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Generating 3D City Mesh Model Based on Aerial Imagery: A Case Study, College of Engineering Campus

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ABSTRACT

3D city modeling is considered one of the most prominent products in urban planning, simulation, and visualization. Although manually producing 3D models is considered to be very time-consuming and costly, this paper presents the pipeline for generating and sharing a 3D city model from aerial imagery based on the photogrammetric technique. For the 3D city mesh modeling, aerial images with a resolution of 10 cm have been used. Initially, aerial triangulation was achieved to obtain the exterior orientation parameters of the images using ground control points that were measured at the site. Later, the obtained exterior orientation parameters are used in SURE photogrammetric software to produce a dense point cloud and mesh model using the image-matching technique. The produced point cloud and mesh model have been shared using the Cesium website, which has been embedded into the website https://3d-erbil.weebly.com/ for easy access. The published model allows the user to better understand the buildings in the area, which is useful for urban planning. Furthermore, it is possible to make measurements from the shared model and obtain object coordinates for any point on the ground.

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1.Introduction

The 3D city models, in all their different forms, are considered the most common and significant component that aids the user in different applications such as planning, simulations, and navigation. It has become a very important source of information related to buildings, while in the past it was only related to visualization (Ruohomaki et al., 2018). The current trend of 3D modeling is focusing on the digital twins, which are considered to be very beneficial in detailed planning and landscape view, which helps to prepare different scenarios regarding disaster management and urban planning (Lehtola et al., 2022). It is aimed at using digital twin cities to develop the complex environment in highly populated cities (Lehner and Dorffner, 2020). Although different forms of virtual cities are available, such as mesh models and semantic models, all of them are still considered difficult to use as “digital twins” (Stouffs, 2022).

Producing digital twins is considered time-consuming since it accurately represents the ground and the objects beneath it and supplements the development of smart cities (Shahat et al., 2021). On the other hand, the mesh model is specified to have decent geometric and appearance information related to the specific objects, unlike semantic 3D models in which objects and landscapes attribute each object individually (Willenborg et al., 2018).

Based on the literature, various methods and approaches are focused on 3D city modeling using aerial images. Buyukdemircioglu et al., (2018) proposes a workflow for semi-automatic 3D city model generation using vector basemaps and large-format aerial images; however, the method is specified to have some problems, such as manual processing of the images and incorrectly selecting the roof of the building. Lehner and Dorffner, (2020) proposed a strategy for the purpose of producing a 3D city model for the digital twin based on the geodata. Although the method is specified to produce high-level buildings, it depends on available survey and mapping data. (Salleh et al., 2021) generated a 3D city model from aerial imagery sourced from Google Earth. The model has been generated in the CityGML and later visualized on the Cesium platform. A high level of building has been generated, but due to the building footprint, this has caused a location error. Also Sadeq, (2019) digitizing the buildings manually based on CityGML. Overall, these papers present insights into different techniques and tools that can be used to generate 3D city models from aerial images. However, these methods are specified to be very expensive and time-consuming, which is considered a challenge in producing a 3D model in developing countries. Therefore, the focus is to suggest a rapid method for the 3D modeling of the building. For that purpose, 3D photogrammetric products in the form of point clouds and mesh models have been produced from stereo aerial imagery and used as a 3D city model. The mesh model has been used worldwide since it has a very realistic view and can be used for 3D modeling rapidly. Although a mesh model has been produced based on stereo and aerial imagery, the problem is considered very time-consuming since it requires large human resources to achieve the process.

The contribution of this research is generating a textured 2.5D and 3D photogrammetric mesh model based on stereo airborne imagery for visualization purposes, later making the mesh models available online for the public, and obtaining measurements. Furthermore, it can be used for urban planning by suggesting different scenarios that can be added to the model and compared between the scenarios. The proposed 3D city model consists of a polygon mesh, in which the buildings, trees, and other above-ground features are not isolated; all the objects are linked to each other, unlike the CityGML, where the above-ground objects are separated (Biljecki et al., 2015). The only challenge that exists in producing a real city visualization with the photogrammetric mesh is vegetation representation, which covers the buildings (Schmohl et al., 2020).

The structure of the paper is shown to be as follows; the related work is described in this section. The used dataset, generating a 3D mesh, and sharing the model are described in

Section 2. The results are shown in Section 3. The discussion and conclusion are discussed in Sections 4 and 5, respectively.

2.Methodology

The applied workflow in this research, as shown in Figure 1, is based on photogrammetrically processing the images using GCP and then producing a potin cloud and mesh model using SURE software. Later, share the products using the website platform.

