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THE EFFECTS ON COST, TIME, AND ACCURACY WHEN USING UNMANNED AIRCRAFT SYSTEMS TO MEASURE SLOPED EXCAVATIONS

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Abstract
As uses for unmanned aircraft systems (UAS) continue to evolve, opportunities for research to validate improvements in cost, time, and quality become crucial. Specifically, there have been many studies focused on how UASs can simplify the measurement of earthwork quantities, but is there a compromise in the accuracy of the measurements for a reduced effort to obtain them? The objective of this research was to identify if such a compromise exists. This study measured the amount of effort (cost and time) to obtain a level of accuracy (quality) that is consistent with the traditional measurements obtained with ground-based robotic surveying equipment. The researchers performed a quantitative experiment using twelve measurement check points across a one-acre test site (4,047 m^2). The test site was sloped to simulate a level of complexity that would be consistent with a more challenging area of a typical construction project site when obtaining earthwork quantities. The methodology involved measuring three separate UAS flights with differing flight paths and image gathering overlaps and comparing this to a ground-based measurement procedure. An accuracy analysis was conducted on the location of the twelve check points. Time and cost data were computed for all procedures and compared. This study found that not all flight path techniques met industry standards for accuracy while others did. The tradeoff when using the more accurate flight paths was a longer time to obtain and process data. When the overall cost was considered, it was determined that the UAS-based measurement approach was less expensive – resulting in a mixed determination about whether a "compromise" existed. This study further elaborates on the findings and proposes recommendations about how this comparison benefits innovation in the built environment.

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Keywords: efficiency, site work, survey, uas, construction.

1. Introduction

Sloped excavations are common on most construction projects. Sometimes a sloped excavation is for underground pipe or utilities, and other times it is a part of the landscape or for drainage. In order to accurately measure the slope of the excavation, a survey is needed. Among the traditional surveying methods, the robotic total station has become the predominant method of surveying in construction. Traditional methods involve employees trained in surveying using fairly expensive equipment. Because of the cost and time required for traditional surveying, many contractors may be inclined to skip the excavation measurements. Lack of measurements can result in poor quality or even unsafe working conditions.

1.1. Background and rationale

If using a UAS to measure sloped excavations is accurate enough to maintain a safe jobsite and support project quality, this method could save the contractor both money and time. Topographic drone measurements may not be as accurate as traditional survey methods but may be accurate enough to replace traditional survey methods for certain applications. Due to the high cost of state of the art surveying equipment, general contractors typically subcontract surveying activities. Many projects are already using drones on the jobsite for other purposes such as job progress photo documentation. Using drones for this application could expand the current uses of drones with minimal additional equipment cost.

1.2. Purpose

The purpose of this research is to investigate the accuracy, cost, and time associated with using UAS's to measure sloped excavations compared to traditional surveying methods. The key objectives include investigating current methods of measuring slopes, assessing the accuracy of UAS measurements, and identifying the cost and time involved for both methods.

1.3. Scope

The scope of this research uses sloped excavations ranging from 5 to 20 feet. These excavations were measured using both a robotic total station and UAS. The accuracy, time, and cost impacts of using UAS for topographic and slope measurements compared to using a robotic total station was analysed.

2. Literature Review

A study was conducted concerning the current uses of drones in the construction industry and the associated costs. This study found that 70% of contractors use drones to capture aerial images for project management and documentation purposes. It also found that 82% of companies believe drones are a useful tool for project progress documentations [1]. With many construction companies already using drones for documentation purposes and the high approval rating of drone usage, UAS should be rapidly adopted by the remaining construction companies not yet using drones.

2.1. Traditional Slope Measurements using a robotic total station

The slope of an excavation can be determined by many different methods, but the most prominent is using a robotic total station. A robotic total station is surveying equipment that combines electronic distance measurement and automatic target recognition [2]. This equipment can be operated remotely and has been proven to be accurate and effective in monitoring and measuring slopes [3]. One of the main advantages of using a total station is the simplicity of collecting data. After data collection is complete, the data can be processed to determine the absolute coordinates [2]. Another advantage of using a robotic total station to measure sloped excavations is the accuracy of the instrument. Robotic total stations have been proven to be extremely accurate and capable of measurements within 0.5 mm of the actual location [4].

