Enhancing Urban Building Modeling Accuracy with Drone Imagery and Ground Control Points Using SFM/ MVS Techniques

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Abstract

The use of unmanned aerial vehicles (UAVs) for aerial photography has become increasingly popular in various fields, including engineering, urban planning, environmental impact studies, and monitoring of transportation lines, power supplies, and other military applications. One of the main challenges in using drone imagery to model urban buildings is achieving high accuracy in generating 3D models. This paper focuses on improving the accuracy of urban building modelling using drone imagery, structure from motion, and multi-view stereo techniques used in computer vision, augmented virtual reality, geo-science, photography, and aerial photography to create 3D models from pairs of images. The study uses a UAV with a DJI Mavic 2 Pro drone 4K sophisticated camera for up to 31 minutes of flight time. Data collection time at different angles and specific heights while incorporating ground control points to enhance the accuracy of the generated point clouds. A specific location inside Al-Nahrain University was chosen as a fieldwork model, where the images captured by the drone were processed using Agisoft Metashape Pro software to create detailed 3D models for the buildings depending on the Structure form Motion (SfM) technique. The results demonstrate the efficient integration of Ground Control Points (GCP) combined with advanced processing techniques that enhance the model accuracy, achieving highly accurate GCP demonstrating error margins as low as 0.1% based on drone-derived data for urban buildings.

Keywords- 3D Building Models, UAV Image, Multi-view Stereo (MVS), Point Cloud Analysis, Texture Mapping.

I. INTRODUCTION

University and technology are two sides of the same coin, where universities greatly benefit from advancements in the field of aerial imagery and 3D modeling. These advancements have revolutionised the academic methods for studying and documenting educational sites, allowing for more accurate and comprehensive analysis, leading to updating, upgrading, and enhancing technology in this field [1,2]. Traditional fieldwork was the primary method used to study and document educational sites. However, these methods were time-consuming and often resulted in inaccurate, incomplete, or subjective data [3]. Several studies have focused on enhancing the accuracy of collecting and analysing such data; hence, drones and automated or semi-automated 3D modelling have greatly improved the process and analysis of these sites [4,5].

Drones, equipped with high-resolution cameras, can capture large areas of detailed imagery in a significantly shorter time to complete them in an automated or semi-automated manner or through traditional fieldwork [6,7]. This imagery is processed via dedicated software to create accurate 3D models of the analysed sites. Remote sensing and geospatial analysis are important fields in studying the earth's surface, which may affect the overall site model due to the earth's curvature [8]. Not only do 3D models save time, money, and effort, but they also provide a huge amount of data that was previously difficult to obtain [9]. Academics can now study sites from a new perspective, uncovering details and patterns that may not be apparent from the ground. Additionally, the digital nature of such models allows easy sharing and collaboration among researchers, further advancing the analysis of these sites [10].

One of the key advantages of such modelling is the ability to create highly accurate and detailed representations of educational sites such as universities, colleges, classrooms, and labs. This modeling also allows studying and analysing these sites in great detail without the need for physical presence using drones and 3D modelling, which opened new horizons for enhancing spatial analysis and providing valuable insights into the layout, organisation, and evolution of these sites [11]. Furthermore, automated modelling has the potential to reveal previously invisible strong and weak point features in combination with various sensors and data-processing workflows. 3D models of urban structures can have significant implications for various applications. By leveraging these advanced technologies, researchers and practitioners can obtain more precise and reliable outcomes, which depend on the potential of integrating drone imagery, GCPs, SfM, and MVS techniques, thereby enhancing the accuracy of urban building modelling [12,13].

. The advancement of urban building modelling techniques is the most important finding in this research, which can facilitate better decision-making in urban development projects, service-providing centres, disaster response, and cultural heritage preservation [14]. With the development of more advanced drones and imaging technologies, the quality and resolution of aerial imagery will continue to improve, allowing for even more detailed and accurate 3D models [15]. Al-Nahrain University sites constitute an integral part of our educational site in Baghdad, with numerous colleges and other sites that provide services reflecting the evolution of science diversity in the region. Employing 3D modelling techniques to preserve and explore this rich site is an extraordinary goal [16]. Integrating artificial intelligence and machine learning algorithms with automated modelling processes holds excellent potential for further streamlining data processing and analysis [17]. These advancements will enable quickly and efficiently identifying and classifying site features within the 3D models, leading to a deeper site understanding. The role of software and tools tailored specifically for such applications will further enhance the capabilities of automated modelling, making it an indispensable part of scientific research and documentation.

