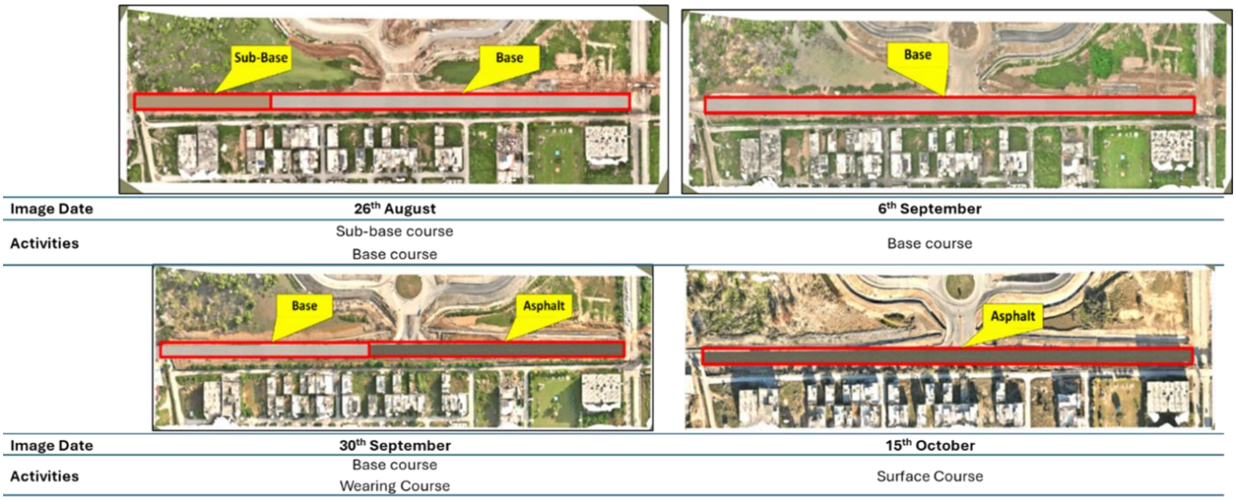

Figure 6. Digital twin of the project site on the mentioned dates along with the status of site.

The end result is represented in Figure 7 where the DT is rendered in 3D along with its environment.

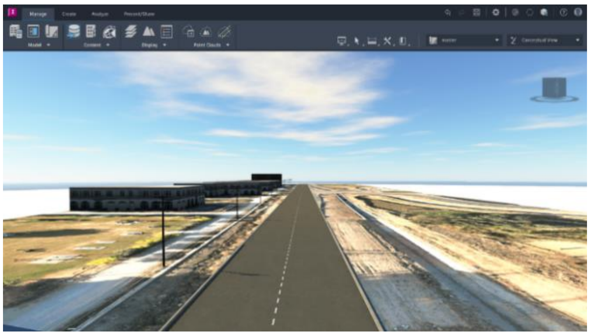

Figure 7. 3D visualization of a preliminary digital twin platform

5 Discussion

Although numerous studies have explored the integration of BIM and photogrammetry, its application in road infrastructure construction remains largely under-explored and overlooked. This study addresses the mentioned research gap by integrating BIM and photogrammetry in the specific environment of road infrastructure and showing practical application in progress monitoring using existing technologies.

The development of 3D BIM model was based on construction drawings of the project. Model development process was followed by the collection of data through aerial photogrammetry technology using a commercial grade drone. Utilization of such RTK-equipped drone ensured precise geospatial information and high resolution of the collected data i.e. 1.87cm/pixel. Moreover, such drones are capable of being used on large-scale projects such as roads which are generally spread over numerous kilometers. The photogrammetric data was processed yielding a dense point cloud and DEM. The data obtained from the point cloud included essential information about project terrain offering a solid foundation for further steps in the workflow.

The DEM was processed to subsequently generate ortho-mosaics. A BIM-enabled Digital Twin (DT) was then developed by integrating high-resolution ortho-mosaic images into Autodesk InfraWorks at regular intervals. The DT was used for successfully computing and monitoring construction progress of road layers.

Previous studies, such as Turkan, Bosche [4] have used photogrammetry and UAV for progress measurement, However, most research has focused on vertical infrastructure, lacking BIM and DT integration. This study leveraged ortho-mosaics to build a reliable and dynamic representation of the project site, adding to its novelty. This study found photogrammetric data collection technology to be cost-effective as well as rapidly deployable. While data interoperability issues were not faced during data collection and processing, such challenges cannot be ruled out if BIM-enabled DT of the road is fed with further data related to scheduling and cost data etc.