The main disadvantages include the initial cost, lines of sight, environmental factors, and maintenance [2]. A reference point must be set to give the robotic total station a baseline for data collection [4]. Access to all measurement points and reference points must be available to collect the data [3]. This means that, if a slope is too steep and cannot be easily walked on, using a robotic total station may not be possible. Even with the high accuracy and advantages of using a robotic total station, other methods may be simpler and more convenient.

2.2. UAS Alternative

One alternative to robotic total stations is using a UAS to measure sloped excavations. Since the creation of drone technology, many different types of drones have been developed. The size of the site, altitude of the flight, and data collection time are the main factors to consider when choosing a drone to measure a sloped excavation. This investigation used a DJI Mavic 2 Pro drone, a quad copter, and Pix4D software for data processing.

2.3. UAS Photogrammetry

Data captured by a single drone flight can now be used by a computer program to create a three-dimensional model of the built environment. One study evaluated the accuracy of georeferenced three-dimensional models created using UAS photogrammetry [5]. Precision was calculated using control points scattered around the test site, and the drone was able to measure these positions with a variance of 4 mm horizontally and 10 mm vertically [5].

The measurement accuracy of UAS photogrammetry has been studied in other applications. Millimeter accuracy was obtained during the experiments of one study. Many conditions must be met to ensure this level of accuracy, including that the control and survey points must be numerous, the lighting must be optimal, and the aircraft must be stable. The experiments also took significant time due to the large number of photographs needed to measure accurately [6]. The main finding of the study was the high measurement accuracy that can be obtained using UAS photogrammetry.

2.4. UAS Topographic Mapping and Measurements

Research has also been conducted on the accuracy of UAS topographic mapping on large sites. One study assessed the accuracy of UAS-based surveys using 18 missions on a 3.5 acre site using two different drones [7]. Root Mean Square Error (RMSE) was used to calculate the accuracy of the topographic measurements. RMSE is measured by finding the number of pixels for each checkpoint. RMSE values less than one pixel are considered to be highly accurate, values between one and three pixels are moderately accurate, and any value greater than three pixels is said to have a low level of accuracy. This study's results found that all RMSE values were under two pixels for all eighteen missions. Higher accuracy was obtained with a higher resolution camera and flight paths taking the photos from a lower altitude [7].

A similar study was conducted on an even larger site of 4.942 acres. The experiment for this study created digital terrain models (DTM) [8]. This model uses color to show changes in elevation. This study focused on the effects of changing the amount of overlap in the photos taken with front image overlaps of 70%, 80%, and 90%. The side lap percentages used in this study were 50%, 60%, and 70%. RMSE was used to analyze the high-resolution topographic [8]. These results show that using an 80% front image overlap and 50% image side lap resulted in the most accurate measurements in the x, y, and z coordinates. The flight with the least accurate results used an 80% front image overlap and 70% image side lap.

Another study was conducted on how the number of ground control points affects the accuracy of topographic measurements collected using UAS [9]. The results of the experiment showed that the error statistics were very similar regardless of the number of ground control points [9]. This study showed that a limited number of ground control points can produce acceptable results for many geotechnical applications.

2.5. Data Acquisition

Most research on the accuracy of UAS topographic mapping has employed the autonomous flight mode of the drone by pre-planning the flight on software such as Pix4D. Most UAS's have Global Positioning System (GPS) navigation capability that allows for autonomous take-off, navigation, and landing with the flight path following a pre-programmed pattern along with automatic camera operation. The flight programming software takes into account the area being surveyed, the amount of picture overlap desired, and the altitude above ground to be flown. Autonomous flights are able to collect asymmetrical images with the same overlap and side lap percentages on each flight. This greatly improves the image acquisition and photogrammetry process [10].

