ACCURATE DSM PRODUCTION FROM UNMANNED HELICOPTER SYSTEMS

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ABSTRACT:

Since the previous ISPRS conference in 2004 there have been several developments in modern navigation and earth observation. One of the new developments is accurate production of dense Digital Surface Models (DSMs), three-dimensional (3D) vector maps, and high resolution orthophotos from unmanned aerial vehicles (UAVs) with a state-of-the-art navigation and control system for hands-off autonomous flights. The authors have successfully completed several scientific and commercial photogrammetric projects using these UAVs for a variety of applications, like for example modelling archeological sites on the Unesco world heritage list, creating high quality and realistic three-dimensional building models for urban planning, producing three-dimensional cadastral and transportation map updates, reconstructing mountain rock faces, and calculating volumes of stock piles. This paper presents the results of four particular show case projects: a highway and the Geofort in the Netherlands and two projects in Switzerland: a corn field and the Rand rockslide. The UAV photogrammetric products have been validated with geodetic terrestrial survey data. Typical products are 2-cm seamless orthophotos, three-dimensional vector maps and dense DSMs of approximately 50 points per m2 with a relative point precision of better than 2 cm in XY and 4 cm in height. The paper finally presents the results of the produced DSMs of the projects with high resolution and accuracy.

1. INTRODUCTION

One of the new developments in modern navigation and earth observation is production of accurate photogrammetric products from unmanned aerial vehicles (UAVs) with a state-of-the-art navigation and control system for hands-off autonomous flights. The authors have completed several scientific and commercial photogrammetric projects using these UAVs for a variety of applications, like for example modelling archeological sites (Lambers et al., 2007), creating high quality and realistic three-dimensional building models for urban planning, producing three-dimensional cadastral and transportation map updates, reconstructing mountain rock faces, and calculating volumes of stock piles.

Figure 1. Geocopter's Photogrammetric UAV

Aerial photography from manned aircraft has proven very successful and cost-efficient for large area mapping projects. For mapping updates of smaller areas of 10 up to 100 hectares, there are various benefits of an autonomous UAV over traditional aircraft operations: the mobilization costs to the project area are lower and the UAV can be quicker deployed. The UAV can take good quality aerial photography under thin clouds, because flying speed is slower and the average flying height of 100 meters above ground level (AGL) is lower. In the Netherlands, this also increases the average 12 "clear sky" days per year for manned aerial photography to an estimated 60 operational days per year for photogrammetric UAV projects. The digital imagery from 100 meters AGL result in very high resolution data (1-3 cm pixel size) using calibrated small format digital cameras with good contrast. From the imagery a Digital Surface Model (DSM) is extracted of approximately 50 points per m2.

UAV photogrammetry also has great potential to become a good alternative to terrestrial geodetic surveys, especially to risky survey work along highways and train tracks, and other dangerous or inaccessible terrain. The main question of course is: how accurate are the photogrammetric products from UAVs? The results of some recent project are shared by the authors in this paper.

2. MODERN NAVIGATION

The authors have developed and used different versions of fully operational rotorcraft UAVs (Figures 1 and 2) for photogrammetric image acquisition, with varying weight, payload, engine and flight performance. All systems feature

attitude stabilization, velocity and position control, rotor speed control, waypoint guidance, and automatic take-off and landing.

Figure 2: The mini UAV of the ETH Zurich

Other system performances are integrated GPS/IMU navigation with Kalman filter, automatic payload compensation, flight data storage on board and live display on ground station, and robust flight controller design. The flight controller supports different flying modes: manual mode, assisted mode for speed commands through a joystick with auto stabilization, and fully automatic mission mode. The fully automatic mode, or mission mode, is used to perform pre-programmed flight trajectories such as photogrammetric flight lines. The flight control computer triggers a nadir mounted digital camera with calibrated lens, and records position, attitude and timing information for further photogrammetric processing.

