

Lessons Learned from Unmanned Aerial System-Based 3D Mapping Experiments

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The use of Unmanned Aerial Systems (UASs) for creating three-dimensional (3D) mapping is n emerging area of research in the Architecture, Engineering and Construction (AEC) domain. The AEC environment has required more advanced management systems for projects successes as complexity increases and schedules are shortened. Three-dimensional mapping could enable progress monitoring, surveying and measuring tasks, and quality control in the AEC industry. However, the process of transforming 2D aerial images to 3D model features has pragmatic challenges. This paper aims at identifying requirements and challenges from field experiments using an UAS for 3D mapping at an university campus and a residential construction site. The experiments involved the following steps: 1) Development of the UAS flight mission plan and selection of the flight mode, 2) Capturing and collecting visual assets from UAS during flights 3) Data processing using the Pix4D software program to perform 3D mapping from the collected images. The main contribution of this paper is the identification of operational requirements and the challenges involved in the use of UASs to perform 3D mapping from the images obtained.

Key Words: Unmanned Aerial System (UAS), 3D Mapping, Photogrammetry and AEC Industry

Introduction

Unmanned Aerial Systems (UASs) consist of one or more Unmanned Aerial Vehicles (UAVs) as a platform and a ground control system including a pilot, visual observer, and other operating elements. The UAV platform, commonly known as a “drone”, is usually equipped with various sensors, such as cameras, Global Positioning System (GPS), compass or other specialized communication devices. UASs can transfer still images or videos (visual assets) obtained from the UAV platform to its ground control station in near real time. The UAS has recently been used for various applications including military missions, law enforcement, research and other commercial applications, such as construction, agriculture, or real estate.

As more precise GPS technology has developed, UASs are able to provide more accurate geo-referenced visual assets. Geo-referencing involves the process of assigning spatial location information to the raster images and vector data. A geo-referenced three-dimensional (3D) model is generated from photogrammetric data processing from overlapping collected images. Photogrammetry is the process of photographic image data recording, measuring and interpreting the image as recovering the exact physical positions in the image (Wolf & Dewitt, 2000). Photogrammetry can be developed in the Exchangeable Image Format (Exif) based on each digital image with the approximate values of focal length and image size (Siebert &Teizer, 2014). The processed 3D model based on photogrammetric and geo-referenced data could improve accuracy of the results of imagery analysis on computational models.

Currently, UASs mainly capture aerial images in order to deliver the data to operators or related project personnel. The aerial photography is usually analyzed for different purposes of UAS applications, such as traffic monitoring (Puri & Valavanis et al., 2007), search and rescue operations (Tomić & Schmid et al., 2012), or surveying for identifying subtle terrain features (Lin & Novo et al., 2011). Since a UAS equipped with GPS, gyroscope, or other sensors can acquire aerial images with geo-references for the points of interest, these can be used for 3D mapping based on the images obtained using photogrammetric methods. For example, Siebert and Teizer (2014) evaluated the performance of 3D mapping for surveying earthwork projects using an UAS. In this study, they used a commercial software, PhotoScan, which allows to geo-referenced data processing with UAS. It can export the processed results to digital orthophotography. More accurate 3D mapping from aerial photography would be utilized for surveying, measuring or controlling quality in the Architecture, Engineering and Construction (AEC) industry. However, these studies have not considered the implications of the 3D modeling process in terms of the user requirements and other workflow challenges that are present during the use of an UAS for such tasks.

This paper aims to explore the workflow for developing a 3D model based on geo-referenced images, particularly, aerial photography obtained from a UAS. This study also identifies the challenges of the 3D modeling process in order to improve the accuracy of 3D mapping for surveying or measuring tasks in the AEC industry. The field test flights were conducted at a university campus and a residential construction site. For this case study, the DJI Phantom Vision 2 Plus UAS platform was used for collecting visual assets, and the Pix4D application was used for 3D mapping based on the collected images.