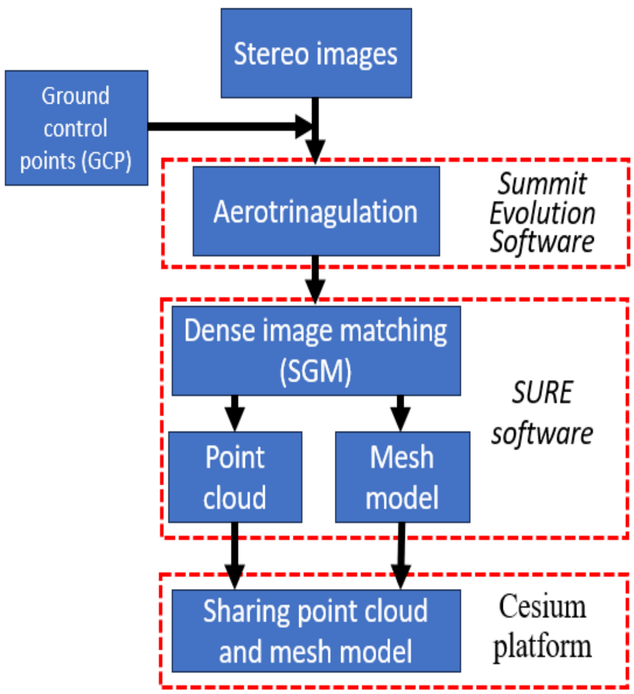


Figure 1 Flow diagram showing the implemented stage in processing stereo images for the point cloud and mesh model generation and sharing. Furthermore, the applied software are shown in each stage

2.1Dataset

For 3D mesh generation, three aerial images with sufficient overlap have been used. The covered area is the College of Engineering and its surroundings. The dataset is sourced from aerial images with a ground sample distance (GSD) of 10 cm, and they are pre-processed for lens distortion.

The aerial image acquisition was conducted by Vossing German Company in 2011, and they are available in the Geomatics Department Lab, College of Engineering, at Salahaddin University-Erbil.

For the photogrammetric process, the camera interior orientation has been used, which was provided with the images. For the exterior orientation, the bundle block adjustment has been implemented, which can be determined using any software that provides the aerotrinagulation solution based on the measured ground control points (GCPs) from the site using the Leica Geosystem 1200. In this research, for image aerotriangulation, the Summit Evolution software has been used, and the results show that the RMSE of the aerotriangulation is 0.34 meters. The result of the exterior orientation parameters is shown in Table 1, which will later be used to determine the object coordinate.

Table 1 The obtained exterior orientation parameters for the aerial imagery, the coordinates are referred to the UTM-Zone 38N.

Image No	Xo	Yo	Zo	ω-deg	ϕ-deg	κ-deg
Img1	412128.2521	3999565.7927	2229.8283	-0.0093	-0.1796	180.1001
Img2	412129.9618	4000051.7956	2230.0561	-0.0188	-0.2096	-179.8575
Img3	412133.1007	4000526.9556	2230.3101	-0.0297	-0.1968	-179.8875

2.2Dense Image Matching

For a long period, the most common image matching technique was based on matching features such as least squares matching, which is also known as area-based matching (Alobeid, 2011). However, by improving the matching algorithms, it has been possible to apply the matching to the whole image, which is known as dense image matching.

The well-known and popular dense matching is introduced by (Hirschmüller, 2008), and is named SemiGlobal Matching (SGM). In the SGM, the corresponding points are obtained hierarchically through multiple paths. In this technique, the matching is applied to all pixels of the stereo images, consequently producing a dense point cloud. Thus, more detailed features of the object can be obtained, which can later be used in the 3D mesh generation.

Similar to all dense image matching, the SGM consists of four stages: computation of the matching cost; cost aggregation; disparity computation; and, disparity refinement.

In the SGM, the matching cost was determined hierarchically based on mutual information (MI). Regarding cost aggregation, it is achieved by applying the global energy function based on using it pathwise from all directions around the pixel. The applied global energy function $E(D)$ is shown below:

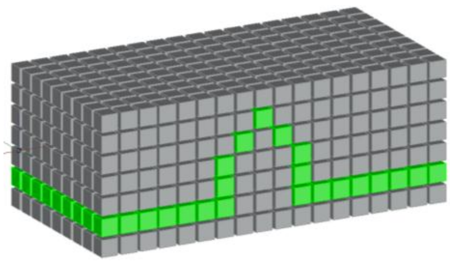
$$E(D) = \sum_{p} \Bigg(C(P, D_P) + \sum_{q \in Np} P_1 T\left[\left|D_p - D_q\right| = 1\right] + \sum_{q \in Np} P_2 T\left[\left|D_p - D_q\right| > 1\right] \Bigg)$$

The energy function $E(D)$ consists of three terms: the matching cost is defined in the first term, the second term adds the penalty for all pixels q to the surrounding pixel Np of p, and the third term is used to penalize the large disparity differences (Hirschmüller, 2008).