Figure 3. Real-time Position Tracking

A ground control and monitoring station shows real-time flight data such as position (Figure 3), speed, attitude, distance, auto-pilot functionality, and several safety features, including status indicators of the serial data-link connection between ground station and aircraft, GPS solution validity, RC radio connection, voltage of power supply and RC receivers/servos, fuel level indicator, and rotor speed indicator. Just in case the data-link

integrity would be lost, the rotorcraft UAV will automatically return to its home waypoint. Two other monitors are available to display real-time color video images and thermal infrared images fed from above.

Figure 4 illustrates a typical field operation. The photogrammetric UAV is brought to the project location in a small van. A generator provides electrical power to the ground station to be self-supportive at remote field operations. Once the flight plan is uploaded to the UAV, the system takes off for the photogrammetric survey flight. A typical survey flight takes about 10 minutes to cover areas of 10 up to 100 hectares. After landing all imagery and metadata is downloaded and backed-up for further processing.

Figure 4. Typical Field Operation

3. PHOTOGRAMMETRIC PRODUCT VALIDATION

Photogrammetric products are generated in a digital workflow of camera calibration, aerotriangulation, image matching to extract a Digital Surface Model (DSM), softcopy stereo models for 3D vector mapping, and orthophoto generation as well as texture mapping. Ground Control Points (GCPs) are used in the aerotriangulation. The workflow development of UAV photogrammetry is based on proven software procedures for large and medium format digital imagery from manned aerial survey aircraft. To date the authors have designed specific workflows based on commercially available photogrammetric software to process imagery from calibrated small format digital cameras, like for example the Fuji FinePix Pro S5, Canon D20 and Nikon 2DXs. The product results of four show case projects are presented below.

3.1 Highway, the Netherlands

The rotorcraft UAV of Geocopter was asked by the Dutch Department of Traffic and Water Management to produce a Digital Terrain data Base (DTB) of a highway. The DTB is actively used to manage national roads and waterways. Its scale 1:1,000 is very detailed, and its accuracy is very high (class 1 absolute sigma XY = 5 cm, sigma Z = 9 cm, class 1 relative sigma XY = 2 cm, sigma Z = 4 cm). Whenever the highway infrastructure is changed after construction work, the DTB gets an update to represent the actual situation. Table 5

lists the project parameters of the 3D vector update of 300 meters highway with UAV photogrammetry. The aerial survey was done in September 2006.

Parameter	Value
Flying height	100 m
Flight lines	3
Photos	39
Ground Control Points	14
Forward lap	60%
Sidelap	30%
Project area size	200 x 300 m2
Footprint one photo	80 x 60 m2
Pixel size	2 cm
Camera	Fuji FinePix Pro S3
Lens	Nikon 28 mm
Time of survey	5 minutes
Weather	high clouds
Wind	calm

Table 5. Highway Project Parameters

Figure 6 represents the photogrammetric block after aerotriangulation with Match-AT (left), and the extracted DSM with Match-T (right). 3D vector mapping to create the final DTB product was done by an experienced photogrammetrist with Summit Evolution Pro. Figure 7 illustrates a part of the DTB over the seamless orthophoto mosaic that was created with Inpho's Orthobox.
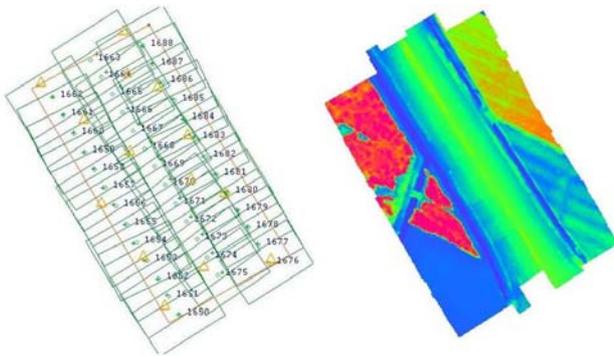
Figure 6. Photogrammetric Block and DSM