II. RELATED WORK

Many previous studies are related to this field due to the importance of such a subject, especially for the last two decades, when modern cities have witnessed huge updates, upgrades, and fast growth. Drescek et al. (2020) presented a holistic workflow for 3D building modelling in semi-urban areas, highlighting the benefits of using spatial ETL solutions with higher resource upgrades for achieving more efficient serving schemes [18].

Backes et al. (2020) explored integrating high-resolution space-borne and drone-based imagery for generating high-accuracy digital elevation models, showcasing the potential of combining heterogeneous data sources for improved DEMs. In a novel approach[19].

Kippers et al., 2021 proposed an approach that integrates external and internal data sources, such as CityGML/ JSON and 2D-floor plan images, for reconstructing 3D city models using deep learning methods which address the modelling of the historical city to refine and enhance the method for building 3D models using drone images which allows gaining a better understanding of the design of structures and the cultural context of historical cities, in particular, to improve the accuracy and quality of the resulting models to meet the needs of historical research and cultural heritage preservation [20].

The researcher Deliry, S.I. Avdan et al. (2021), highlights the growing interest in high-resolution topographic surveying using UAV and SfM-MVS technologies, focusing on improving the results' accuracy and ensuring their suitability for practical use. The author wondered whether the new method had sufficient accuracy for surveying and mapping applications as an alternative to traditional methods. The study addressed accuracy assessment and validation of products, emphasising the importance of quantitative studies in this context; in addition, the study synthesised and analysed previous studies on the accuracy of topographic models derived from UAS-SfM-MVS, reflecting the current and potential accuracy and limitations of this technology. It represents an essential direction toward a deeper understanding of these tools' capabilities in providing accurate and reliable data for surveying and mapping applications [21].

Pepe, M., Fregonese, L., et al. (2022) use the SfM and MVS in building 3D models of historical structures, according to the research conducted by Beebe et al. In the past, large images collected by atmospheric sensors had limited use in this method due to calculation problems and weak overlaps. With nine years of scaling up digital computing and live geo-routing, cities created using these images have been certified in the old city of Porto [22].

Liu X et al. (2022) prove with no question that the accuracy of direct identification was acceptable and that increasing the number of basic control points and their equal distribution leads to improved accuracy. Emphasises the importance of having a ground control point close to the centre of the field to improve the accuracy and reliability of the direct positioning method [23].

Wang et al. (2022) use aerial photography at oblique angles taken by drones to efficiently and cost-effectively reconstruct 3D models of landscapes. The performance of different types of drones was evaluated in this context, and the accuracy results varied between the different aircraft, as the results showed that the M300RTK drone was the best in accuracy among the aircraft studied. The study also showed that the reconstruction accuracy of the 3D models was not related to the flight altitude but rather depended mainly on the camera accuracy and the distribution of control points on the ground [24].

Q. Li, H. Huang, et al. (2023) use drones for aerial photography in smart cities. Improving aircraft trajectories has increased the accuracy of 3D models, especially in urban environments. The study shows that this solution can effectively improve and modernise cities, considering city scalability is always available [25].

Szypuła, B. et al. (2024) stated in their research that unmanned aerial vehicles (UAVs) have been increasingly used in terrain imaging for environmental research projects and other activities. Several variables, such as the type of equipment, the seen-site graphing, and the weather and terrain conditions, affect the quality of the altitude models derived from these aircraft. Therefore, attention was paid to improving accuracy using additional measurements by GNSS-RTK, which estimates the accuracy of the models in both directions: elevation and horizontal. Mathematical accuracy of the UAV models ranged between 2.7-2.8 meters (MAE) and 3.1 to 3.3 meters (RMSE) for height, and about 2.1 meters for horizontal accuracy was indicated. [26].

III. Methodology

With technological advancements and the growing demand for accurate and detailed 3D city models, an automated process is necessary to generate these models. One such approach is the utilisation of drones and photo-manometry equipment and techniques, which have shown significant potential in capturing high-resolution images and detailed information about urban areas. Drones equipped with cameras can capture multiple images of an urban area from various angles and positions.