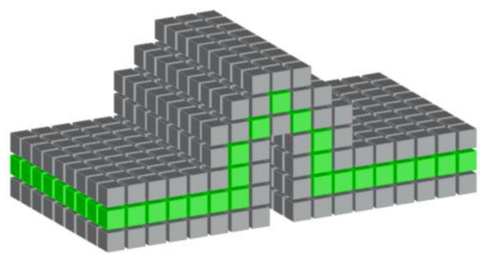
Based on the literature, it has been shown that SGM is the most advanced algorithm in stereo image matching, and it is based on integrating global and local methods for pixel-wise matching by implementing the process of cost function optimization (Wu, 2021). The SGM algorithm is considered an algorithm that can be used to extract building features for better representation and reliable products (Alobeid, 2011; Wenzel et al., 2013).

In this research for mesh generation, the SURE software has been implemented (nframe, 2023). The software is commercial and is specified for dense image matching and generating the textured mesh model. The processed images led to obtaining a 2.5D DSM and a 3D mesh model. Generally, the performance of the image matching can be increased with using aerial images with higher radiometric quality, thus will lead to obtain point cloud that specify to be better accuracy and more details of the objects (Haala and Kada, 2010). Furthermore, the radiometric information is essential for using the mesh model int the visualization application through combining it with the geometric data.

The SURE software is based on the improved revision of the SGM. In the SGM, the disparity search (i.e., parallax range) is specified by representing the matching cost as a cube-shaped arrangement, as shown in **Figure 2** (a). In this case, the process will be time- and memory-consuming since each pixel will be applied to the same parallax range. To solve this problem, a dynamic parallax range is applied by reducing the search space and focusing only on the pixels around the corresponding point, as shown in Figure 2 (b). In this process, the image pyramid with different resolutions has been used to narrow the search space range. Initially, the image matching is applied to the low-resolution image by using the whole search parallax, which ensures the implementation of the algorithm without specifying the search range, thus reducing the computation time dramatically (Rothermel and Wenzel, 2012).



(a)



(b)

Figure 2 The cost computation matrix, the grey boxes represent the potential cost, and the green boxes represent the true conjugate points. (a)The horizontal domain represents the image space, which is the original cost computation matrix that is used in the SGM, (b) the SGM and the dynamic concept that is used in the SURE software.

Later, the obtained corresponding points are triangulated for point cloud generation, which will be used for the derivation of digital surface models (DSMs) and orthophotos. In addition to the 3D mesh model, the SURE software provides true ortho, which can be used directly for GIS applications. In addition to the products obtained, the polygon mesh model has also been generated based on the generated point cloud. Frequently, the volumetric representation is used for the general data structure to preserve the meshes with specific classes (Zach, 2008). The meshed surface is used for the visual representation, which is based on volumetric surface integration (Szeliski, 2022).

The mesh surface is usually represented in wireframe or shaded mode. For real city visualization, the textures have been added to the polygon 3D mesh model (Guidi and Remondino, 2012). The textured mesh model is considered the most desirable model since it gives a complete geometric and outlook representation. Using textured 3D mesh in city modeling is continuously becoming more attractive to operators. With the mesh model, it is possible to define the buildings as having a continuous surface that consists of a set of tringles comprised of edges and vertices. Furthermore, the textured mesh surface can be used as input for the 3D city model reconstruction, which is the main source for the digital city twins.