Figure 7. Accurate 3D Vector Map over Orthophoto Mosaic

The accuracy of the 3D vector data product was validated with very precise terrestrial tachymeter data produced by the Dutch Department of Traffic and Water Management. Figure 8 presents the comparison between one of the 3D profiles from the terrestrial survey (black line), and the same 3D profile from UAV photogrammetry (green line). The associated F-test and U-test results of the height differences are listed in Table 9.
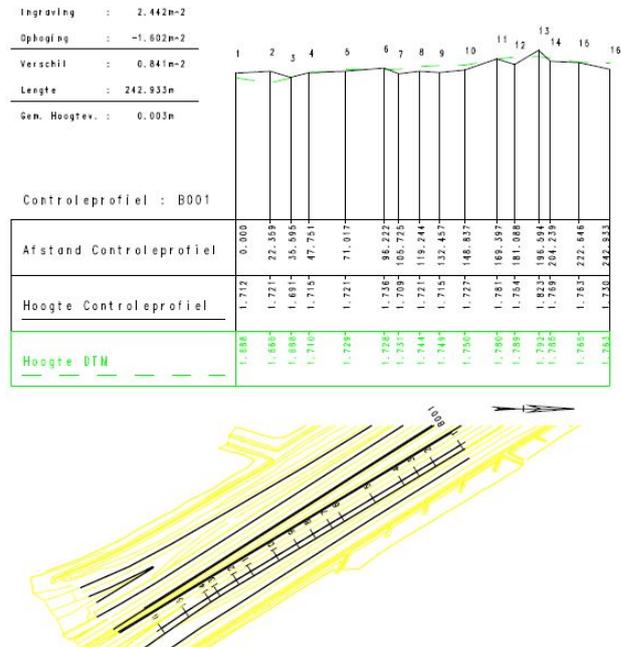
Figure 8. Comparison of 3D Profiles: Terrestrial versus UAV

Parameter	Value
Average height difference	0.0035
Calculated standard deviation	0.0256
Calculated F-value	1.0475
Critical F-value	2.0385
Accepted according to F-test?	Yes
Calculated sigma of height differences	0.0063
Calculated U-value	0.5537
Critical U-value	2.5758
Accepted according to U-test?	Yes

Table 9. QC Report of UAV Profiles

3.2 Geofort, the Netherlands

The Geofort is one of many fortresses of the "Dutch Waterline". The Netherlands first began using water to protect the country during the Eighty Years' War by breaching dikes to flood polders. The first waterline was built in 1672 against the invading French forces. Flooded landscape variations such as rivers and dikes left some areas passable or navigable by the enemy, so these access points were defended by the forts where troops were housed and artillery was positioned. The Geofort is now owned by Staatsbosbeheer, a government organization managing natural heritages. This fortress is currently being transformed into an educational attraction where the public can discover the world of maps, navigation, virtual reality and photogrammetry in an easily accessible way. The aim is to open the fortress to the public in 2009.

The rotorcraft UAV of Geocopter was asked to produce the actual DSM and orthophoto of the Geofort. The system flew in fully automatic mode over this site in April 2008 and captured the airborne photogrammetric imagery in four parallel flight lines at 100 meters above ground level. Table 10 lists the project parameters of the UAV survey flight.

Parameter	Value
Flying height	100 m
Flight lines	4
Photos	80
Ground Control Points	20
Forward lap	60%
Sidelap	30%
Project area size	500 x 300 m2
Footprint one photo	80 x 60 m2
Pixel size	2 cm
Camera	Fuji FinePix Pro S5
Lens	Nikon 28 mm
Time of survey	12 minutes
Weather	high clouds
Wind	fair

Table 10. Geofort Project Parameters

Figures 11 and 12 display the level of detail of the aerial photography and the extracted DSM points from Match-T.

Figure 11. Snapshot of Geofort Orthophoto
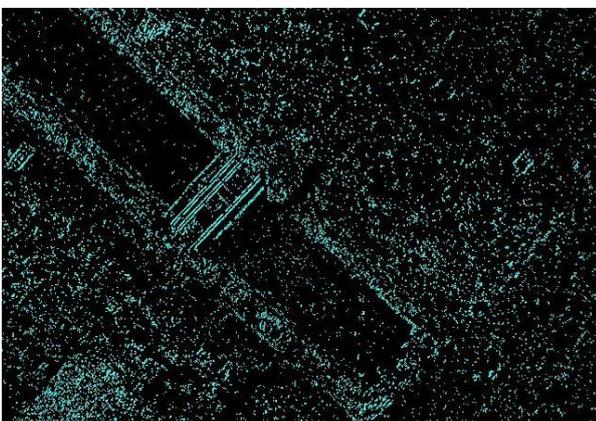
Figure 12. Snapshot of Geofort DSM

3.3 Corn field, Switzerland

This project was conducted to determine to what extent topography can affect the rate of cross-pollination. The effect of topography on cross-pollination was investigated in 2005 and 2006 in canton Zurich.

