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STRATEGIES TO MODEL COMPLEX ARCHITECTURAL OBJECTS USING UNMANNED AERIAL SYSTEMS (UAS)

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Abstract: The use of Unmanned Aerial Systems (UAS) and photogrammetry are becoming attractive for creating three-dimensional (3D) models in many surveying applications of construction engineering. Although several researchers have introduced and evaluated UAS and photogrammetry technologies' potential in various applications such as earthwork surveying and building components modeling, there is still a lack of a comprehensive investigation of the UAS and photogrammetry applications from the perspective of practice. This paper aims at identifying and summarizing the optimal strategies of 3D mapping and modeling for existing buildings regarding the efficiency and accuracy from field experiments at a facility in Kentucky. The strategies discussed in this paper involve the development of the UAS images acquisition plans and the selection of data processing options for point cloud model using the Pix4D software program. For a complex structure, the efficiency relates to the number of image locations needed to model the object with its geometrically complex components and the number of subprojects that will be merged for faster processing. The accuracy is evaluated through the measurements comparisons and the effect of visualizations. The experiment results and illustrations are useful as a reference for researchers and practitioners in need of guidance to efficiently implement UAS and photogrammetry technology for their applications.

1 INTRODUCTION

Unmanned aerial systems (UAS), is an all-encompassing description that encapsulates the aircraft component, sensor payloads, and a ground control station. The unmanned aerial vehicle (UAV) platform is equipped with various sensors including cameras, Global Positioning Systems (GPS) and other specialized communication devices. The UAVs are capable of operating at different levels of autonomy controlled by a ground control station that is the activity hub during UAV missions and provides necessary capability to plan and execute UAV missions (Natarajan 2001). The UAS can transfer visual assets collected by UAVs platform to its ground control station in near real time (Costa 2016). Photogrammetry, a technology using visual assets to derive measurements and three-dimensional (3D) models of real-world objects or scenes, uses the mathematics of light rays to build up information about the geometry of objects and the location of the camera when the images are taken. The photogrammetry technology aims to process or convert images captured by the UAS into various outputs such as point cloud models according to different needs. As more accurate GPS and camera technologies have developed, the use of UASs are becoming increasingly popular in various domains such as archaeology and cultural heritage (Bendea et al. 2007 and Gómez-Candón et al. 2014), forest and agricultural (Grenzdörffer et al. 2008), environment surveying (Ezequiel et al. 2014), emergency management (Chou et al. 2010 and Molina et al. 2012), and transportation (Puri et al. 2007). In the civil engineering domain, UAS have been adopted to solve various problems such as bridge inspection (Metni et al. 2007 and Hallermann et al. 2014), soil erosion (d'Oleire-Oltmanns, Marzolff et al.

2012), earthwork monitoring (Siebert and Jochen 2014) and measurement (Wang, X et al. 2017), and 3D model creation (Xie et al 2012).

So far, much research has been conducted in building modeling since 3D building reconstruction from digital images is needed for an increasing number of tasks related to measurement planning, construction, environment, transportation and facility management (Braun et al. 1995). However, the digitization of complex architectural structures remains a challenge. Since fully automatic image understanding is hard to solve, semi-automatic components are usually required to support the recognition of complex buildings by a human operator (Haala 2010). In addition, many potential difficult-controlled factors would have a significant influence on the quality of modeling. In the last two decades, many approaches have been designed to deal with Light Detection and Ranging (LiDAR) point clouds obtained from ground level vehicles, but expensive device cost and unavoidable severe occlusions cause hindrances to its implementation. In contrast, the UAS provides more flexibility and significantly improves the efficiency in both time and cost for capturing images of large complex facilities. Everything has two sides. Although the UAS is more effective in collecting visual data of all sides of buildings and robust against occlusion, the point clouds computed from UASs often have more noise or poor re-projections, which may lead to inaccurate measurements or weak visualizations. The primary objective of this paper is to identify and summarize influential factors and challenges of the modeling process, particularly image acquisition planning and data processing, based on photographs captured by UASs. The field test flights were conducted at a baseball stadium. For this case study, the DJI Inspire 1 was used for capturing images, and the Pix4Dmapper photogrammetry software was used for image processing and model creations.