2.3Sharing the 3D mesh model

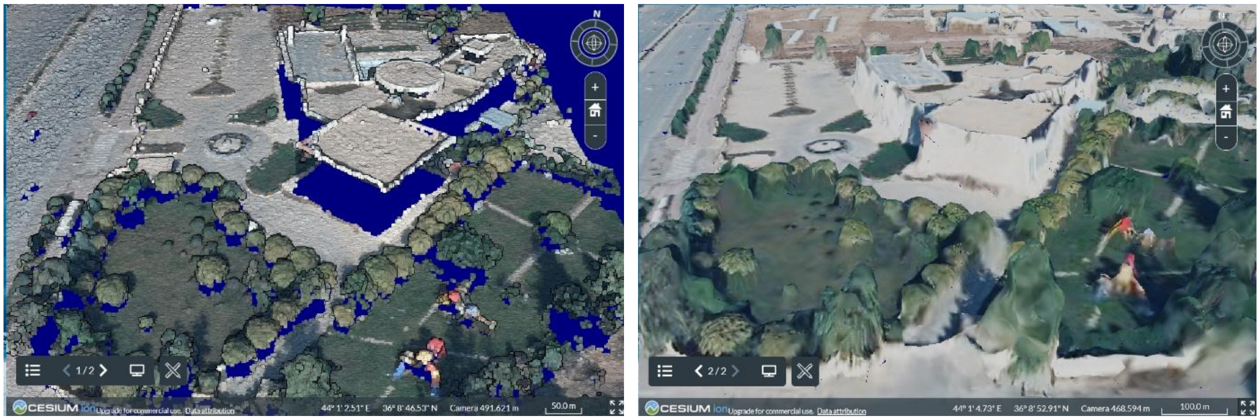
The offline mesh data is considered to consume large storage data and require special software for visualization; therefore, it is preferred to stream through the internet and directly view the interest area in addition to making measurements on the web model directly (Schmohl et al., 2020). The best method to access and view the generated point cloud and mesh model is by sharing it online. which helps to directly view the object through the web browser without installing any visualization software.

In this research, the website that is used to share the 3D globes and 2D maps online is called the Cesium platform. It is an open source program based on the JavaScript library for browsing and visualizing data without a plugin. The Cesium is specified for the 3D earth and map access, which was created by the Cesium Consortium community (Anh et al., 2019). The Cesium is based on WebGL (web graphic library), accelerated graphics hardware, cross-platform, and -browser with dynamic data visualization (Keysers, 2015).

3.Result

For the point cloud and mesh model generation, the SURE software has been used. It is based on the SGM algorithm. The first stage was focused on point cloud generation and then publishing it online using the Cesium site, as shown in Figure 2 (a). It can be noticed that the point cloud has identified the buildings, which are produced from the image-matching technique. Based on the point cloud, the triangulated mesh model has been generated and then published online, as shown in Figure 2 (b). It can be noticed that the points are clearly visualized, and the user can easily identify the objects from the mesh model. The proposed method is shown to produce a mesh model more rapidly than the manual method, which is specified to be very time-consuming and costly due to manually digitizing the building (Sadeq, 2019) or using extra data (Buyukdemircioglu et al., 2018; Lehner and Dorffner, 2020).

The format of the uploaded point cloud, which is also recognized by the website, is based on the LAS format, while the uploaded mesh model is based on the OBJ format. For easy access to the point cloud and mesh model, the shared models have been embedded on the website https://3d-erbil.weebly.com/ .



(a) (b)

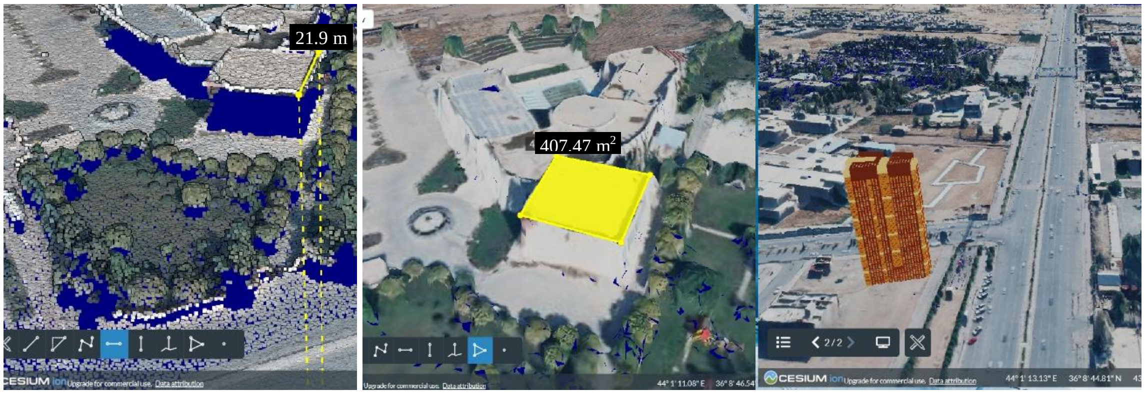
Figure 2 The generated point cloud and mesh model based on the SGM algorithm using stereo aerial imagery for the engineering campus at Salahaddin University-Erbil, which is published online through the website https://3d-erbil.weebly.com/. (a) showing the point cloud, the blue colour represnt the gap which has not been filled (b) showing the mesh model.