UAV survey flights were conducted over two sites (longitude 8° 40' E, latitude 47° 25' N, flying height about 500 and 450 meters above mean sea level) (Eisenbeiss, 2007 and 2008). In 2005, all imagery over the corn field was acquired in 20 minutes under autonomous flight with stop points. The time of flight was reduced to 5 minutes in 2006 under autonomous cruise mode. The obtained images were oriented with software packages LPS (Leica Photogrammetry Suite 9.0, Leica Geosystems Geospatial Imaging, LLC) and ISDM (Image Station Digital Mensuration, Zeiss Intergraph, 2000). The aerotriangulation of the UAV images was performed with a σ_0 of less than 0.5 pixels and an RMSE for the control points of less than 1 dm for both test areas.

A 10-cm GSD elevation model was generated with SAT-PP software (Satellite Imagery Precision Processing, ETH Zurich, Zhang, 2005), that was modified to also process imagery from calibrated small format digital cameras. At last, the orthophoto with 3-cm resolution was produced with LPS. The accuracy of the results was mainly affected by difficulties in the aerotriangulation, which was because of the high repetitive texture in the corn fields. Figure 13 illustrates the matching result with SAT-PP: feature points and edge matching.
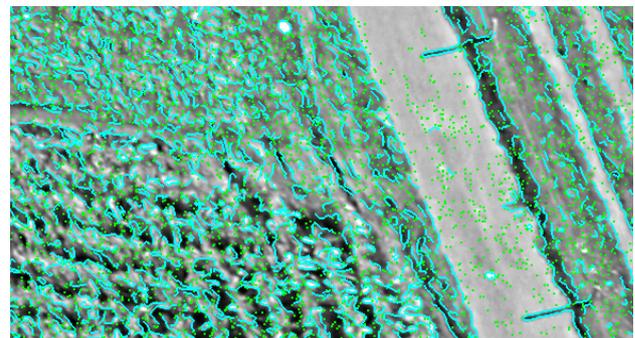
Figure 13. Matching Result with SAT-PP of the Corn Field

The generated DSMs and orthophotos were together integrated in a GIS, and used for high resolution measurements on the outcrossing in corn. Figure 14 shows the orthophoto draped over the DSM (both from 2005), combined with the Swissimage orthoimage (swisstopo®) draped over the DHM25 (swisstopo®), and the position of the cross-pollination data.

The accuracy of the DSM was not possible to verify since reference data of the corn field was not available. However, the results from the orientation of both years are quite consistent; therefore the DSMs of both years have the same accuracy level.

Figure 14. 3D View in GIS of DSM and Orthphoto

3.4 Randa, Switzerland

The goal of this project is the characterization of the May 1991 Randa rockslide failure (Figure 15) surface using UAV photogrammetry. The project is embedded into the project "Progressive development of shear/slide surfaces in rock slopes (Phase III)" of the Engineering Geology group at ETH Zurich (Randa, 2008 and Eisenbeiss, 2008).

trace length. To meet these requirements, the DSMs were constructed from high-resolution images taken from locations close to the rock outcrops whose position is known with a sufficient degree of accuracy. In the framework of this project, digital photographs of the 1991 failure surface were taken from a UAV which is a suitable technology for imaging inaccessible outcrops with a high resolution.

Photographs of the rocky outcrops were used to derive a dense DSM with 10-20 cm spatial resolution, and a height accuracy of 1-2 cm, allowing for detailed morphometric analysis and characterization of fracture surfaces. To achieve a height accuracy of 1-2 cm, a large image scale was required involving the acquisition of many images and control points. Furthermore, the control points used to orientate the images should also be very accurate, better than 1 cm. For the object coordinates of these points this accuracy can be achieved, even if they are natural points, by measuring them geodetically with a total station. However, access to the site is limited. Therefore the control points could only be installed at the border of the site.

