

**MOBILE 3D MAPPING FOR SURVEYING EARTHWORK  
USING AN UNMANNED AERIAL VEHICLE (UAV)**

Sebastian Siebert<sup>1</sup> and \*Dr. Jochen Teizer<sup>2</sup>

<sup>1</sup> *Bickhardt Bau Aktiengesellschaft  
Industriestraße 9  
36275 Kirchheim, Germany*

<sup>2</sup> *RAPIDS Construction Safety and Technology Laboratory  
School of Civil and Environmental Engineering  
Georgia Institute of Technology  
790 Atlantic Dr. N.W.  
Atlanta, GA, 30332-0355, U.S.A.  
(\*Corresponding author: teizer@gatech.edu)*

# MOBILE 3D MAPPING FOR SURVEYING EARTHWORK USING AN UNMANNED AERIAL VEHICLE (UAV)

## ABSTRACT

Unmanned Aerial Vehicles (UAV) as a data acquisition platform and as a measurement instrument have become attractive for many surveying applications in civil engineering. However, their performance is not well understood for these particular applications. The specific scope of the presented work is the performance evaluation of a UAV system that was built to rapidly acquire mobile 3D mapping data for large earthmoving construction sites. Details to the components of the developed system (hardware and control software) are explained. A novel program for photogrammetric flight planning and its execution for the generation of 3D point clouds from digital mobile images is explained. A performance model for estimating the position error was developed and tested in several realistic construction environments. Results to these tests are presented as they relate in particular to large excavation and earth moving construction sites. Results and experiences with the developed UAV system are in particular useful for researchers or practitioners in need for successfully adapting UAV technology for their application(s).

## KEYWORDS

Aerial surveying, camera, geomatics, laser scanning, mapping, photogrammetry, range point cloud, total station, safety, surveying, unmanned aerial vehicle (UAV), vision sensing.

## INTRODUCTION

Until recently, Unmanned Aerial Vehicles (UAV) or drones were mostly developed and used for military applications. These systems were remotely-controlled aircrafts or helicopters. They were equipped with precision sensors (e.g., inertial motion units (IMU) and gyroscopes) for recognizing the alignment and position of the aircraft. A microcomputer made autonomous navigation without much manual involvement of a pilot possible. Due to the cost and size of these sensors, a non-military use especially in small UAV system was not feasible for many commercial applications. With the recent availability of highly accurate and low-cost Global Positioning Systems (GPS), the possibility opened up to maintain a UAV system's position in a global reference system nearly everywhere in the world and in real-time. However, selective availability of such GPS signals prevented most commercial applications. It was until mid-1990 when the accuracy of GPS for commercial applications dropped to just a few meters (GPS 1995). The development of cost-efficient and light gyroscopes to measure alignment and orientation primarily for smart telephones enabled many hobby modelers to update their airplane or helicopter models to a fully functional UAV. Most of the UAV developers gained their first experiences with model aircrafts.

With the arrival of precise GPS and gyroscope technology the performance, especially the payload, endurance, and flexibility for diverse and reliable application of UAV systems was significantly improved. Most recently, light-weight digital photo or video cameras converted autonomous UAV to highly mobile sensor platforms. However, few applications in civil engineering have yet been explored, but promise to provide cost- and task-efficient approaches to conventional approaches. In particular surveying applications which in the past relied on GPS, Robotic Total Station (RTS), laser scanning, tachymetry, air- or space-borne technology are either ground or aerial-based, and depend on the terrain, are limited in range, very labor intensive and costly, have high measurement errors, and/or time consuming to perform. These approaches can – if UAV technology proves to be accurate and reliable – eventually be assisted or replaced for a specific segment in surveying applications. Although several researchers have previously introduced the UAV technology to civil engineering applications (Eisenbeiß 2009), its performance in the harsh construction environment has yet to be explored and evaluated.

The potential range of surveying tasks which UAV technology is able to perform is shown in Figure 1. This figure also displays the UAV system the researchers built. The worldwide use of UAVs is regulated by the specific national federal administrations. For safety and security reasons commercial UAV use is typically restricted to flights within line-of-sight (LOS) of an operator. Typically the operator is referred to a *pilot*. It ensures a pilot has permanent control and interaction in case of unexpected events, e.g., other aircraft(s) operating nearby or changes of any of the environmental conditions that might influence the flight conditions, e.g. wind parameters.