4.Discussion

This research presented a rapid pipeline for sharing the point cloud and polygon mesh generated from aerial images via photogrammetry. The point cloud has been produced based on using the SURE software to implement a dense image matching algorithm. The textured mesh integrates the 3D geometry and radiometric value of the scene, which assists in better visualization and understanding of the scene. The extracted point cloud was mainly obtained for horizontal surfaces, while the vertical surface was not detected, as shown in Figure 3 (a). This is due to using only vertical images with a tilt that does not exceed 0.5 degrees, as shown in Table 1. Consequently, in the mesh model, the gap has been filled with triangles, while the texture has been interpolated using the surrounding pixels. To extract the point cloud and assign real textures to vertical surfaces, it is necessary to use oblique images in addition to vertical images (Haala et al., 2015).

Although it is possible to access the point cloud or the mesh model through the Cesium site, it is also possible to embed the code within the website. As shown in Figure 3, the point cloud and mesh model are part of the website, and they can be easily accessed by the user.

In addition, to visualize and make measurements from the model, either linear or surface measurements, it is also possible to use the model in the planning process to infer the final model impression that is used in the design by the architects. As shown in Figure 3 (c), a visualized mesh model with a high-raised building is located on the main road.



(a) (b) (c)

Figure 3 Embedding the model in the personal website https://3d-erbil.weebly.com/ . (a) measuring an object on the point cloud; (b) measuring area on the mesh model; (c) examining the landscape after adding a high-raised building.

Although different websites are currently available for 3D modeling, such as OpenStreetMap, it should be taken into consideration that they are not complete and some of the buildings are not accurate to obtain measurements because, although the planimetric measurements have been obtained from the optical imagery, the heights are suspicious and not accurate.

As shown in Figure 4 (a), the left circle shows the slope on the roof of the building has been ignored, while on the generated mesh model, the slope of the surface is clearly identified, as shown in the Figure 4 (b). On the other hand, in the right circle in the Figure 4 (a), it can be noticed that large and varied heights are given to the buildings. Whereas in the Figure 4 (b), the right circle shows the height of the building is accurately represented.

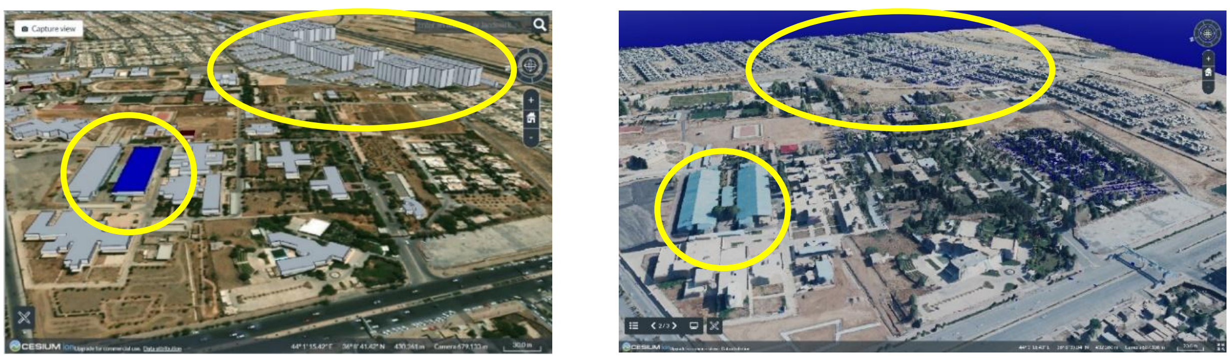

(a) (b)

Figure 4 City Model Comparison (a) openstreet map with overloaded 3D objects; (b) the generated and uploaded 3D mesh model over the study area. The yellow circles show the difference between the open street and mesh models**.**

5.Conclusion

The presented contribution has shown the ability to use stereo aerial imagery for the purpose of rapid and accurate point cloud and mesh model generation. The implemented SURE model, which is based on the SGM algorithm, has shown the potential to produce dense point clouds that can later be used for the production of high-quality mesh models. The produced textured mesh model has the ability to be used as a 3D city model that can be used in visualization, which is important for urban planning. Furthermore, the obtained details of the mesh model can be considered more realistic for urban planning than the Level of Details (LoD1) model (Ying et al., 2020), since the extracted details of the objects are higher and higher textures are given to the objects.

The Caesium platform has proven to be very powerful for sharing the point cloud and mesh model, which can later be used to visualize the model. Moreover, it is also possible to use the shared online data to obtain measurements without conducting field surveys, which are usually time-consuming.

For future studies, it is recommended to use oblique images that can be obtained from the UAV to generate a model with more facade details, which enhance the visualization and measurement processes.

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