UAS Applications and Photogrammetry for 3D Mapping

The interest in UAS commercial use in various domains has been growing recently, and UAS applications have been studied in order to determine how to efficiently and effectively implement them. Specifically, in the construction and transportation domains, UASs have been used for monitoring soil erosion (D'Olerie-Oltmanns, Marzolff et al., 2012), creating 3D models (Hudzietz & Saripalli, 2012), bridge inspection (Morgenthal and Hallermann, 2014; Eschmann & Kuo et al., 2012) and construction safety inspections on jobsites (Irizarry, Gheisari, et al., 2012). Research has also been conducted in UAS-based photogrammetry for 3D mapping (H. Eisenbeiß, 2009; Barazzetti & Remondino, 2010; Jizhou & Zongjian, et al. 2004; Neitzel & Klonowski, 2011).

Photogrammetry is defined as the process for obtaining reliable information about the properties of point of interests without physical contact with objects, and for measuring or interpreting the information based on the result of the process (Schenk, 2005). Photogrammetry for processing 3D mapping generally has three steps: (1) data acquisition (input), (2) data processing and (3) data production (output). The input can be in the form of visual images through the process of recording and collecting the patterns of electromagnetic radiant energy. The output can be categorized as visualized products, computational analysis results, and maps. The visualized photography can be composed of a single photo or by many overlapped photographs. The photogrammetric process converts these inputs into outputs.

The developed 3D model can be computed and exported as a point cloud, ray cloud, or an orthorectified photo After processing, a quality report is generated describing the quality of the information in the developed 3D model. Adjusting parameters, such processing time and point density, during any of the process steps can yield improvements in the accuracy of the resulting 3D model. The non-adjustment of those parameters can result in less accurate models. An UAS-based photogrammetry process requires flight mission planning before the step of collecting aerial images during flight. Pix4D, one of the applications available for 3D mapping, can integrate the UAS flight plan and the process of 3D mapping on a mobile application. The UAS can perform autonomous (flight path and capturing of the images without operator intervention) or manual (flight path and capture of the images controlled by the operator) flight mission depending on the Pix4D setup. Then, the UAS can collect the aerial photography following the flight mission and waypoints defined by the application. The Pix4D desktop application is then used for the visualization step using the collected visual assets. It processes geo-coordinated photos and aligns them with direct or indirect geo-referencing. Then, the 3D mapping is built by the application.

Experimental Field Test Flights

A total of 11 field test flights were performed at a university campus and a residential construction site between May and June 2015. Each flight lasted about 10 to 15 minutes. A total of 396 visual assets, including photos and videos were collected by the UAS. In the field test, the DJI Phantom 2 Vision Plus (See figure 1-a) was mainly used but a 3D Robotics Iris+ (See figure 1-b) was also used for the collection of visual assets during the field tests. These UASs are equipped with high-resolution cameras; specifically DJI Phantom has 4384×3288 resolution for still images and 1080p30 & 720p for video recording (DJI, 2015). Effective pixel range is 12 Megapixels (MPs), and

Iris+ has resolution 4300×2750 and high frame rate 1080p20 for video recording with 12MPs pixel range (Gopro, 2015) The Pix4D application was selected for 3D mapping using visual assets collected from these platforms. Table 1 describes the parameters of each field test. Three different points of interest, such as terrain, a completed building and building construction were categorized in the field tests. The camera model and aircraft used in 10 of the tests was PHANTOMVISIONFC200 5.0 4608x3456 (RGB) for the DJI Phantom 2 vision plus and GoPro Hero4 black for the Iris+. Flight mode was autonomous or manual. There are cases where manual mode was use to test features and capabilities of equipment before actual experiments were performed. A total of 10 autonomous flights and two manual flights were performed to identify the best result of image overlap based on flight mode. In addition, vertical and oblique aerial photography was used on each site in order to identify the best parameter for obtaining more accurate and higher quality 3D Mapping. Flight speed and altitude were consistently set at 4m/s and 50meter, respectively per software developer recommendations. Future studies could consider variations of these and other parameters to determine their impact on the results of the 3D mapping process.