1. **Study Design**

2. Creating a 3D model of Al-Nahrain University comprises two main stages: the fieldwork stage (collecting site images) and the office work stage (pre-processing the images using software to create a 3D model).

2. Data Collection

During fieldwork, aerial images of the university site are captured using the UAV's camera. The UAV captures 380 high-resolution images of 3648 x 5472 pixels with a total flight time of over 27 minutes, flying over the site from various angles and positions. The primary goal of this stage is to gather visual data for the subsequent modelling process.

The DJI Mavic 2 Pro UAV from DJI Innovations was utilised to create the 3D model of the site area. The DJI Mavic 2 Pro is an advanced drone offering impressive aerial photography capabilities, including an effective range of up to 8 km, a maximum flight time of 31 minutes, a 4K adjustable camera, a large 1-inch CMOS sensor, GPS, advanced obstacle sensing in four directions, an automatic return-to-home feature, and a lightweight design of approximately 907g as shown in Figure 1.

Figure 1. DJI Mavic 2 Pro UAV and the camera onboard

3. Ground Control Points (GCPs)

Foam-made, brightly colored markers were distributed as GCPs used in aerial monitoring operations and the creation of 3D models and photogrammetric maps. GCPs offer several benefits, including improving model accuracy, controlling deviations, adjusting geographical parameters, and comparing with ground data, as shown in Figure 2.

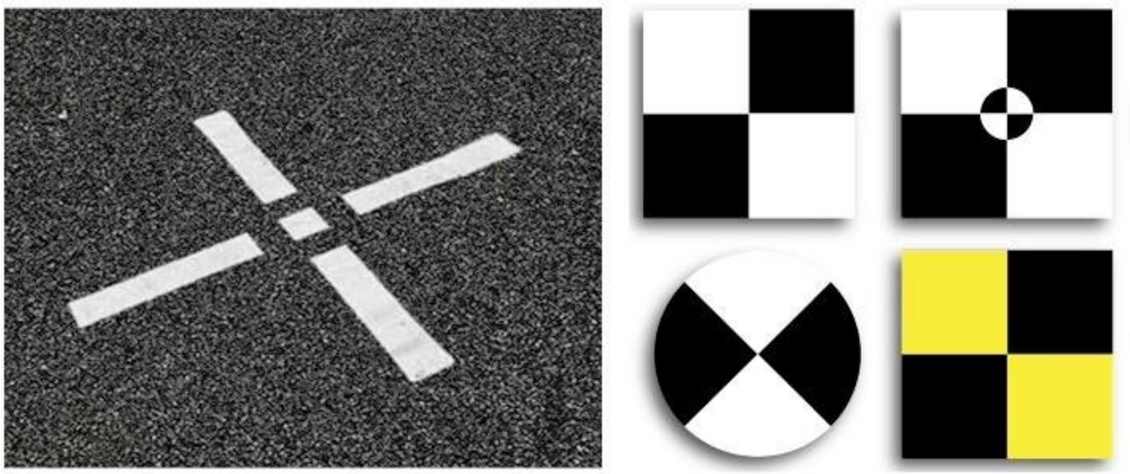


Figure 2. Different shapes of GCP

4. Flight Plan

Once the UAV is deployed to capture images of the university area, a flight plan must be prepared to set the flying site initially by marking the start and finish points of the dedicated area and specifying a certain slope degree for capturing images (90°, 75°, and 45° in this site). After completing the fieldwork, the collected images are transferred to the office for pre-processing to create the 3D-site model.

5. Image Processing

Images were captured as follows: 218 pictures at 90° flying for 14 minutes, 86 pictures at 75° flying for 7 minutes, and 76 pictures at 45° flying for a little over 6 minutes to complete the necessary image shapes and positions to ensure the completion of the 3D shape. After capturing the images, photo-grammetry software pre-processes the images to exclude those that do not meet system requirements such as clarity, resolution, capturing features, accuracy, or position.

6. 3D Model Generation

Processing the images to create a 3D model involves identifying common points in multiple images, triangulating their positions, extracting the building area by utilising the point cloud from which ground points have been eliminated, and reconstructing the 3D geometry of the scene.