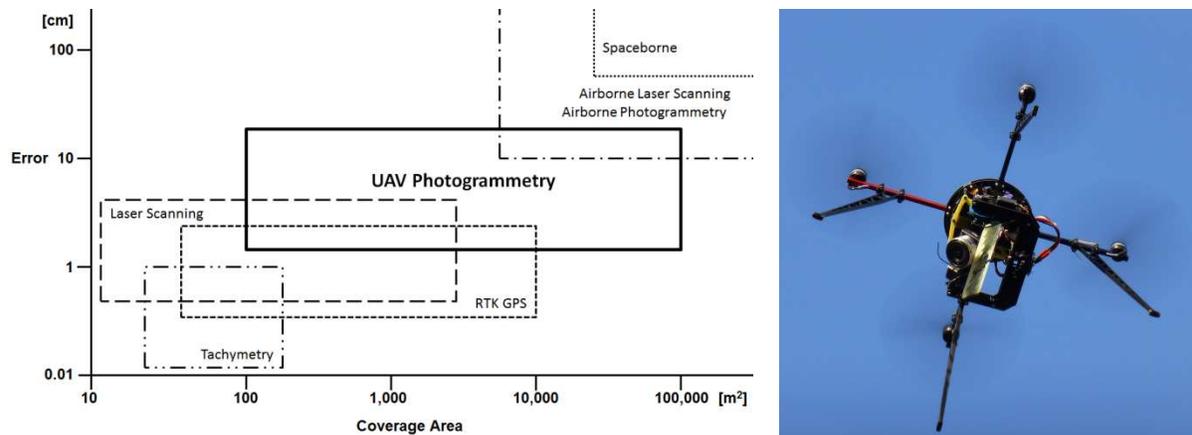


Figure 1 – Potential UAV application area in surveying tasks (modified; Eisenbeiß 2009) and the developed UAV.

### DESIGN, COMPONENTS, AND ASSEMBLY OF UAV

The developed UAV system was specifically designed to successfully complete surveying tasks in civil engineering applications. The system is based on a quadcopter principle. Quadcopters have distinct advantages compared to other existing UAV approaches. Some of the advantages are its low purchase, operation, and maintenance costs, its flexibility to operate (start and land) in very small surveying assignments, the easiness to steer it reliably in autonomous and pilot mode, and to keep it under control when harsher ambient environments exist, e.g., strong winds. Its main limitations, e.g., limited range and flight time, are secondary since many federal regulations allow line-of-sight (LOS) operation only.

The design of the developed quadcopter is based on components of the Mikrokopter Quad XL (Mikrokopter 2013). The quadcopter that was assembled has four brushless electrical motors and 12 inches long carbon fiber propellers. Its total size in diameter is one meter. The quadcopter is able to produce an absolute thrust of 9 kg. It's empty (without battery and camera) and gross weight is 1 and 2.6 kg, respectively. The lithium polymer battery weighs 0.6 kg and provides 14.8 volts at a capacity of 6,600 mAh. A payload of 1.5 kg can be added. Some of it was used to mount a Sony NEX5N (16 mm fixed focal length, 16.1 MP per image) camera system.

The frame of the quadcopter is made out of lightweight materials such as aluminum and carbon fiber reinforced plastic. It has space for the motors, battery, electronic parts, and the camera mount. The Flight Control Unit (FCU) is the core part of any UAV. It is able to process and implement the input commands from the pilot or the autonomous navigation routine into certain navigational tasks. The Inertial Measurement Unit (IMU) is designed to recognize the actual alignment, acceleration, and barometrical altitude. The four brushless motor controllers receive their commands from the FCU to trigger the rotational speed of the motors. The FCU is also directly connected with a low cost differential GPS receiver and a magnetic compass. It is designed to extend the navigational capabilities of the quadcopter, e.g., functions become possible like position hold, coming home, and flight according to pre-identified waypoints.

The flight trajectory data for a waypoint route is typically stored in a digital file that is submitted to the UAV with a wireless data upload link from a ground control station, a mobile computer or smartphone. Thanks to a XML-based file structure of the waypoint file it is possible to create a waypoint route with an external software solution. The current waypoint file is limited to 100 points which specify global position, flying altitude above ground, heading, speed, and the external control for pitch and triggering of the camera. It also allows specifying the time the quadcopter spends at a waypoint location and the required accuracy before the camera takes a photo. Photos are normally taken on the fly. The camera mount on the bottom of the quadcopter includes two servo motors which control the pitch and roll angles of the camera. This allows the camera to stay in a nadir position during the flight. The camera shutter is controlled with an infrared-trigger device that is connected to the FCU.