2 PHOTOGRAMMETRIC PROCESS

Photogrammetry is a technology of image processing to interpret the shape and location of an object from one or more photographs of that object. The primary purpose of a photogrammetric process is the 3D reconstruction of an object in digital form (coordinates and derived geometric elements) or graphic form (images or maps) (Luhmann et al. 2014). This study uses an UAS to capture images on the site. Normally, the process begins with the flight mission planning. Once all the requirement and parameters are defined for the flight mission, a flight plan or an image acquisition plan is developed and aerial imagery is collected based on the project specifications. At the same time, a ground control survey needs to be conducted to improve the positional accuracy of the 3D outputs. After the image acquisitions and the ground control survey, methods of image interpretation and measurement are required to complete the transformation between images and object.

To be more specific, the shape and position of an object are determined by reconstruction bundles of rays which define the spatial direction of the ray to the corresponding object point. From the intersection of at least two corresponding and separated rays, an object point would be located in 3D space. Every image generates a spatial bundle of rays. A dense network, which is used to orient and calculate the associated 3D object point locations, is generated when all the bundles of rays from multiple images are intersected (see the Figure 1). During this process, Automatic Aerial Triangulation and Bundle Block Adjustment are key procedures to process the images. Automatic Aerial Triangulation is performed to determine the position and the orientation of the camera at the moment of each image being captured. The interior orientation parameters decide the internal geometric model of the camera, and the exterior orientation parameters specify the spatial position and orientation of the camera in a global coordinate system. The Bundle Adjustment is the program that processes the photographic measurements to produce the final XYZ coordinates of all the measured points. Both procedures are achieved through photogrammetry processing software based on complex mathematical models. In this way, the photogrammetry software is capable of converting 2D images into various 3D outputs. In the following sections, essential factors and the process will be discussed based on experimental field flights.