7. Structure from Motion (SfM) Technique

The office work stage begins with Agisoft Metashape Professional software to process the images and create a 3D model using the SfM. SfM is a photogrammetric range imaging technique for estimating three-dimensional structures from two-dimensional image sequences that may be coupled with local motion signals. SfM can reconstruct 3D structures by finding matching points in multiple images taken from different angles and calculating their positions in 3D space through triangulation.

8. Multi-View Stereo (MVS)

Multi-View Stereo (MVS) is a technique that reconstructs detailed 3D models from multiple images from different viewpoints. It works by finding correspondences between images to build a dense 3D representation. MVS complements SfM by enhancing the detail and accuracy of the 3D models.

9. Scale-Invariant Feature Transform (SIFT)

Scale-Invariant Feature Transform (SIFT) is an algorithm that detects and describes local image features. It is widely used in image matching and object recognition tasks due to its robustness to scale, rotation, and illumination changes. SIFT is essential for identifying critical points in images that can be matched across different viewpoints in SfM and MVS processes.

10. Random Sample Consensus (RANSAC)

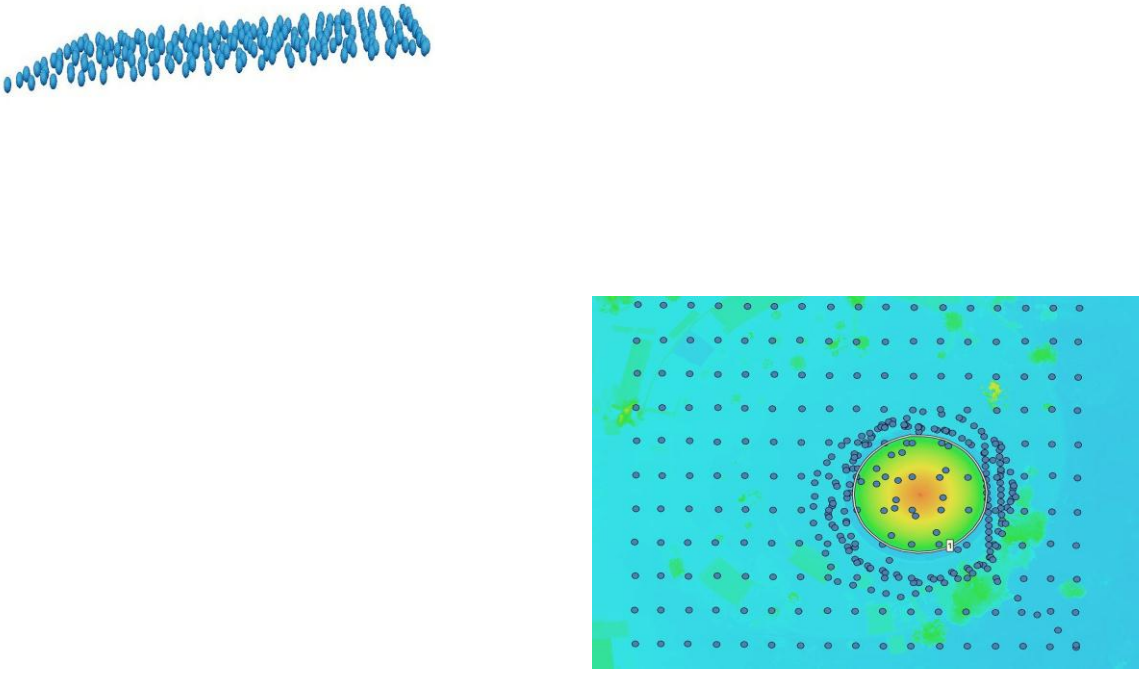
RANSAC is an iterative method used to estimate the parameters of a mathematical model from a set of observed data that contains outliers. In the context of 3D modelling, RANSAC separates inliers (data points that fit a model well) from outliers, thus ensuring accurate geometric reconstruction and simplifying region representation in the 3D model.

These techniques collectively enable the automated generation of accurate and detailed 3D models from photographic data, providing valuable tools for urban planning, development, and other applications. The textured and detailed 3D model can be further analysed and utilised for various applications such as urban development planning, infrastructure assessment, and virtual reality simulations. By leveraging drones and photogrammetry techniques, this automated workflow saves time and resources and generates highly accurate and up-to-date 3D models of urban areas. As advancements in drone technology continue to progress, the potential for automated 3D model generation in urban areas will expand and inspire new visions for data-driven decision-making and visualisation in urban environments.