In the current design, the quadcopter is able to stay about 16 minutes in the air and can travel a total distance of about 1 km at a flying altitude of maximum 400 m. Although these technical characteristics are

available, the surveying assignments the quadcopter was given in this research required it to travel only about 400 m at a time and at an altitude of about 100 m. The quadcopter can be both manually controlled or put in an autonomous flight mode. A commercially-available 2.4 GHz transmitter (as it is used to steer many model aircrafts or helicopters) was used for manual control purpose. An 868 MHz data link provides the possibility to maintain real-time flight information and wireless waypoint transmitting. Equipped with a differential GPS receiver, the quadcopter was able to follow autonomously a pre-defined 3D flight trajectory of up to 100 waypoints.

Essential building expertise for the hardware assembly both researchers have was assisted by a professional. The modular UAV design allows adding or replacing quadcopter components as a user requests, e.g., camera mount and wireless data signal transmission. This is particularly helpful in optimizing the design for practical uses in civil engineering applications. The total hardware cost is estimated to a few thousand dollars only (about \$6,000), thus offering attractive investment-return opportunities for users.

### FLIGHT PATH PLANNING AND DATA COLLECTION PROCESS

At an early research stage it was realized that the commercially-available flight preparation tool was insufficient in handling photogrammetric surveying applications. The Mikrokopter Flight Planning Tool (MK FPT) was modified to minimize the manual effort in the flight planning process. The modified version of the computer program addressed some specific aspects of aerial photogrammetry for surveying applications in civil engineering, e.g., overlapping of photo imagery to guarantee the appropriate overlapping coverage. All that is left for a pilot is to select the region of interest (survey area) on an interactive map, camera model, photo size and resolution, flight altitude above ground, flight speed, and the longitudinal and traversal coverage area of each photo. The flight planning software uses these parameters to compute a full flight plan consisting of the waypoints where the quadcopter takes along its flight path the photos automatically. The file format that stores the flight plan is .WPL. Up to 100 waypoints can be entered in an user-interface with very little manual effort. The user clicks on a satellite map to define start and end point of the flight path. Based on a preset resolution, an optimized flight path is automatically generated.

The following flight process was developed: (1) prepare UAV for flight, e.g., check its hardware including frame, motors, propellers, battery, sensors, availability of signal, (2) turn on the (photo) camera, (3) upload the waypoints for the flight path, (3) check the environmental conditions including surrounding airspace, wind, human hazards, (4) turn quadcopter on, lift it off the ground manually, and switch to autonomous flight mode. After lift-off, the quadcopter is following its preset tasks autonomously. At each waypoint the quadcopter takes a photo. In case of an unexpected event, a manual intervention is possible at any time. When the last waypoint is reached, the UAV returns automatically to its lift-off location by switching to the “coming home” mode. The landing can be performed either manually or automatically. The data acquisition is now complete. If the size of the survey area is too large for one flight, additional flights can be performed.