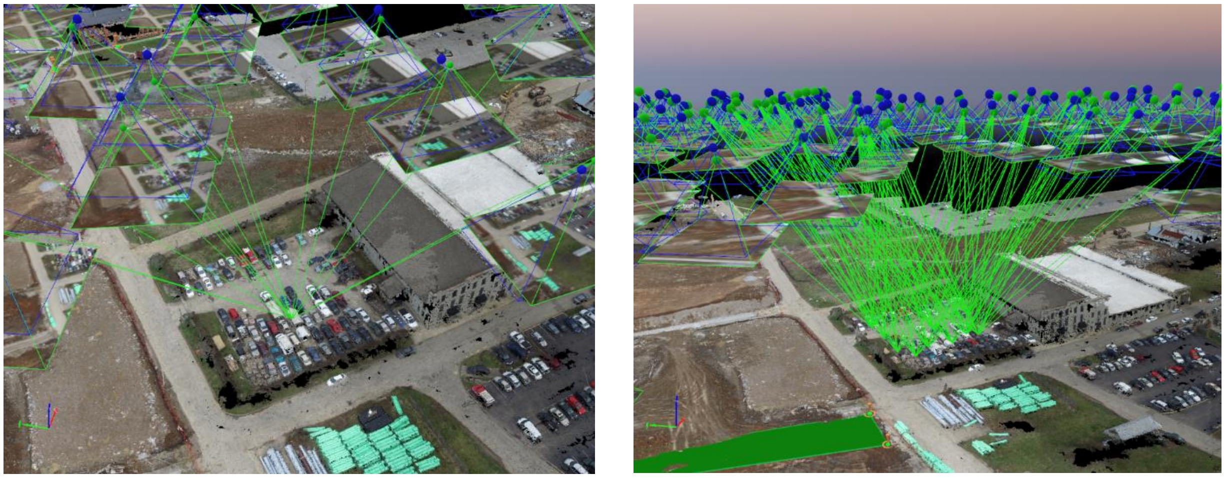


Figure 1: Bundle of Rays from Multiple Images

3 EXPERIMENTAL FIELD TESTS

3.1 UAS and the Pix4D 3D Mapping Application

The UAS used for image acquisition in this study is the DJI Inspire 1. This UAS is a vertical takeoff and landing aircraft powered by a 22.2V battery (Figure 2). Its system has a maximum takeoff weight of 7.71lbs and maximum wind resistance up to 10m/s. Flight time depends on sensor weight and weather conditions. The maximum flight time is approximately 18 minutes. The UAS is equipped with a 20mm lens, and the stock camera has 4096 × 2160 resolution for still images (DJI 2017).

Figure 2: DJI Inspire 1

In this study, Pix4Dmapper photogrammetry software is selected to process images and generate 3D point cloud model of the building. The UAS can perform manual or autonomous flight missions on the site under the control of Pix4D mobile applications (Figure 3). The UAS can fly automatically based on the designed parameters and flight paths. The operator also can manually control the UAS to capture images. The Pix4Dmapper is the desktop applications that is used to convert collected aerial images into a 3D point cloud, a Digital Surface Model (DSM) / a Digital Elevation Model (DEM) or an Orthomosaic (Figure 4).

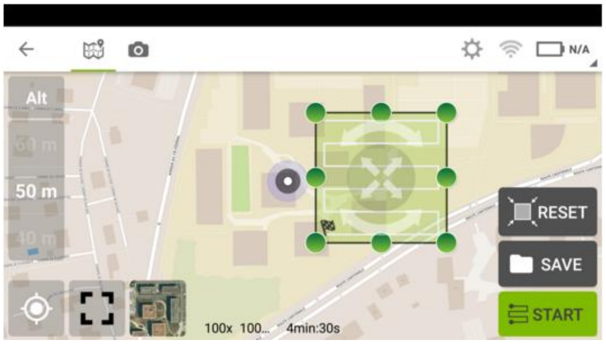


Figure 3: Pix4D Mobile Application

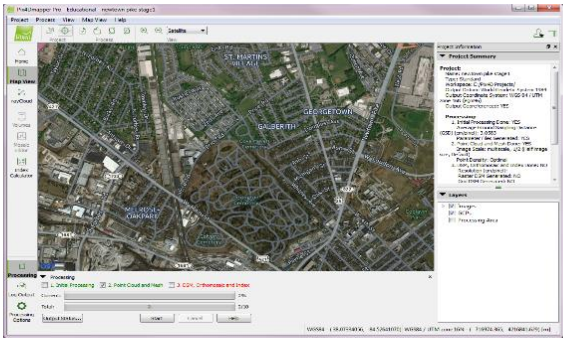


Figure 4: Pix4Dmapper

3.2 Flight Missions Planning

The experimental test was performed at a baseball stadium and surrounding parking lots covering a total of 859,048 square feet. For a large and complex structure, an efficient mapping is the first and the most important step to create a high-quality model. Efficient mapping answers the question “how many image positions are needed for modeling a complex structure?” As introduced earlier, Pix4Dmapper is an image processing software that is based on automatically finding thousands of common points between images. Each characteristic point found in an image is called a key point. When two key points on two different images are found to be the same, they are matched and are referred to as a tie point. Each group of correctly matched key points will generate one 3D point. When there is high overlap between two images, the common area captured is larger and more key points can be matched together. The more key points there are, the more accurately 3D points can be computed. Thus, the key rule is to maintain high overlap between the images. The recommended overlap for most cases is at least 75% frontal overlap (with respect to the flight direction) and at least 60% side overlap (between flying tracks). When taking pictures of a building, at least two flights are needed to make sure of enough overlap between images from different angles. The first round is flying the UAS around the building with a 45° camera angle, and then fly a second or third time around the building increasing the flight height and decreasing the camera angle with each round. Also, a smooth transition between each round is essential to modeling vertical objects of the structure. It is recommended to take one image every 5-10 degrees to ensure enough overlap, depending on the size of the facility and distance to it (Figure 5).