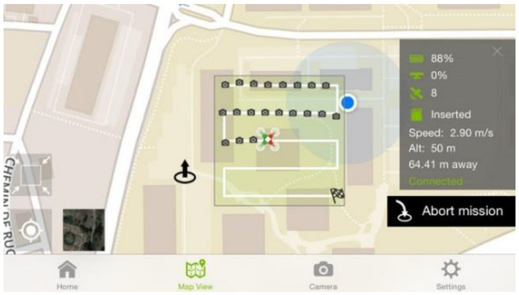
(a) DJI Phantom 2 Vision Plus (b) 3DR IRIS+

Figure 1. Platforms- DJI Phantom 2 and 3DR IRIS+

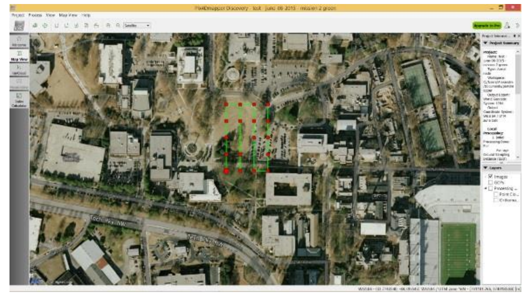
The Pix4D 3D Mapping Application

The Pix4D application was selected for field tests in this study since its companion mobile application (Pix4D Mapper) has the capability of taking a defined flight plan and performing autonomous or manual control of the UAV platform (See figure 2-a). It also has the desktop component for processing UAS based photogrammetry and 3D mapping capabilities. In addition, the desktop component can provide a satellite-view (See figure 2-b) showing the geo-referenced information (left side of screen) and the flight mission plan (green line) as well as the locations where the geo-located images were obtained (red dots). The combination of the two applications allows for the transfer of the images taken with the UAS directly to the desktop-based application. The Pix4D application can convert the collected images into a 3D point cloud, a 3D Digital Surface Model (DSM) or an Orthomosaic. The connection range between the mobile applications controlling the UAS should be within 500 meters. The recommended system requirements for a computer running the application include at least 16 GB RAM and 30 GB free storage space for medium size projects ranging from 100 to 500 images at 14 MP resolution.

This experiment consists of three steps, (1) Establish flight mission plans, (2) Collecting visual assets during UAS flights and (3) develop 3D Mapping (Pix4D data processing). This paper aims to explore the workflow for developing a 3D model based on geo-referenced images, particularly, aerial photography obtained from a UAS, identifying requirements and challenges from field experiments at an university campus and a residential construction site. The flight mission of the UAS should be well defined in order to obtain a good 3D mapping model. A Pix4D based flight plan considers a flight altitude of 50m, and it has longitudinal and transversal overlapping of 60% and 50% respectively. Based on the defined flight plans, the UAS will fly over the point of interest, specifically an academic building and gross terrain areas in the Georgia Tech Campus and a residential building construction site near Atlanta. In autonomous flight mode, the UAS can automatically fly itself following the green-line and take aerial photography on the locations marked with the red spots (See figure 2). The UAS operators would have to designate the flight path and the locations for collecting aerial images in manual flight mode.