Utilising drones for automated 3D model generation revolutionises urban planning and development, where detailed and accurate 3D city model production through this process provides invaluable insights to urban planners, architects, and policymakers. In addition, these models have significant applications in environmental impact assessment and disaster management.

IV. RESULTS AND DISCUSSION

It's obvious from the captured pictures that the first crucial step is the image pre-processing to prepare the site point cloud where all the GPS of each picture is installed all over the site, as shown in Figure 3. The pre-processing ensures the best cloud site quality by discarding the inaccurate image position or, inaccurate image properties or inaccurate image capturing technique. In the mosque case out of 382 images where taken, only 8 were discarded, which means that the discard rate is about 2.1%, and this leads to the image capturing process being significant.



a:- the site point cloud side view

b:- the site point cloud top view

c:- the site 2-D cloud view

d:- the site 3-D cloud view

Figure 3. The site point cloud setting for creating the 3D-Model for the final image of the site

The creation process of the 3-D model using the Agisoft Metashape Professional software uses the following: -

1. SfM (Structure from Motion) & MVS (Multi-View Stereo).
2. RANdom SAmple Consensus (RANSAC) & Scale-Invariant Feature Transform (SIFT).
3. Ground Control Points (GCPs).

They depend on the calibration coefficients of the photographing, visualising, de-noising, and sensing processes, where these coefficients are important for distortion removal and updating the lens and sensor properties. These coefficients are:-

F :- Represents the (Focal Length), which is the magnification factor representing the real distance from the lens to the capturing point that compensates for the distortions due to that distance.

Cx:- Represents the (X-Coordinate of the Control point), which is the interception adjustment of the visual point and processes with the x-axis of the lens.

Cy:- Represents the (Y-Coordinate of the Control point), which is the interception adjustment of the visual point and processes with the y-axis of the lens.

K1:- Represents the (Radial Coarse Distortion Coefficient) which is the compensation for the radial distortion of the captured body on the image edges

K2:- Represents the (Radial fine Distortion Coefficient), which compensates for the radial distortion of the captured image in detail.

K3:- Represents the (Distortion Correction Model coefficient) which is the compensation for the curvature deformities that are particularly expected to correct lenses in optical camera photography and other optical lenses to clarify or modify these radiographic distortions.

P1 & P2:- Represents the (Tangential Distortion Coefficients), which are the compensation for the image distortion coefficients; hence, they are essential in the correcting the deformed images.

By applying the university mosque as a case study, the calibration coefficients are normalised to cover the range from (-1) to (1); this means if the correlation coefficient between any two calibration coefficients is (1), then the two values are positive relationship while (-1) means full reverse relationship, which leads that Zero correlation coefficient means no relationships between the calibration coefficients (Singular). Table 1 illustrates the correlation matrix for the images captured using SfM with no GCP. The software applies MVS and RANSAC to distinguish between the ground level and the building's roves and curvatures.

Type	**218**	**Resolution**	**Focal Length**	**Pixel Size**
Frame	**Images**	**4000 x 3000**	**4.74 mm**	**1.58 x 1.58 µm**

TABLE 1. CORRELATION COEFFICIENTS AND CORRELATION MATRIX FOR THE MOSQUE IMAGES

	Value	**Error**	**F**	**Cx**	**Cy**	**K1**	**K2**	**K3**	**P1**	P2
F	**4346.7**	0.18	1.00	-0.02	-0.74	-0.11	0.12	-0.11	0.07	-0.33
Cx	**46.2677-**	0.11		1.00	-0.01	0.01	-0.01	0.01	0.81	0.02
Cy	**-22.7269**	0.19			1.00	-0.02	-0.04	0.04	-0.04	0.61
K1	**0.00873231**	8.9E-05				1.00	-0.96	0.91	-0.01	0.01
K2	**0.0179714**	0.00037					1.00	-0.98	0.00	-0.05
K3	**-0.021501**	0.00047						1.00	0.00	0.04
P1	**-0.00260388**	8.5E-06							1.00	0.02
P2	**-0.000182752**	9.9E-06								1.00

GCP creates new reference points for the drone while capturing the necessary images, raising the system accuracy and reducing overall system errors and deviation. The GCP increases the correlation coefficient relationship and accuracy by dedicating reference points while creating the 3-D model, which also increases the rate of distinguishing between the building ages and curvatures using MVS and RANSAC algorithms. Figure 4. represents the GCP points sat on the mosque site, while Table 2 states the error reduction and correlation coefficients increment while using the GCP.