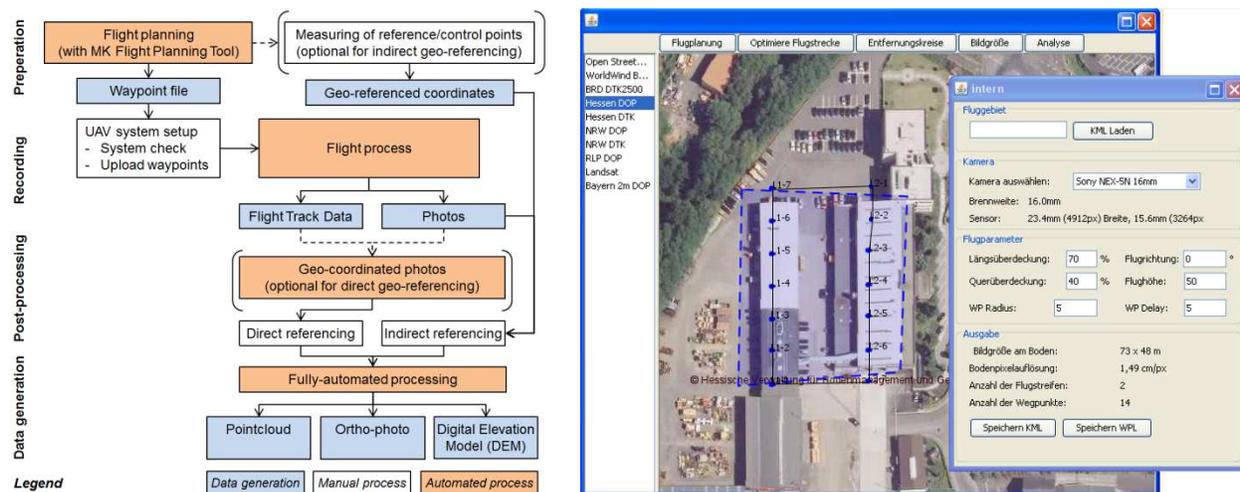


Figure 2 – Flight methodology (left) and developed UAV flight path planning interface with waypoints (right).

## PHOTOGRAMMETRIC DATA PROCESSING AND GENERATION OF 3D POINT CLOUDS

Photogrammetric data processing is needed to generate a geo-referenced 3D point cloud from the unordered, overlapping, and surface image collection. Existing Structure from Motion (SfM) algorithms are used to automatically extract features in the images, e.g., contour lines, edges, and feature points. Homologous areas, interior and exterior orientations are computed in a bundle adjustment. The Exchangeable Image Format (Exif) metadata from each digital image further provides approximate values for the focal length and image size.

A detailed review how to generate 3D point clouds from photo imagery can be found in related literature by Lowe (2004) and Snavely et al. (2007). They applied SIFT (Scale Invariant Feature Transform) for key-point detection. Furukawa et al. (2010) proposed a multi-stereo-view approach for large unorganized datasets. Furukawa and Ponce (2010) presented an algorithm for generating referenced 3D point clouds that are based on the computation of rectangular patches in overlapping areas of adjacent images.

A commercially-existing software solution by AgiSoft PhotoScan (2013) was used to establish the relation between the unordered image data collection. This software has been recently optimized for the use with UAV. The software's professional edition allows to geo-reference the results in a specific coordinate system. It exports these to a digital elevation model or orthophoto. The recommended computer processing requirements for such large data gathering projects with more than 100 images are a 64-bit operating system with at least 16 GB RAM.

The data processing is not complicated. First, the aerial images are imported from the camera to the computer. It is necessary that the images have an adequate overlap between each other. From the Exif metadata, their approximated interior orientation (focal length and image sensor size) is determined. Thereafter the processing of the image collection begins. It is split in three main parts: (1) align photos, (2) build geometry, and (3) build texture (if required). Each part gives several possibilities to adjust parameters, which have an influence on the accuracy and structure of the results and the processing time. It is possible to export these results as a colored point cloud, a digital elevation model with matched texture, or an orthophoto. An automatically generated report assesses the quality and accuracy to each step in the data processing process.

It is essential to geo-reference the data for further use in surveying applications. This task can be completed in two different ways within PhotoScan: direct and indirect geo-referencing.

Direct geo-referencing can be achieved by using time-stamped GPS data which is recorded during the flight. Synchronization of the internal camera time and GPS time is achieved automatically. The exposure position of the image will be integrated in the Exif data as geographical coordinates in the WGS84 format. PhotoScan integrates all data and makes an adjustment to the exterior orientation of the images. As a result, a point cloud is transferred to the given coordinate system.

Indirect geo-referencing can be applied by measuring reference targets that were deployed on the ground in the area of interest before the flight. These targets must be clearly visible in the images. Should targets not be available, it is also possible to use existing features in the environment which are fixed, e.g., manhole covers or road markings. These reference points must be surveyed with a suitable survey method (e.g., differential GPS or tachymetry). During the data processing process it is also necessary to manually identify the reference points in the model provided by PhotoScan. The measured coordinates of the targets will be referenced to the model. Accordingly, the complete model will be geo-referenced using a spatial transformation. At least three reference points are needed for this process, but it is recommended to use significantly more.

Direct geo-referencing offers the advantages that no ground-based surveying and neither manipulation of the 3D point cloud are necessary. It is faster than indirect geo-referencing. However, indirect geo-referencing can take full advantage of using the GPS data that was recorded during flight and relate it easily to the GPS data which was collected in the field. As such, the user has to decide if the final product of a referenced point cloud should be achieved faster (preference should then be given to a direct geo-referencing method) or if higher accuracy is required (indirect geo-referencing should be preferred). Existing commercially-available photogrammetric data processing software can perform the referencing task of 100 images taken during a UAV flight within about three hours.