This study also investigated the effect of different flying altitudes on the accuracy of topographic measurements in easting directions, northing directions, and elevation. The findings clearly show that the most accurate results come from lower flight altitudes. As the altitude increases, the accuracy decreases in a linear relationship [10]. The impact of image quality was also included in the experiment. Pix4D software has three kinds of point cloud densification options including low, optimal, and high-quality modes. The findings showed that the higher resolution point clouds resulted in slightly more accurate measurements, but high-quality mode takes much more time to process the images and stitch them together. It is recommended to use high-quality images if a lot of vegetation is present [10]. Gridding is a critical parameter that can impact the accuracy of UAS-based topographic surveys. There are two main categories of gridding: single and double gridding. Using a double grid should increase the number and quality of images, but it can greatly increase processing time and cause more error sources. It is recommended to use a single grid for UAS-based topographic mapping [10].

2.6. Research Gaps and Limitations

All research to date on the accuracy of UAS topographic measurements has focused on large sites using a variety of UAS types, flying altitudes, photogrammetry software, image overlap, image quality, flight modes, and gridding systems. Accuracy assessments of UAS on sites less than half an acre or on a specific slope have not been widely researched. The cost and time impacts of UAS topographic measurements compared to robotic total stations have not been studied. Because of the potential for substantial cost and time savings using a UAS, because contractors may likely have a readily available UAS already being used onsite, and would be more likely to measure sloped excavations even on small construction sites, and because of the importance of these measurements to construction safety and construction quality, a systematic comparison of topographic measurements of slope by UAS versus robotic total stations in terms of accuracy, time requirements, and cost could be valuable to the construction industry.

3. Research Methodology

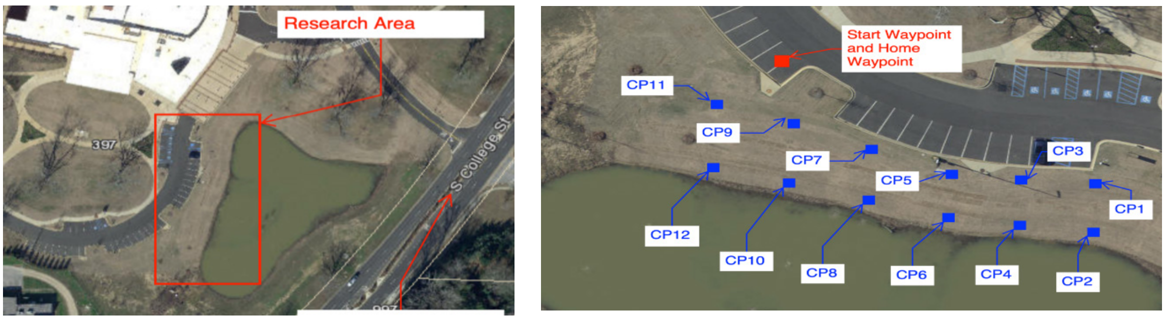
This research study consists of four phases. The first phase is experiment preparation, the second phase is data acquisition, and the third phase is data processing. The fourth and final phase includes the results and analysis of all data collected.

3.1. Phase 1: Preparation

3.1.1. Checkpoint Establishment

A slope feeding into a water retention area was selected as the experimental area for this research study. Wood survey stakes were driven into the ground at each of these points to ensure that they are clearly visible in the images collected from the drone. The stakes and hubs are not needed to measure the slope of the hill at the experimental site, but they will be used to ensure the topographic measurements of the robotic total station and UAS are from the exact same location. Refer to Figure 1 below.

Fig. 1. (a) Experiment Location, (b) checkpoints



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3.1.2. Flight Planning

The flight plans will be created using the Pix4DCapture application on a smartphone. The Pix4DCapture application is used to program flight information based on flight pattern, location, flight altitude, angle of the camera, front overlap, side overlap, and drone speed. After all the settings are selected, the flight plan is created by drawing a ‘fence’ around the area to be flown. This can be seen in Figure 2 below. This application can then be connected to the UAS controller to autonomously fly the set location and collect aerial images according to the programed settings.