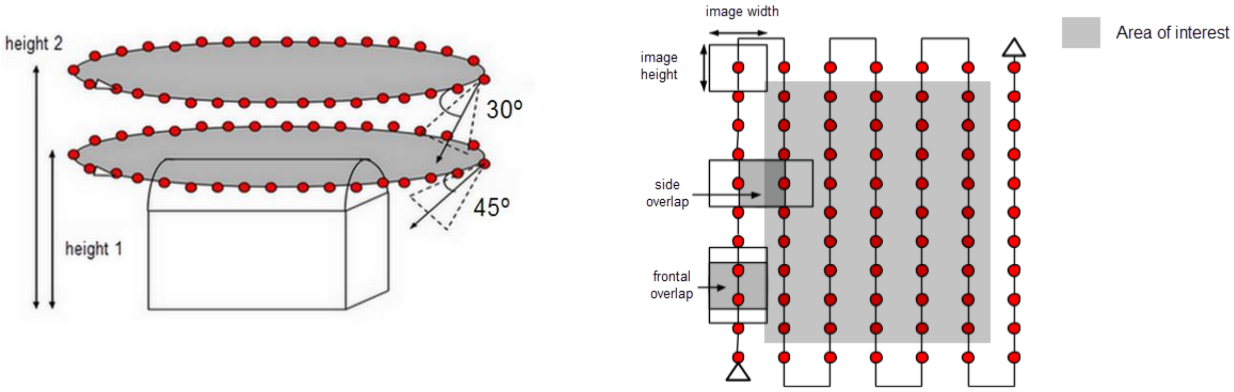


Figure 5: General Image Acquisition Plan for Buildings (Pix4D, 2017)

When the data is extremely large due to a vast area of interest, it may result in the poor reconstruction of models, especially large buildings. Small components may not be captured by the UAS. A model is constructed based on incomplete information will have lots of missing areas. Therefore, multiple flight missions can be combined into one single project, which would likely be the case for large facilities such as stadiums. In this study, the data acquisition plans, or the flight mission plans are shown in Table 1:

Table 1: Data Acquisition of the Baseball Stadium

Flight Number	Location	Flight Mode	Number of Images
1	Inner circle of stadium	Manual	290
2	Outer circle of stadium	Manual	280
3	Parking lots	Auto(Grid Pattern)	105
4	The field of stadium	Auto(Grid Pattern)	90
	Total		765

The first two flights are grid pattern missions covering the horizontal surface of the area of interest, which are the field of the stadium and the parking lots. The grid flight pattern is a basic and efficient flight plan to ensure adequate overlapping between images for flat surfaces. The flight height for a grid pattern is 50m, which is automatically given by Pix4D Mobile applications. For the vertical surfaces, images should be gradually captured at different heights and angles along the desired object. Although the flight duration will be longer, the reconstruction is better than that created based on images captured from a long distance considering the actual height of the target. Two layers of photos are taken at the inner surface, and two another layers are taken at the outer surface the stadium (Figure 6 and Figure 7).