DSMs were produced automatically using advanced multi-image matching techniques, and orthoimages were generated. The orthoimages are used for 3D visualisation and visual interpretations. The first results from a test flight in May 2007 are given in Figure 16. The left image represents a zoom-in of one of the acquired photos. The right image is the derived DSM of Randa, showing 50 times higher resolution than the existing lidar dataset of the site.

Figure 15. Randa rockslide
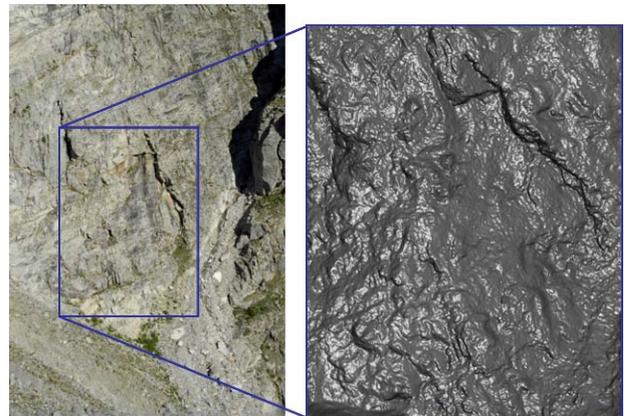
Figure 16. Snapshot of Randa Photo (left) and DSM (right)

Data collection of this project did primarily involve a detailed investigation of the visible failure surfaces and back scarps of the 1991 events at Randa. Although an important part of the sliding surfaces is covered by debris, the visible parts of the detachment surface are large and include both secondary sliding planes as well as lateral and back scarps showing in detail the interactions between all fracture sets, faults and rock bridges. These interactions are critical for the evolution of rock slope instability. Given the size, the steepness and the dangerous access to these outcrops, fracture mapping will be performed from inspection of high-resolution digital surface models (DSMs) and stereo photographs of the slope.

The resolution of the generated rock surface models allow for the recognition of planes and traces describing fractures and faults contributing to the 1991 slope failures. It also permits accurate measurements of fracture and fault orientation and

4. DSM COMPARISON

The authors have been using SAT-PP and Match-T for accurate DSM production. While SAT-PP was used for the maize field and Randa project, the highway and the Geofort were processed with Match-T. Both software packages are based on a matching approach using a coarse-to-fine hierarchical solution with a combination of multi image matching algorithms and automatic quality control. The software matches three kinds of features - feature points, grid points and edges on the original resolution - progressively starting from low-density features on the low resolution level of the image pyramid. A TIN of the DSM is reconstructed from the matched features on each level of the image pyramid by using the constrained Delauney triangulation method. This TIN in turn is used in the subsequent pyramid level for approximations and adaptive computation of the

matching parameters. Least squares matching methods are used to achieve more precise matches for all the matched features and for the identification of some false matches. Finally, the interpolated regular DSM grid from the matching results is derived.

The authors expect to present the first results of a comparison between two DSMs of the same area, one extracted from SAT-PP and one extracted from Match-T, at the conference.

5. CONCLUSIONS

Recent developments in modern navigation and earth observation over the past four years have resulted in reliable UAV platforms for photogrammetric surveys. Typical products are 2-cm seamless orthophotos, three-dimensional vector maps with a relative point precision of 2 cm in XY and 4 cm in height and dense DSMs of approximately 50 points per m2.

For mapping updates of smaller areas of 10 up to 100 hectares, there are various benefits of an autonomous UAV over traditional aircraft operations. These are related to mobilization costs, flexibility, number of operational flying days, very high resolution data, and high point density DSMs. UAV photogrammetry also has great potential to become a valid alternative to terrestrial geodetic surveys, especially to risky survey work along highways and train tracks, and other dangerous or inaccessible terrain.

Future work will focus on enhancing system performance of UAV photogrammetry.

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