Fig. 2. Programmed Flight Path

Three flights were planned. All used a 75 foot altitude, 80% front overlap, and fast drone speed. Experiment 1 used a single grid pattern (as shown above) and 50% side overlap. Experiment 2 used a single grid with 70% side overlap, and experiment 3 used a double grid (not shown but a second grid perpendicular to the single grid) with 70% side overlap. These were the configurations chosen for this study.

3.2. Phase 2: Data Acquisition

To determine the accuracy of the topographic measurements obtained from the UAS, accurate three dimensional coordinates of all checkpoints were obtained using a robotic total station – a Trimble RPT600 was used. For time comparisons, the total station was set up, measured all checkpoints, and taken down 3 separate times and the activity timed with a stop watch. This was included in later analysis.

The drone used to fly the programmed flight and collect the photo images was a Mavic 2 Pro. During each of the three experiments, a stop watch was used to measure the time it took to plan the flight, set up the drone, fly the mission, pack the drone back into its case, upload and process the data. Each of these time categories were recorded separately for later analysis.

3.3. Phase 3: Data Processing

Digital image processing was used to combine the digital images collected during each UAS flight into one model. Digital image processing is the stitching together and manipulation of digital images completed by software on a computer. Pix4DMapper was the software used to process the images. A densified point cloud is then created by using a set of three-dimensional coordinate points that reconstruct the images together [11]. The software is able to generate digital surface models and orthophotos. From these models, digital terrain models and contour maps can be created to determine three-dimensional coordinates at all checkpoints throughout the research area.

3.4. Phase 4: Results and Analysis

3.4.1. Accuracy and Slope Assessment

Root Mean Square Error (RMSE) is used by the American Society of Photogrammetry and Remote Sensing (ASPRS) for assessing three-dimensional coordinate accuracy [11]. The horizontal and vertical accuracy will be measured by comparing the coordinates of each checkpoint with the coordinates from the same point measured by the robotic total station. The RMSE values of horizontal and vertical measurements will be compared to the horizontal accuracy standards for orthophotos and the vertical accuracy standards for digital elevation data from ASPRS. Table 1 shows the horizontal tolerance for different classes of horizontal measurements obtained by orthophotos and the tolerance of vertical accuracy for elevation measurements in vegetated areas (ASPRS Accuracy Standards for Digital Geospatial Data, 2015).

Table 1. Horizontal and Vertical Accuracy Classes (additional classes not shown – refer to ASPRS document)

Horizontal Class	RMSE Values (cm)
I	Pixel Size x 1
II	Pixel Size x 2
III	Pixel Size x N

Vertical Class	Vegetated Vertical Accuracy (cm)
I	2.9
II	7.4
III	14.7

3.4.2. Time and Cost Assessment

To assess the time impacts of using UAS to measure sloped excavations, duration must be accurately recorded for each step of topographic measuring. During the data acquisition phase, the time spent on the UAS checkpoint measurements and robotic total station checkpoint measurements were recorded three times for each experiment.

Cost is a major factor for many construction companies. Saving money is essential to maximize the profit on each project. To compare the cost of using UAS versus robotic total stations to measure sloped excavations, the cost of labor will be compared. The labor cost will be measured by using the average time spent on each experiment multiplied by an hourly labor rate. A one person survey crew with a robotic total station was given an hourly rate of $225. This was assumed to be subcontracted. The hourly rate for the UAS crew considered a UAS pilot at $53 per hour with one visual observer at $41 per hour. These were assumed to be employed by the contractor.

4. Data Analysis

This section discusses the results of UAS-based sloped excavation measurements using photometric surveys for each experiment.

4.1. Horizontal, Vertical, and Slope Measurements

The photogrammetry model for each of the three experiments were processed with Pix4DMapper software to create an orthomosaic model and a digital surface models as shown in Figure 3 below.