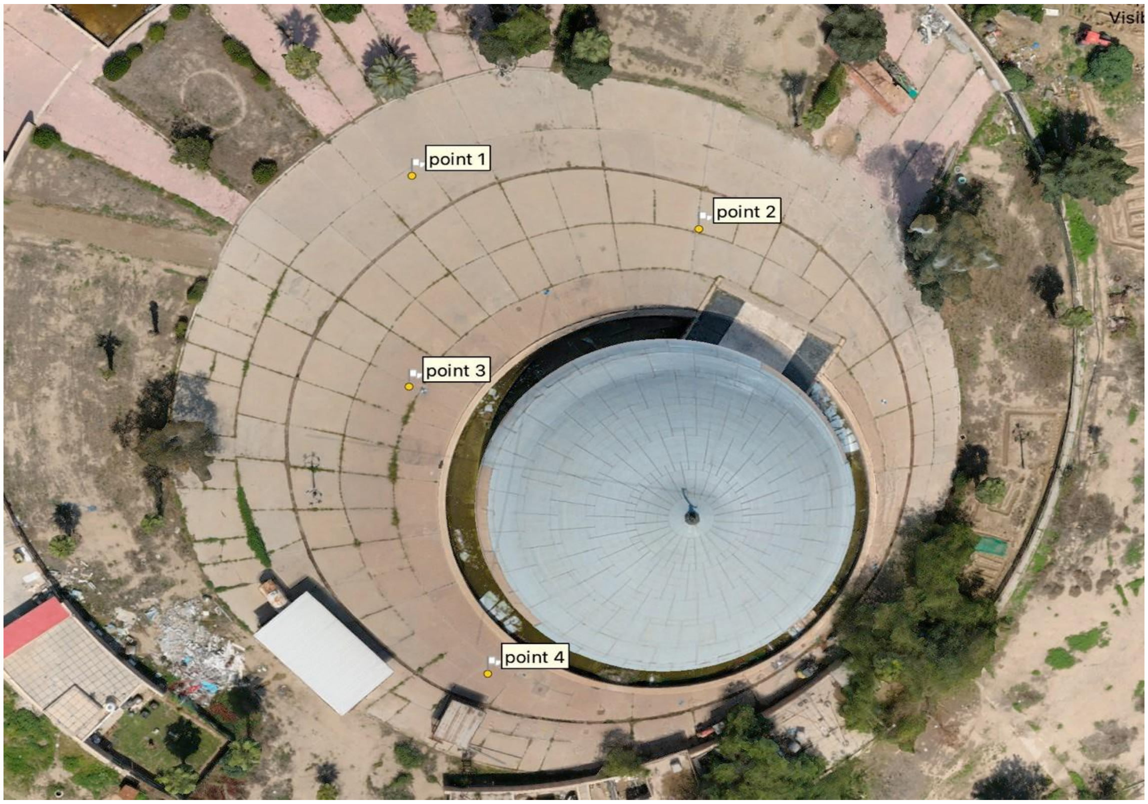
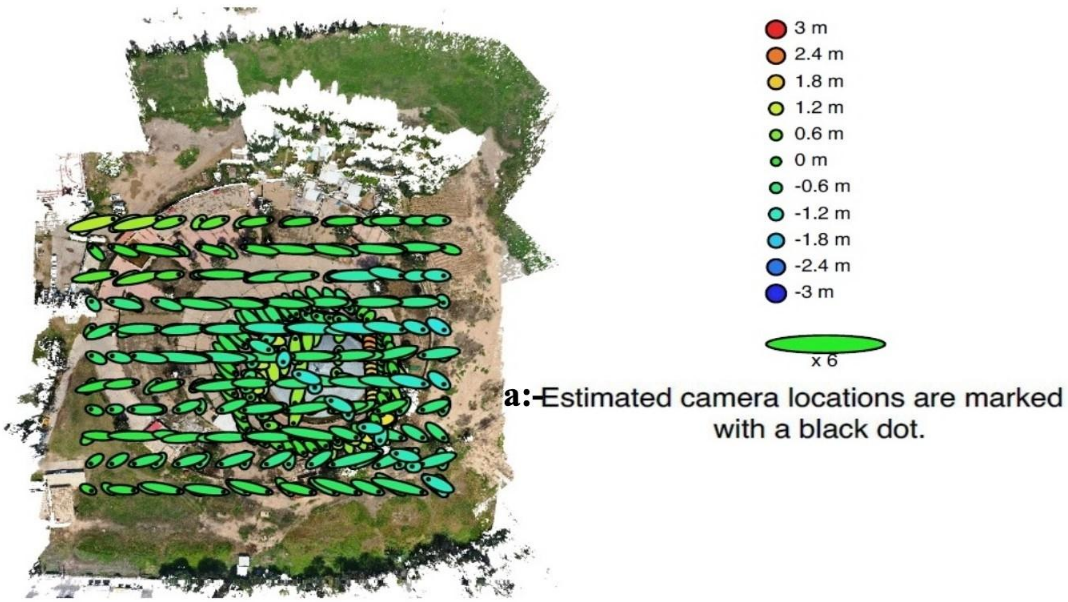