(a) Pix4D Mobile Application View



(b) Pix4D Desktop Application Satellite View

Figure 2. Pix4D Application

Table 1. ***UAS* Field Tests**

Flight Test Parameters						
	Test Location	**Point of Interests**	**Platform**	**Flight Mode**	**Type of Visual Asset**	**Visual Asset (Number)**
1	Georgia Tech	Terrain	3DR Iris+	Autonomous	Vertical	44
2	Georgia Tech	Building		Autonomous	Vertical	55
3	Georgia Tech	Building		Autonomous	Oblique	23
4	Georgia Tech	Terrain / Building		Autonomous	Vertical / Oblique	122
5	Georgia Tech	Terrain		Autonomous	Vertical	38
6	Georgia Tech	Building Construction		Autonomous	Oblique	48
7	Residential Construction Site, GA	Terrain	DJI Phantom 2 vision plus	Autonomous	Vertical	37
8	Residential Construction Site, GA	Terrain		Autonomous	Oblique	58
9	Residential Construction Site, GA	Terrain		Autonomous	Oblique	63
10	Residential Construction Site, GA	Building Construction		Manual	Oblique	30
11	Residential Construction Site, GA	Terrain / Building Construction		Autonomous and Manual	Vertical / Oblique	94

Experiments with UAS based 3D Mapping

The process used by Pix4D for 3D Mapping is shown in Figure 3. The 3D mapping process involves overlapping thousands of common key-points between images. First, the key-point extraction is automatically processed. Extracted key-points on each group of images will be matched and overlapped in order to generate a 3D point cloud. According to the Pix4D introduction guidebook, this application can pick up over 60,000 key-points per image, and an average over 6,000 key-points can be matched per pair of images in the case of a medium size project (14MP) (Pix4D, 2015). Once initial processing is completed, point densification and filtering is performed. 3D points can be computed where there is visual content. If some objects have little visual content, the 3D point may have less accuracy. Pix4D runs the Ray Cloud Editor displaying the automatic key-points found from the camera (blue points) as shown in Figure 4. Once the dense 3D points cloud is developed (See figure 4), filtering is performed in order to reduce "noise" and improve image quality by removing redundant points. Ground control points can be added to improve the quality and accuracy of the result.

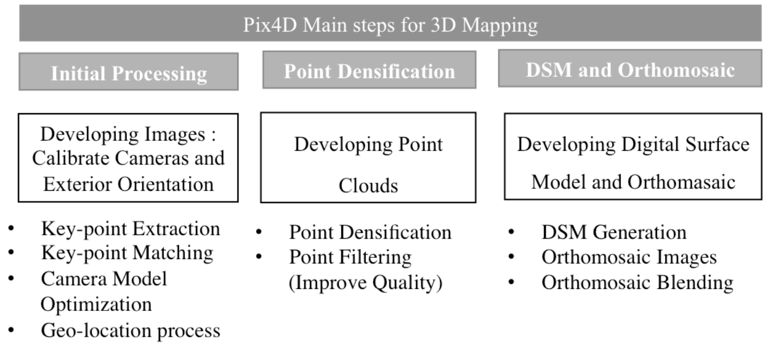
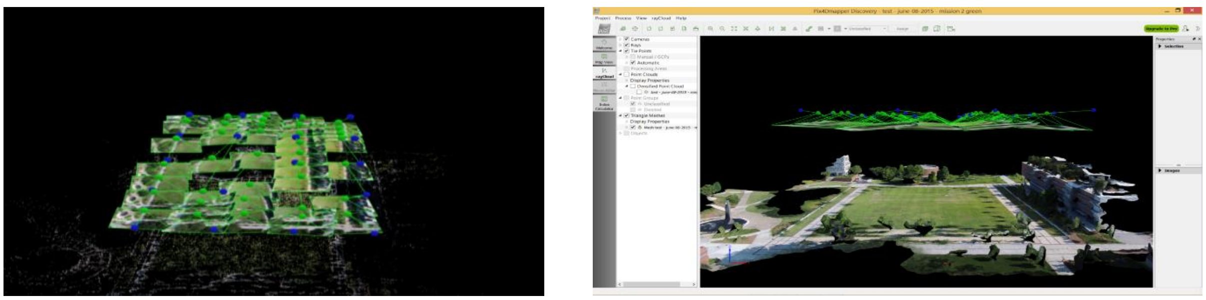


Figure 3. Pix4D Processing for 3D Mapping (Adopted from Pix4D Introduction Guide)