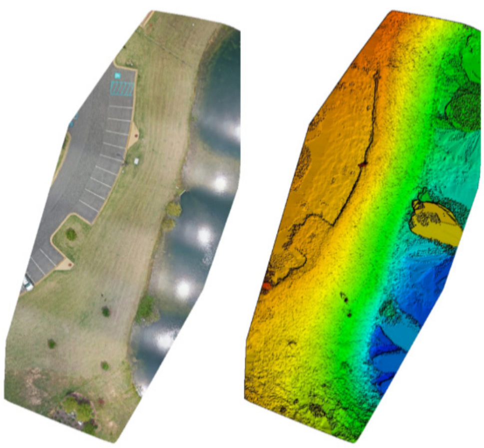

Fig. 3. Orthomosaic Model (Left) and Digital Surface Model (Right) from Experiment 1

Any point in the orthomosaic model can be selected to give the calculated three-dimensional location obtained from the drone flight. The horizontal distances, vertical distances, and slope measurements obtained in UAS experiments were compared to the same data from the robotic total station to find the delta in each measurement. These deltas were used to calculate the RMSE by taking the square root of the sum of the measurements in the horizontal direction, vertical direction, and slope and dividing by the count of the measurements.

4.2. Accuracy Comparison

The UAS-based distances measured in the three experiments were compared to the same distances calculated from the robotic total station. This comparison used RMSE to determine the accuracy of the UAS-based photometric values with the assumption that the values collected by the robotic total station were precisely correct. The RMSE values were computed in centimeters to simplify comparison to the accuracy standards for digital elevation data. The RMSE values can be seen in Table 2 below.

Table 2. RMSE Values and Horizontal / Vertical Data Accuracy Classes

	Horizontal RMSE (cm) (Class)	Vertical RSME (cm) (Class)	Slope RSME (cm)
Experiment 1	42.623 (XVII)	74.562 (VII)	0.090
Experiment 2	10.369 (V)	24.693 (IV)	0.035
Experiment 3	5.877 (II)	3.956 (II)	0.006

Using UAS photogrammetry models from experiment 1, the horizontal and vertical measurements were not consistent or accurate. In this case, the measurements did not meet the industry standards for accuracy. While Experiment 2 was more accurate horizontally, this scenario did not reach an acceptable of accuracy.

Experiment 3 used a double grid flight plan with 80% forward overlap and 70% side overlap at a flying altitude of 75 feet and was the most accurate of the three experiments. The horizontal and vertical measurements were consistent and accurate due to the increased number of photographs used to produce the orthomosaic model. The horizontal measurements ranged from 1.949 to 7.987 centimeters off of the measurements obtained from the robotic total station. The vertical measurements were incorrect by a range of 0.132 to 7.234 centimeters. In this case, alternate hypothesis 1 proved to be true. The application of UAS in measuring sloped excavations did reach an acceptable accuracy class of the ASPRS Accuracy Standards for Digital Geospatial Data in experiment 3. The RMSE values for experiment 3 were significantly lower because of the number of images collected to produce the orthomosaic model.

4.3. Time Comparison

The time spent on data collection and processing for each experiment was measured with a digital stopwatch and recorded. The data collection phase was split into setup time, data collection time, and disassembly time. The breakdown of times can be seen in Table 3 below. The 3 robotic total station timings were so close, only the average time for each category is shown in the table.

Table 3. Time Comparison (min:sec)

	Setup	Data Collection	Disassembly	Data Processing	Total Time
RoboticTotal Station	8:08	10:07	3:18	13:54	34:27
UAS 1	3:50	3:17	1:22	61:05	69:34
UAS 2	3:32	3:28	1:14	75:15	83:29
UAS 3	3:48	8:13	1:14	118:46	131:01

The total time using the UAS was much longer than the average robotic total time. In the data collection phase the drone was able to collect the data faster than the robotic total station. This relative efficiency of the drone in data collection is due in part to the longer times required to set up and take down the robotic total station and also due to the extensive amount of walking to each checkpoint in order to get the measurements. The Trimble RPT600 used a Panasonic tablet that was able to record the data and export them into an Excel file. The Excel file simply had to be saved on a flash drive and loaded onto a computer. This made the processing stage quick and easy. The majority of time in data processing for UAS was Pix4DMapper processing the images to create the orthomosaic and digital surface models. Once these models were created however, locating each checkpoint was as simple as clicking on the survey hub and recording the three-dimensional coordinates. In all, application of the UAS in measuring sloped excavations took more time compared to using a robotic total station to measure the slope.