## ERROR ANALYSIS AND EVALUATION IN A TEST BED ENVIRONMENT

For the use in surveying applications an absolute accuracy analyses of the point cloud is mandatory. Preliminary results from a first approach were published in Neitzel et al. (2010) and Neitzel and Klonowski (2011). Their purpose was to compare several low cost and free software solutions for SfM under similar conditions. The error of their UAV and data processing software solutions was measured using a test bed environment in the size of 100 by 150 m. Corner points of a parking lot were surveyed in height and position using tachymetry. Nearly 500 control points were measured for the error analysis using PhotoScan. An average positional error of 5.6 cm and a height error of 2.5 cm were measured. In their research, they further reported that the results largely depend on the topography of the test bed area.

The research presented in this paper conducted new experiments in the same test bed, however, using additional and modified features: integrated geo-referencing, advanced export functions, script support, optimizing camera parameters, and point clouds with the help of measured reference points. This new measurement required fewer photos from an altitude of only about 50 m. The images taken at the new altitude had also more overlapping areas with each other. Finally, instead of using four, nine reference points on the ground were used (see “x” in Figure 3). Adding more features to the referencing process significantly contributed to a reduced error. As shown in Table 1, the maximum error of a single point was reduced to 4.9 cm. The maximum height error was reduced to +/- 6.4 cm. Even better results can be expected when a better UAV design and camera with higher resolution are used.

The errors of the conducted measurement in 2012 can also be visualized and compared to the ones of Neitzel et al. (2011) in 2010. No significant changes can be observed for the positional errors (left image in Figure 3). The thickness of the arrows displays the size of the error at a given location (marking stripes on the parking lot). However, much more moderate height errors in the bottom right area of the test bed area can be seen (right image).

Table 1 – Errors of the same UAV system in the same test bed environment but operating with different parameters.

	Neitzel et al. 2011	2012
Software	Agisoft PhotoScan Standard 2010	Agisoft PhotoScan Professional 2012
Flying altitude (resolution)	30 m (0.7 cm/pixel)	50 m (1.2 cm/pixel)
Reference points	6	9
Image count	99	49
Average positional error	5.6 cm	0.6 cm
Average height error	-2.5 cm	-1.1 cm

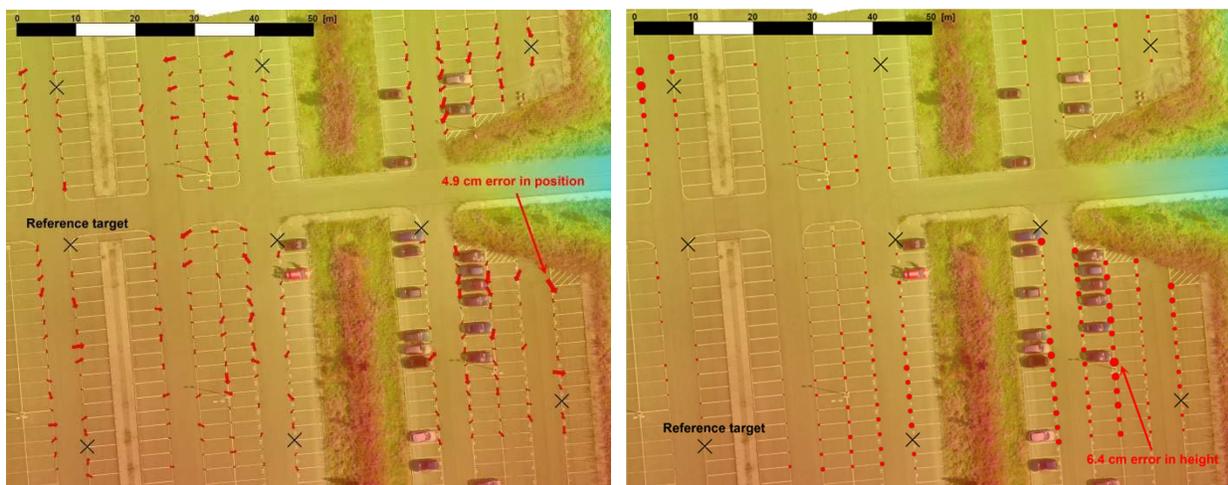


Figure 3 – Results of the 2012 measurements: Arrows indicating the size and orientation of errors in position (left) and circles indicating the size of errors in height (right).