Figure 4. GCP points appearances and positions on the site

Type		**Focal Length**	**Resolution**	**Pixel Size**
Frame	**218 images**	**10.26 mm**	**5472 x 3648**	**2.41 x 2.41 µm**

TABLE 2. CORRELATION COEFFICIENTS AND CORRELATION MATRIX FOR THE MOSQUE IMAGES USING GCP POINTS

	Value	Error	F	Cx	Cy	K1	K2	K3	P1	P2
F	**2962.53**	0.15	1.00	-0.19	-0.01	0.20	-0.23	0.33	-0.06	0.01
Cx	**-12.1479**	0.049		1.00	-0.07	-0.09	0.08	-0.09	0.62	-0.01
Cy	**12.1019**	0.044			1.00	0	0	0	-0.01	0.56
K1	**0.179765**	9.2E-05				1.00	-0.96	0.92	-0.09	0
K2	**-0.533549**	0.00033					1.00	-0.98	0.06	0
K3	**0.511602**	0.00038						1.00	-0.06	0
P1	**-0.000104492**	4.5E-06							1.00	0
P2	**3.32066E-05**	3.6E-06								1.00



An ellipse colour represents a Z error. Ellipse shapes represent X and Y errors

Figure 5. The estimated errors due to camera position with and without using GCP

TABLE 3. THE ESTIMATED ERRORS WITHOUT USING GCP

X error (m)	Y error (m)	Z error (m)	XY error (m)	Total error (m)
1.23634	0.618047	0.776999	1.38221	1.58564

Average camera location error. X - Longitude, Y - Latitude, Z - Altitude.

Table 4. The estimated errors with the use of GCP

X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total error (cm)
25.0113	29.9384	6.70597	39.0112	39.5834

Control points RMSE. X - Longitude, Y - Latitude, Z - Altitude.

The errors between the use of GCP while capturing the site images and not using it while pointing the site are shown in Figure 5. with a dramatic change in the occurred error, which displays the point positions of the camera while capturing the images, Table 3 demonstrates the error estimations while capturing without GCP, where the overall error is 1.585m, and Table 4 demonstrates the error estimations while capturing images using GCP, where the overall error is 39.583cm.

V. CONCLUSION

This study demonstrates the possibility of enhancing the accuracy of urban building modelling using UAV imagery and increasing the number and correct distribution for the GCP using SFM/MVS techniques. By leveraging these technologies, urban planners and developers can get highly accurate and detailed building models that support various planning and development activities. The results demonstrate that the SFM/MVS approach outperforms traditionnel methods in accuracy, detail, and efficiency, providing a cost-effective, fast-tracking, and scalable solution for urban construction modeling. Despite some limitations, such as obtaining aviation approvals and environmental constraints, the results have significant implications for urban planning and development, paving the way for more sustainable and resilient urban environments.

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