4.4. Cost Comparison

The total time spent in each experiment to measure the slope at the experimental location was used to find the associated cost. The total time spent was multiplied by the hourly rate of an appropriate worker to calculate the cost of performing the slope calculations in each experiment. The cost calculations can be seen in Table 4 below.

Table 4. Slope Measurement Cost

	Hourly Rate - Operator	Hourly Rate – Visual Observer	Time (hours) - Operator	Time (hours) – Visual Observer	Total Cost
RoboticTotal Station	$225	N/A	0.59	N/A	$132.75
UAS 1	$53	$41	1.16	0.14	$67.26
UAS 2	$53	$41	1.475	0.14	$83.95
UAS 3	$53	$41	2.2	0.22	$125.08

The average cost for the robotic total station to measure the sloped excavation was $131.25. All three UAS experiments cost less than using a robotic total station. This proves alternate hypothesis 3 to be true. The application of UAS in measuring sloped excavations reduced the cost compared to using a robotic total station to measure the slope. However, the most accurate UAS measurements were obtained from UAS experiment 3, and the cost of this experiment was $125.68 because the double grid flight plan required more time to capture the additional images and to process the additional associated data. This cost was only slightly less than that of all three robotic total station experiments. If the measurement accuracy of a double grid flight plan is needed in order to use UAS to measure sloped excavations on construction sites, there will not be as much cost savings relative to robotic total station measurements.

4.5. Discussion

The results of the three UAS experiments differed because the varied flight parameters affected the number of orthophotos collected in each experiment. The number of orthophotos affected the detail of the orthomosaic and digital surface models created from Pix4DMapper and the time required to process the images.

5. Conclusions and Recommendations

In this research study, the results varied between the different experiments conducted with the UAS in measuring a sloped excavation. The accuracy of UAS experiments 1 and 2 did not meet industry standards, while experiment 3 did meet the accuracy standards. In all three experiments, UAS-based slope measurements took more time when compared to a robotic total station, but UAS-based slope measurements also cost less when compared to a robotic total station. Given the differing results of each experiment, there is much to be learned about measuring slopes with drones.

However, the time for data processing was a significant factor in the UAS calculations which was compounded by counting operator hours for this process. It should be noted that the majority of data processing time is the time taken for the computer program to run which can be done unattended once it is set up. Making adjustments for this would significantly reduce the cost of the UAS operations.

5.1. Conclusions

The inaccuracy of slope measurements using UAS in this study ranged from 5.877 to 42.623 centimeters in the horizontal direction and ranged from 3.956 to 74.562 centimeters in the vertical direction. The major inconsistencies were derived from the different flight plans used in each experiment. The main correlation found in this study was that the most accurate slope measurements were produced by the UAS flight plan that collected the largest number of images. The most accurate experiment used a double grid flight plan with 80% forward overlap and 70% side overlap. This flight collected 151 images.

In short, this research shows that, with certain flight plans, UAS's could be used to accurately measure sloped excavations and save money when compared to using a robotic total station. Using a UAS should not be viewed as a replacement for traditional survey methods but another option to measure slopes. The application of a UAS would be very beneficial if a robotic total station is not available within the needed time frame, if the slope is steep, or if the slope is hard to traverse.

5.2. Recommendations for Further Study

The first recommendation would be to use the double flight grid on multiple experiments to determine the consistency of UAS slope measurements. On a much larger site, the data collection time could be much longer using a robotic total station. If this is the case, UAS could save significant time in measuring sloped excavations. Another recommendation is to complete a similar study utilizing a drone other than the DJI Mavic 2 Pro and a different software program than Pix4D to determine the impacts on accuracy, time, and cost. This future research could define more precisely the parameters when using UAS to measure sloped excavations would be the most beneficial to the construction industry.

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