## UAV PERFORMANCE MEASUREMENT IN A FIELD-REALISTIC SCENARIO

Existing performance results relate mostly to optimal test bed scenarios and conditions. Measuring the error performance of a UAV system ultimately requires evaluation in a realistic field study. Various test sites under realistic conditions were selected to measure the error performance of the developed UAV system and to highlight its advantages and current limitations. A secondary objective of these field trials was to generate very dense 3D point clouds from aerial photogrammetry (orthophotos with more than 100 points per square meter). Ground truth data was measured using conventional survey techniques, e.g., processes which generate highly accurate surface models from differential GPS receivers and tachymetry. Since obtaining such models is time consuming and resource (personnel and instrument) intensive, the field user had in mind estimating large earth-volumes in excavation and hauling applications rapidly for potential later use in advanced productivity and progress monitoring. As earth volume estimates generated by a UAV-based surveying approach may differ from any conventional surveying method, great interest was put on measuring the errors in the generated 3D surface models.

The location of the test site was Friedewald, Germany. The widening of an existing highway required the removal of an old clay pigeon shooting range (see Figure 4). Since such clay material is considered hazardous waste under German law, the site required specialized excavation and treatment before any of the clay material could be repurposed. The estimated area of specialized excavation had a size of 17,000 m<sup>2</sup> (200 x 85 m) and a specified depth of several centimeters over the entire area. GPS-controlled excavators were proposed to excavate the contaminated top soil applying lean principles (reducing if possible any waste such as rework, too much, or too little excavation). The general contractor asked the research team to conduct a performance analysis of the developed UAV system. As explained earlier, survey and documentation of results with a RTS-based surveying approach was compared to the automated UAV-direct geo-referenced mapping approach. Both results were referenced to a global coordinate system that was eventually used to control the excavating equipment. The following explains procedures and results.

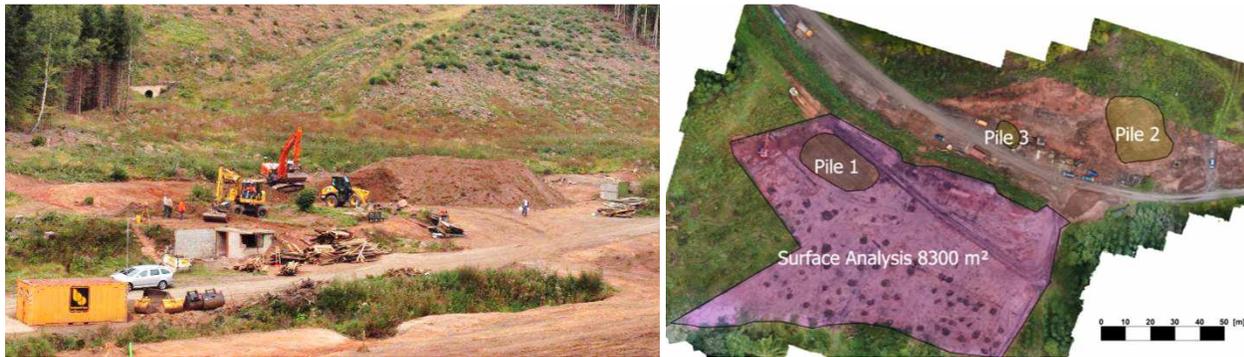


Figure 4 – Field trial environment (left) and plan view of the generated ortho-image with the selected earth piles that were used for the comparative study (right).

The UAV survey was prepared as previously explained by (1) measuring and marking of eight ground control targets in the observation area using a GNSS receiver and SAPOS (German DGNSS Reference Station System) and (2) planning the flight trajectory with the developed flight planning tool and the following attributes: camera (Sony NEX5N with 16mm fixed focal length), flying altitude of 70 m, longitudinal overlap 80%, lateral overlap 60%.

A total of 64 images were recorded providing a ground resolution of 2 cm per pixel at an estimated mean error of 2 cm (horizontal) and 6 cm (vertical). A more detailed error analysis was performed in some of the selected excavation area, e.g., a larger area (8,300 m<sup>2</sup>) and three smaller earth piles. All were measured with the RTS and UAV. The terrain did not change between both measurements. Potentially existing interferences from vegetation in both surveys were removed. Since the area was cleared already from trees and large bushes, this manual task took only a few minutes for both surveys. 3D surface models based on data from both survey methods were generated. The results were compared.