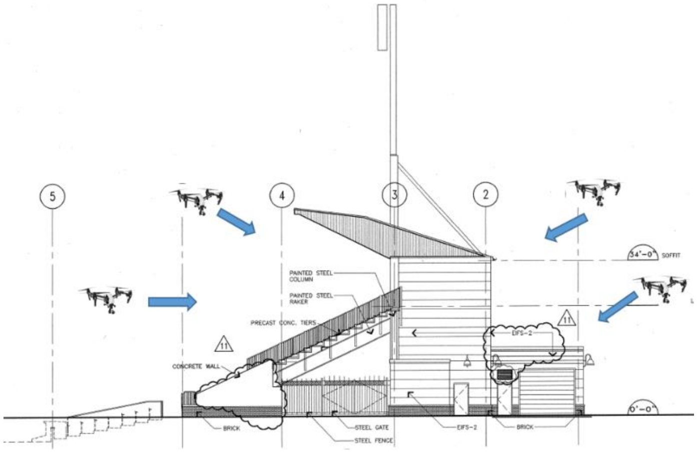


Figure 6: UAV Flight Strategy (Positions and directions) for Vertical Surface of Stadium

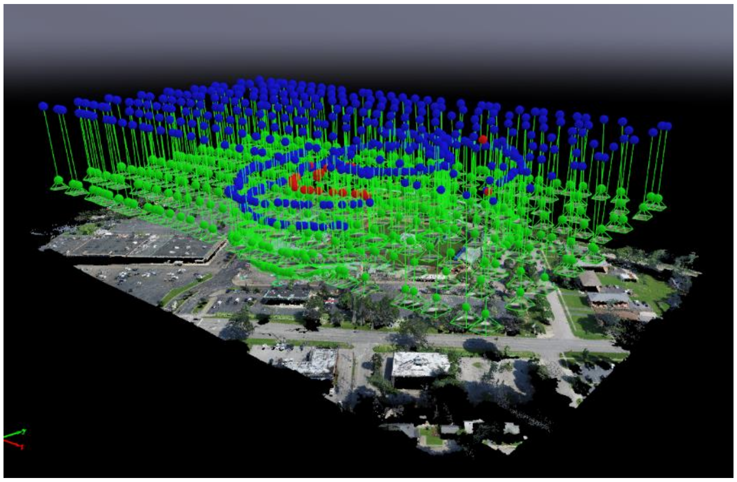


Figure 7: Camera Positions

3.3 Introduction of Ground Control Points (GCPs)

The images captured by the UAV are geolocated. The default Coordinate system is WGS84, which is the standard U.S. Department of Defense definition of a global reference system for geospatial information and is the reference system for the Global Positioning System (GPS). Although Pix4Dmapper can process images and build the model without geolocation, it may result in an imprecise model if less than three images are geolocated. Without the actual coordinates measured by GPS, Web Map Service or tapes, scales and measurements of the model will have high errors. Therefore, the use of Ground Control Points (GCPs) is a basic and effective method to provide the highest possible accuracy for the resulting model. GCPs are points with known coordinates measured by highly accurate GPS units in the area of interest. GCPs are capable of giving scales, orientations, and positions to the results. They are used to georeference a model and reduce noise. The geotags of images may be inaccurate, and thus the 3D model is relatively correct in position. The linear measurements should be applied to fit the entire project to correct scale. In this study, due to the large data set, each data set will be processed independently and then merged after to reduce processing time. In the merging process, the GCPs are the connector between each subproject. Only when the accuracy of each subproject are at the same level, then they can correctly match and merge together.

In this study, the whole project is divided into four subprojects based on the image acquisition plans, which are inner and outer circles of the stadium, the field of the stadium and the parking lots. Normally, The GCPs should be placed evenly in the area of interest to minimize the error in scale and orientation. If all GCPs are located at the same location or one side of the area, then the georeference will lose its balance, which will result in inaccurate result. Additionally, it is also recommended to place one GCP in the center of the area to further improve the quality of the reconstruction. According to some literature and guidance provided from Pix4D, a minimum number of 5 GCPs is recommended. Five to ten GCPs are usually enough for large projects (Pix4D 2017). The topography of the test field in this study is not complex. More GCPs do not significantly contribute to improving the accuracy. The distribution of GCPs in this experiment is shown in Figure 8. The coordinates of GCPs are obtained by the WMS (Web Map Service). The Root Mean Square (RMS) error in the X and Y directions are 2.02% and 1.51% respectively. The RMS error in the vertical direction is 7.46%, which is much higher than that in the horizontal direction. One possible reason is that the GCPs are not measured by a highly accurate device such as GNSS. In this study, the GCPs are mainly applied for correct connections of each model. More precise measurement method and detailed quantitative accuracy analysis will be conducted in the future study.