(a) Ray Cloud *(b) Point Cloud*

Figure 4. Developed Point Cloud

Field Test Results

A total of 11 3D mapping field tests were performed. Two laptop computers with different system specifications were used for processing in order to identify the minimum hardware specifications required to run the 3D models with high quality. The CPU specifications of the first laptop was Intel ® Core ™ i5 -420QM CPU @1.60 GHs 2.30 GHz and its RAM specification was 8.00 GB. The second laptop used had much higher performance and its specifications included an Intel ® Core ™ i7 -3820QM CPU @2.70 GHs 2.70 GHz and 16.00 GB's RAM. During the data processing stage, different file formats were generated, such as P4D or JPG in order to identify which file type can produce the best results with 3D mapping. When one flight mission and 3D mapping processing are successfully completed, a P4D file, containing geo-location information stored in the EXIF data is created.

The image processing method could vary depending on how the visual asset was collected. The Full Aerial Nadir type is used for images collected when the axis of the camera or lens is perpendicular to the ground. The Full Aerial Oblique type can be used for images collected with the axis of camera/lens tilted at an angle from 3 to 90 degrees to the ground: Based on the result of these experiment, the developed 3D Mapping from field tests 1, 2, 3, 4, 6 and 7 were not precise enough to conduct accurate measurement tasks due to a great amount of fails in texture of the points of interest. This could be caused by issues such as reflectiveness of surfaces, angle at with images were captured, speed of UAS while capturing images among others. In contrast, the 3D models from field test 5,8,9,10 and 11 have better quality for the terrain and building construction application. It is possible to measure construction progress, monitor laydown area, and survey site areas in construction sites with the results obtained. Based on the processing parameters (See table 2), a 3D mapping having higher point density (test 10 and 11) is more accurate than the one with optimal point density. Higher point density has more density of point features around each output raster cell so it means higher point density has more accuracy. The P4D file showed better performance than the image format without geo-location data (JPG). In addition, multi-scale images resulted in better accuracy of the 3D Mapping process than smaller image scale, however a much longer time was required for processing because multi-scale images have more key-points than smaller image scale. This allows more accurate matching of the images during the registration process (aligning photos).

Table 2. **3D Mapping Parameters and Results**

	System Performance	File Type	Processing type	Image scale	Point Density	Average Ground Sampling Distance	Covered Area	Quality Result (Total Time)
1	Intel ® Core ™ i5 - 420QM (8GB RAM)	JPG	Full Aerial Nadir	½ image size, Default	Optimal	2.24 cm	0.0142 km^2	Not Accurate (52m55s)
2		JPG	Full Aerial Nadir	½ image size, Default	Optimal	1.91 cm	0.0096 km^2	Not Accurate (46m37s)
3		JPG	Full Aerial Nadir	½ image size, Default	Optimal	21.7 cm	0.0001 km^2	Not Accurate (47m51s)
4		JPG	Full Aerial Nadir	½ image size, Default	Optimal	2.27 cm	0.001 km^2	Not Accurate (03h12m)
5		P4D	Full Aerial Nadir	½ image size, Default	Optimal	2.18 cm	0.0113 km^2	Accurate (39m22s)
6	Intel ® Core ™ i7 - 3820QM CPU (16GB RAM)	P4D	Full Aerial Nadir	½ image size, Default	Optimal	2.36 cm	0.0187 km^2	Not Accurate (14m08s)
7		P4D	Full Oblique	½ image size, Default	Optimal	17.09 cm	0.0002 km^2	Not Accurate (03m07s)
8		P4D	Full Aerial Nadir	½ image size, Default	Optimal	17.18 cm	0.0004 km^2	Accurate (02m06s)
9		P4D	Full Aerial Nadir	½ image size, Default	Optimal	10.91 cm	0.0002 km^2	Accurate (04m56s)
10		P4D	Full Oblique	Multi-scale, Original image	High	2.36 cm	0.0001 km^2	Accurate (44m39s)
11		P4D	Full Aerial Nadir	Multi-scale, Original image	High	2.37 cm	0.4004 km^2	Accurate (04h38m)

Lessons Learned from Experiments

From the experiments, a consecutive 3D Mapping process using UAS and Pix4D was described, and operational requirements and challenges are initially derived with 4 main categories of workflow, hardware, software and environment for developing more accurate 3D Mapping process using an UAS.