The points recorded and measured by the RTS and UAV were 202 and 122,275, respectively. The overlapping area between the two models was 7,761 m<sup>2</sup>. A triangulated surface mesh model was generated for each point cloud. Subtracting both models from each other resulted in a volume difference of 149 m<sup>3</sup> or an average height difference of 1.9 cm (=149/7,761 m) over the entire overlapping area. Table 2 displays more interesting results as they relate to the RTS and UAV comparison. It also includes a comparison how long each survey technique took. The circles in Figure 5 explain at what locations (center or circles) the error of the UAV system was high and small (large and small circles, respectively). The numbers in Figure 5 indicate the differences in elevation between the RTS and UAV measurements which were taken from 142 accessible locations on the project. The mean of the height error between the RTS and UAV measurements was 4.2 cm with 5.9 cm as the standard deviation.

Table 2 – Comparison of results to RTS and UAV survey applied to a larger excavation area.

Survey method		RTS survey	UAV-mapping
Coverage area		14,330 m <sup>2</sup>	24,900 m <sup>2</sup>
Time needed	Preparation	120 min	60 min
	Recording	420 min	15 min
	Evaluation	120 min	60 min
	Overall	660 min	135 min
Point count		350	More than 2,000,000
Point density		0.02 points/m <sup>2</sup>	Up to 561 points/m <sup>2</sup>
Mean accuracy of the transformation		Horizontal 0.3 cm Vertical 0.2 cm	Horizontal 0.9 cm Vertical 0.2 cm Pixel error 0.5 pixels
Accuracy of targets		Horizontal 0.7 cm Vertical 0.3 cm	Horizontal 3 cm Vertical 0.5 cm

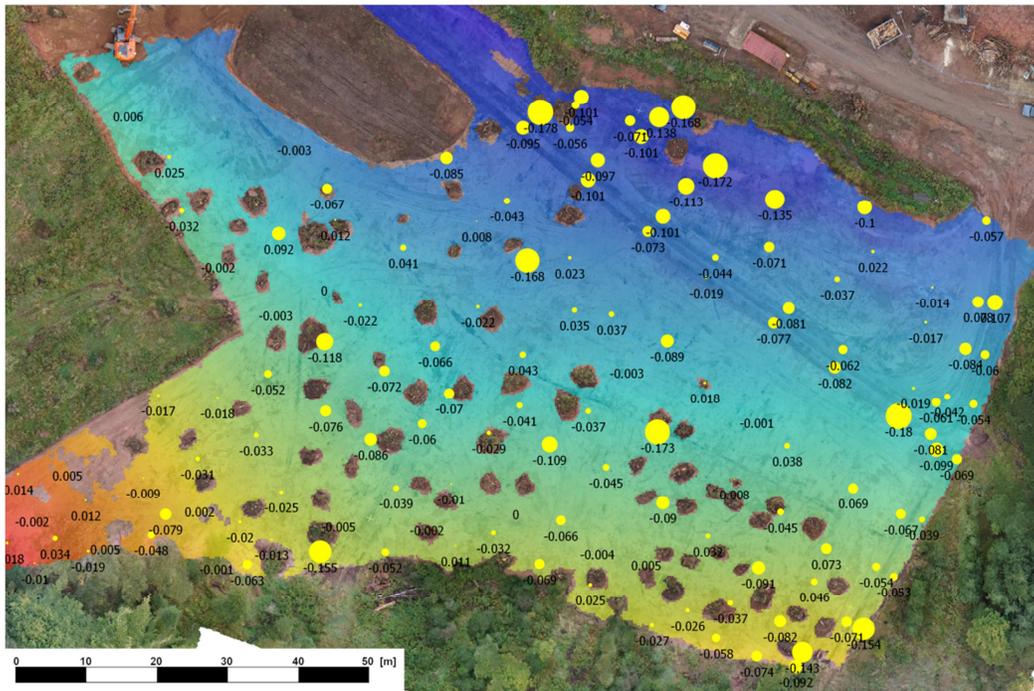


Figure 5 – Error location and size (in m) of UAV-generated survey data in a field-realistic environment.