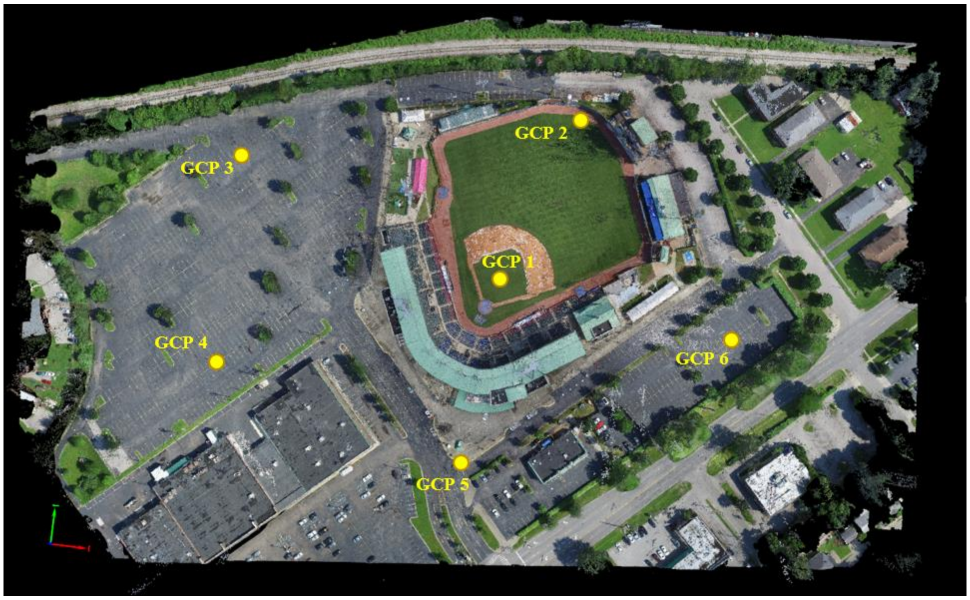


Figure 8: Distribution of GCPs in the 3D Point Cloud Model of the Stadium

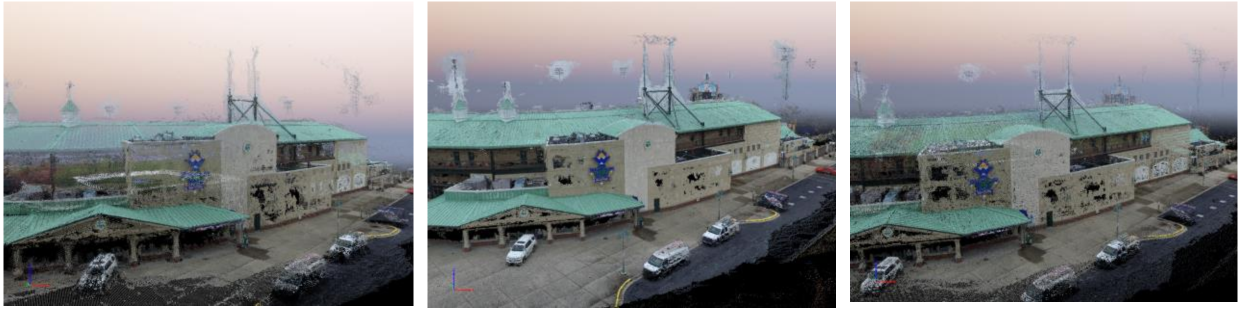
3.4 Processing Options

As introduced earlier, the photogrammetry will process the keypoint extraction. Key points for each group of at least two images will be matched and overlapped to generate a 3D point. Therefore, the number of 3D points directly decides the quality of a point cloud model. Various values of processing parameters are available to be selected depending on the needs of visualization and accuracy. Image scale and point density are two important parameters for the construction of 3D point cloud models. Image scale defines the scale of the images at which additional 3D points are calculated. For example, ½ image scale means only half size images will be used to compute additional 3D points. Point density is a parameter that defines the density of the point cloud. Low point density indicates a 3D point is computed for every (16/image scale) pixel. These two parameters are interactive with each other, and they decide the point cloud densification and processing time together. Options of the combination of these two parameters are flexible based on specific requirements. It is difficult to figure out the optimal combination that can reach a balance between quality and processing time. For instance, if the ½ image size and low point density are selected, the final point cloud is computed up to 4 times faster and occupies up to 4 times less RAM than medium point density. In this study, the default option given by the software are half image size and medium point density, which can create a high-quality point cloud model. However, some situations need more points to reconstruct the model, such as projects with large areas of vegetation. Eight combinations are tested to see the different effects on the number of 3D densified points and processing time (Table 2). The CPU specifications of the desktop are Intel(R) Core(TM) i7-4790 CPU @ 3.60GHz, and its RAM is 32GB. The operating system is Windows 7 Professional, 64-bit. Total 110 calibrated images are used to model partial exterior of the stadium, which is processed for each test.

Table 2: Impact of Image Scale and Point Density on the Number of 3D Points and Processing Time

	1 (Original image scale)	1/2 (Half image scale)	1/4 (Quarter image scale)	1/8 (Eighth image scale)
High Point Density (High)	30658912 7h:38m:42s	26998922 3h:09m:10s	6866345 1h:36m:22s	1741207 33m:55s
Medium Point Density (Medium)	27214691 5h:12m:50s	7242172 01h:30m:22s	1819896 25m:33s	453997 05m:10s
Lower Point Density (Low)	7317936 2h:34m:58s	1937440 49m:52s	473420 15m:06s	120608 11m:58s