1. Workflow
   - *Flight Plan:* Establishing a well-defined UAS flight plan influences the collection of image pairs with more key-points, and results in more accurate overlapping and 3D Mapping process. Aspects to consider include the flight mode (autonomous vs. manual), flight paths and the type of visual assets.
2. Hardware
   - *Mobile Devices and Connection with UAS:* The Pix4D mobile application can work on both iOS and Android environments. From this experiment, an operation of Pix4D on Android showed better connection between UAS and mobile devices because Android based Pix4D has better compatibility with DJI Phantom Vision 2+ than iOS's version of the app. This is a software vendor issue. If an UAS

is operated in manual mode, the display of mobile devices should be also considered since the operator should keep track the UAS' flight path and the location of image capture through the display.

- *Platform:* 3DR Iris+ and DJI Phantom 2+ were used for collecting visual assets during flights. Iris+ is capable of autonomous flight under pre-defined flight plans, and DJI Phantom can integrate with Pix4D in order to define an autonomous flight plan. Depending on factors such as operator's skill, UAS specifications, such as battery power, camera features, user interface for control of UAS, and safety features, such as lost-link actions or emergency response systems, the platform can be selected. In this experiment, DJI Phantom Vision 2+ was mainly used.

3. Software
    - *3D Mapping Application:* There are several 3D Mapping applications available. Each application may require different work environment or hardware specifications. Image overlapping with key-points among image pairs is the most important process for a more accurate 3D mapping process. Different applications have different mechanisms for extracting key-points, matching them and overlapping them.
4. Environment
    - *Weather Conditions:* Weather conditions are considerable operational challenges. Specifically, sunlight and time for flight may influence image specifications. Shadows and glare from reflective surfaces can affect the results of the 3D mapping process. Of course, the process can not be performed in rainy or extremely windy conditions as this directly affects UAS flight.
    - *Interference with sensors*: Since UAS is equipped with electrical sensors like Gyroscope or Compass, it can be affected by communication interference if there are magnetic sources around the UAS. During the development of the UAS flight plans, this should be considered and large metal objects or reinforced concrete structures not used as takeoff locations.
    - *Visual Line of Sight Flight (VLOS):* During several of the field test flights, the UAS loss connection with the Pix4D application. Lost-link procedures approved by FAA in the COA involve the hardware's capabilities to return to point of origin defined by the GPS coordinates of takeoff location. The UAS could not collect some images during lost-link and the quality of the 3D Mapping was not precise in this case. Equivalent safety is ensured as the images are captured by the device and not by individuals at high elevation. Therefore, it is important to consider this during flight planning to ensure the ground control unit does not loose communication with the UAS.

Conclusion

UAS and mobile 3D Mapping applications can be integrated to perform photogrammetry and 3D Mapping based on aerial photography collected during UAS flight. This 3D Mapping process can support surveying tasks, quality control processes, and progress control and measurement tasks in the AEC industry. This paper presented the results of experiments with two UAS platforms and two computing systems or varying performance for UAS-based photogrammetry with the Pix4D application. The initial processing for overlapping and matching all key-points among all image pairs is the most important factor to improve the accuracy of a 3D Mapping process. The more key-points are defined; the better quality 3D Mapping process can be achieved. For improved quality of the 3D Mapping process, the main lesson learned from the field experiments considered four factors. The operational requirements related to workflow, hardware, software and environment should be considered and challenges addressed in order to achieve more accurate and higher quality 3D Mapping results. Future work should quantitatively analyze the performance of representative 3D Mapping applications in combination with more UAS platforms. The results could improve our understanding of UAS integration into construction environments.

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