The UAV surface model was on average about 1.9 cm higher than the RTS surface model. Potential reasons for this observation are: (1) thickness of the ground control points (reference targets had a height of 1 cm), (2) the general tendency of measuring too low with a RTS (e.g., having the surveying pole/rod slightly penetrating the ground surface), (3) impact of vegetation and surface conditions (e.g., areas with standing water that cannot or hardly be measured using a RTS), and (4) number of survey point (a higher number of measured points eventually

makes a UAV-based measurement technique more accurate since the measurement resolution is denser). Latter two reasons were specifically observed and noted in the field experiment.

For these reasons, three isolated earth piles (see Figure 4) were measured in more detail. Results are shown in Table 3. The differences in the surveyed earth volumes for the three piles were between 8-16%. Since fewer points were taken with the RTS, it is assumed the measurement with the UAV provides a more accurate earth volume estimate. However, to avoid over- and underestimating of the volumes a terrestrial dense point cloud laser scanning approach should have been utilized to compare the results more accurately. Although such alternative surveying methods need to be applied in future research, it may provide little practical value because earthwork estimating work which is conducted frequently through field inspection and personal site visits requires fast data collection and analysis. Most earth volume estimates are measured with a RTS because it offers sufficiently accurate data. It is often preferred over laser scanning since it is less expensive, collects fewer points, and is easier to setup.

Table 3 – Survey results of RTS and UAV on three earth piles

	Area	RTS		UAV		Error	
	[m <sup>2</sup> ]	[m <sup>3</sup> ]	Points	[m <sup>3</sup> ]	Points	[m <sup>3</sup> ]	[%]
Pile 1	443	730	29	789	3,877	59	8%
Pile 2	440	997	40	1,090	2,617	93	9%
Pile 3	95	81	24	95	454	14	16%

## DISCUSSION AND CONCLUSION

This paper presented an approach for evaluating the performance of an Unmanned Aerial Vehicle (UAV) in test bed and field-realistic environments. It explained the hardware components as well as a novel flight path planning tool that allows a pilot to launch the UAV for automated surveying tasks. The methodology on how photo images taken by a camera attached to the UAV are geo-referenced was explained. The UAV was evaluated in a test bed environment and its performance was assessed by comparing its results to other research publications. Furthermore, test trials in field-realistic environments were conducted to demonstrate the applicability of UAV and photogrammetric surveying for civil engineering applications. The evaluation focused in particular on the magnitude of the errors of a UAV-based photogrammetric approach as it compares to conventional surveying techniques that were used for ground truth measurements. Factors and errors influencing UAV-based photogrammetric measurements were defined and discussed. Results of these tests demonstrate improvements compared to previous research. However, some technical limitations may need resolution, such as the battery life limiting the flight duration. Future work may also address on developing case studies of using UAV in harsh work environments.

## REFERENCES

- Agisoft (2013). <http://www.agisoft.ru> (Accessed June 25, 2012).
- Eisenbeiß, Henri (2009). *UAV photogrammetry*. Dissertation, Institute of Geodesy and Photogrammetry, ETH Zurich.
- Furukawa, Y., Curless, B., Seitz, S.M., and Szeliski, R. (2010). “Towards Internet-scale multi-view stereo”, *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 1434-1441.
- Furukawa, Y. and Ponce, J. (2010). “Accurate, Dense, and Robust Multiview Stereopsis”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, (32)8, 1362-1376.
- GPS (2005). <http://www.gps.gov/systems/gps/modernization/sa/> (Accessed January 15, 2013).
- Mikrokopter (2013). <http://www.mikrokopter.de> (Accessed, June 15, 2012).
- Lowe, D. (2004). “Distinctive image features from scale-invariant keypoints”, *International Journal of Computer Vision*, 60(2), 91–110.
- Neitzel, F., Klonowski, J., Siebert, S., and Dasbach, J. (2011). “Mobile 3D Mapping mit einem low-cost UAV-System am Beispiel der Deponievermessung”, *Proceedings of Oldenburger 3D Tage (Photogrammetrie Laserscanning Optische 3D-Messtechnik)*, Wichmann Herbert, 300-311.
- Neitzel, F., and Klonowski, J. (2011). “Mobile 3D mapping with a low-cost UAV system”, *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, 38, 1-6.
- Snavely, N., Seitz, S.M., and Szeliski, R. (2007). “Modeling the World from Internet Photo Collections”, *International Journal of Computer Vision*, (80)2, 189-210.