(a) High and 1 image scale (b) High and 1/2 image scale (c) High and 1/4 image scale



(d) High and 1/8 image scale (e) Low and 1 image scale (f) Low and 1/2 image scale

(g) Low and 1/4 image scale (h) Low and 1/8 image scale (i) Medium and 1/2 image scale (Optimal)

Figure 9: 3D Point Cloud Models of the Stadium Using Different Values of Point Density and Image Scale

The Figure 9 presents the point could models (part of the stadium) when different combinations are applied. According to the results, it is observed that higher point density and larger image scale result in longer processing time and better visualization. There is almost no improvement of the model quality after the medium level of point density cooperated with the half image scale but the processing time becomes significant longer. Therefore, the medium level of point density and ½ image scale are optimal regarding the efficiency and the quality of visualization.

3.5 Environment

In addition to the image acquisition planning, GCPs, and processing options of photogrammetry software, some environment elements are also important for 3D modeling of architectures. The weather conditions are challenges for both UAS operations and the quality of images. The winds cause air turbulence for UASs and result in blurred photos. Flying in the wind may drain the UAS battery faster than normal. The UAS also cannot fly in raining and snowing weather conditions. So far, most UASs in the market are not waterproof. Thus water may seriously damage the UAS. When the weather is cold, the chemical reactions in batteries slow down, lowering the battery capacity. A fully charged drone battery that typically allows 20-25 minutes of flight time may only provide around 10 minutes in cold weather. Cold weather can also have a negative influence on the drone sensors, which may lead the drone to be less responsive to control inputs. Besides, shallows can also affect the results of the 3D mapping process. Insufficient lightness may cause poor color contrast of the model and more noises (Figure 10.). During flight time, some temporary obstacles especially moving objects such as people may impact the image acquisition, which will become noise needing to be moved manually in the model. Finally, yet importantly, safety increasingly becomes a major concern when operating the UAS in a populated area or near tall objects. The major risk is mid-air collisions. If an UAS fails, it is possible that the public on the ground could be seriously injured because of the falling debris. These safety issues may indirectly limit the designs of flight missions and then impact the accuracy of modelling.