6 Conclusion

This study has several notable contributions to the body of knowledge. First, it confirms the extent to which the integration of photogrammetry data and BIM can be successfully implemented in the road construction environment. Additionally, it demonstrates how DTs can be effectively utilized in road construction using existing technological capabilities. Furthermore, it verifies that BIM-enabled DT powered by photogrammetry can not only facilitate effective road visualization but also help in reliable monitoring and measurement of progress across large-scale construction sites efficiently. Finally, it highlights how commercial-grade drones can be efficiently utilized in road construction for applications that extend far beyond basic videography, offering significant practical benefits.

Future research should explore the integration of Artificial Intelligence (AI) with BIM-Photogrammetry in the specific environment of road construction. Future research can also explore how BIM-Photogrammetry integration can be leveraged for addressing challenges related to construction quality of roads.

References

[1] Herrera, R.F., et al., *Cost overrun causative factors in road infrastructure projects: A frequency and importance analysis*, in *Applied Sciences (Switzerland)*. 2020.

[2] Aziz, R.F. and A.A. Abdel-Hakam, *Exploring delay causes of road construction projects in Egypt*, in *Alexandria Engineering Journal*. 2016, Faculty of Engineering, Alexandria University. p. 1515-1539.

[3] Vick, S.M. and I. Brilakis, *A Review of Linear Transportation Construction Progress Monitoring Techniques*, in *16th International Conference on Computing in Civil and Building Engineering, ICCCBE2016*. 2016. p. 1106-1113.

[4] Turkan, Y., et al., *Automated progress tracking using 4D schedule and 3D sensing technologies.* Automation in Construction, 2012. **22**: p. 414-421.

[5] Lo, Y., et al., *Monitoring Road base course construction progress by photogrammetry-based 3D reconstruction.* International Journal of Construction Management, 2023. **23**(12): p. 2087-2101.

[6] Vick, S. and I. Brilakis, *Asphalt Road Layer Detection for Construction Progress Monitoring*. 2017. p. 271-278.

[7] Wang, T. and H.M. Chen, *Integration of building information modeling and project management in construction project life cycle*, in *Automation in Construction*. 2023, Elsevier B.V. p. 104832.

[8] Castañeda, K., et al. *Building Information Modeling Uses and Complementary Technologies in Road Projects: A Systematic Review*. Buildings, 2024. **14**, DOI: 10.3390/buildings14030563.

[9] Vick, S. and I. Brilakis, *Road Design Layer Detection in Point Cloud Data for Construction Progress Monitoring.* Journal of Computing in Civil Engineering, 2018. **32**(5): p. 04018029.

[10] Roosevelt, C.H., et al., *Excavation is destruction digitization: Advances in archaeological practice*, in *Journal of Field Archaeology*. 2015. p. 325-346.

[11] Li, J., et al., *Non-Terrestrial Networks-Enabled Internet of Things: UAV-Centric Architectures, Applications, and Open Issues*. 2022. p. 1-24.

[12] Cavoukian, A., *Scopus - Document details - Privacy and Drones: Unmanned Aerial Vehicles | Signed in*, in *Information & Privacy, Ontario Canada*. 2012.

[13] Fina, L., et al., *Entropy-Based Distributed Behavior Modeling for Multi-Agent UAVs*, in *Drones*. 2022. p. 1-19.

[14] Zidek, K., et al., *Digital twin of experimental workplace for quality control with cloud platform support*, in *EAI/Springer Innovations in Communication and Computing*. 2020. p. 135-145.

[15] Bhise, G.S., *Construction Monitoring and Reporting using Drones and Unmanned Vehicles (UAV'S)*, in *International Journal for Research in Applied Science and Engineering Technology*. 2024. p. 5872-5884.

[16] Kiriiak, N., *Development and implementation of technical decision for digital support of construction using photogrammetry methods*, in *Nuclear Engineering and Design*. 2021, Elsevier B.V. p. 111366.

[17] Golparvar-Fard, M., et al., *Visualization of Construction Progress Monitoring with 4D Simulation Model Overlaid on Time-Lapsed Photographs*, in *Journal of Computing in Civil Engineering*. 2009.

[18] Puri, N. and Y. Turkan, *Bridge construction progress monitoring using lidar and 4D design models.* Automation in Construction, 2020. **109**: p. 102961.

[19] Jacob-Loyola, N., et al. *Unmanned Aerial Vehicles (UAVs) for Physical Progress Monitoring of Construction*. Sensors, 2021. **21**, DOI: 10.3390/s21124227.

[20] Nwaogu, J.M., et al., *Application of drones in the architecture, engineering, and construction (AEC) industry*, in *Automation in Construction*. 2023, Elsevier B.V. p. 104827.

[21] Bori, M.M. and Z.E. Hussein, *Integration the low cost camera images with the Google earth dataset to create a 3D model*, in *Civil Engineering Journal (Iran)*. 2020. p. 446-458.

[22] Murtiyoso, A., et al., *Open source and independent methods for bundle adjustment assessment in close-range UAV photogrammetry*, in *Drones*. 2018. p. 1-18.