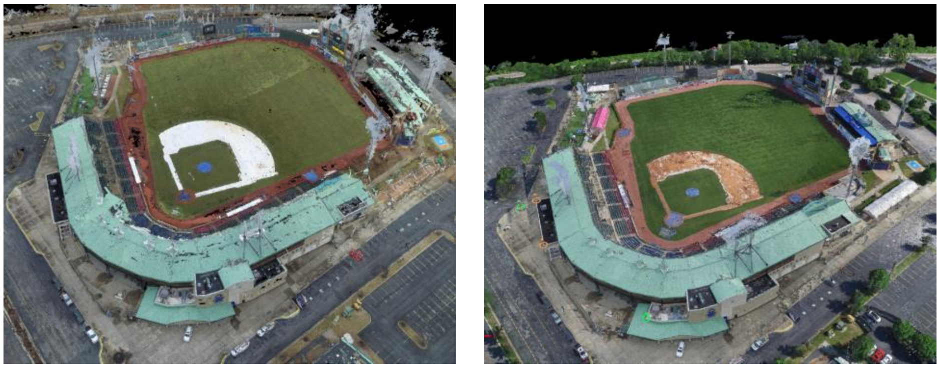


Figure 10. 3D Point Cloud Models Created Based on Images Captured in Cloudy and Sunny Weather Conditions

4 CONCLUSION

The UAS and photogrammetry technology can be cooperated to perform 3D modeling of large and complex structures. This paper discusses strategies for image data acquisition, adding GCPs, selections of processing parameters and some potential environmental factors. An experimental field test is conducted, and the results present and compare the 3D points cloud models created under different conditions. To be more specific:

- Hardware: In this study, a DJI Inspire 1 was used for collecting images during flights, and it can integrate with Pix4D mobile application to design and control flight missions. The Pix4D desktop application is used to process images and build the model. The processing speed largely depends on the computer hardware. According to the software guidance, for a large project (between 500 and 2000 image), 16GB or larger RAM is required to process images. For the future study, more comparisons are needed to identify the capacities when using different devices.

- Flight Mission Planning: In order to obtain high accuracy models, a high overlap between the images is required. The image acquisition plan should be designed carefully and correctly to reach enough overlap and perform efficiently. For a large complex structure, a project is always divided into multiple subprojects to improve processing speeds and perform separate quality control. Therefore, a smooth transition between each flight is as important as adequate overlapping between images.

- GCPs: For the use in surveying application, an absolute accuracy test is mandatory. The GCPs are applied to geolocate a model and then improve the absolute accuracy of the model. The distribution of GCPs is one of the major factors which have impacts on the accuracy. GCPs should be distributed evenly in the area of interest to minimize the error in scale and orientation. Also, it is unnecessary to have a large amount of GCPs. An excess of GCPs would not help improve accuracy but requires more time and labors.

- Processing Options: During modeling, various processing options controls the quality of the model. Image scale and point density are two important parameters for the construction of 3D point cloud models. The selection of the combination depends on the requirements concerning the effect of visualization and process speed.

- Environment: Weather condition is the uncontrollable factor in the process of data acquisition by an UAS. Some technical limitations such as battery life need solutions to strengthen the capacity and safety of operating an UAS.

However, this study mainly focuses on how various strategies of UAS operations and photogrammetry processing impact on the quality, also the effect of visualizations of 3D models. This study attempts to provide preliminary discussions and basic reference for 3D modeling by the UAS and photogrammetry. A further comprehensive quantitive accuracy analysis is necessary to prove the effectiveness and efficiency of applying UAS in 3D modeling. Also, more comparisons with other popular photogrammetry platforms and UAS are useful to explore the optimal strategies in different situations.

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