

# The Potential of Unmanned Aerial Vehicles for Mapping

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## ABSTRACT

Unmanned aerial vehicles (UAVs) can be used for mapping in the close range domain, combining aerial and terrestrial photogrammetry and as alternative for aerial mapping technologies in small scale areas. At the current state mainly low-cost UAVs are used in mapping projects with low budgets. However, in the last years low-cost UAVs reached a level of practical reliability and professionalism which allow the use of these systems as mapping platforms. UAV based mapping provides not only the required accuracy with respect to cadastral laws and policies as well as requirements for the generation of elevation models in small-scale areas such as gravel pits, UAVs are also competitive to other measurement technologies in terms of economic aspects.

In the following an overview on various UAVs will be given and their classification with respect to mapping task will be introduced. In addition, a generic workflow for the photogrammetric UAV flight planning, image acquisition, quality control and data processing will be explained. Complementary to the workflow two applications will be presented which focus on the practicability of UAVs in cadastre applications and generation of elevation models of small-scale areas.

## 1. INTRODUCTION

The content and text elements of the following article are based on the PhD thesis "UAV Photogrammetry" (Eisenbeiss, 2009) and have been extended by current developments.

UAVs are unmanned aerial vehicles which are inhabited, reusable motorized aerial vehicles. These systems can fly autonomously, semi-autonomously or manually steered by a pilot from the ground using a remote control. Instead of the aberration UAV synonyms like UAS (Unmanned Aircraft Systems) and UVS (Unmanned Vehicle Systems) can be found in the literature.

UAVs can be used as mapping platforms. These platforms are equipped with photogrammetric measurement systems, including, but not limited to small or medium size still-video or video cameras, thermal or infrared camera systems, multispectral cameras, range camera sensors and

	Aerial	Close Range	UAV
Planning	(semi-)automatic	manual	automatic-manual
Data acquisition / Flight	assisted/manual	autonom/assisted/manual	autonom/assisted/manual
Size of the area	km <sup>2</sup>	mm <sup>2</sup> - m <sup>2</sup>	m <sup>2</sup> - km <sup>2</sup>
Image resolution /GSD	cm-m	mm - dm	mm - m
Distance to the object	100m- 10km	cm - ~300m	m - km
Orientation	normal case, recently also oblique	normal/oblique	normal/oblique
Absolut accuracy of the initial orientation values	cm - dm	mm-m	cm - 10m
Image block size/ number of scans	10 - 1000	1 - 500	1 - 1000
Special applications (examples) and features	large scale areas (Mapping, Forestry, Glaciology, 3D-City modeling)	small-scale areas and objects (archaeological documentation, 3D modeling of buildings)	small- and large-scale areas (archaeological documentation, monitoring of hazards, 3D modeling of buildings and objects)
		architectural and industrial photogrammetry	applications in inaccessible areas and dangerous objects
	aerial view	terrestrial view	aerial view
			real-time applications (monitoring)

Table 1: Features of aerial, close range and UAV photogrammetry.

airborne LiDAR sensors, or a combination thereof depending on the payload of the UAV. Furthermore, for the determination of the trajectory, UAVs feature by default an integrated GNSS/INS system (global navigation satellite system / inertial navigation system), barometric altimeter and compass systems.

UAVs open various new applications in the close range domain, combining aerial and terrestrial photogrammetry, but also introduce new (near-) real time application and low-cost alternatives to the classical manned aerial photogrammetry (see Table 1).

First investigations related to mapping based on UAV-borne LiDAR systems were done in the field of robotics started at Carnegie Mellon University. Thrun (2003) described initial results for a helicopter mapping system combining a SICK LMS laser range finder, a Crossbow IMU (inertial measurement unit), a Honeywell 3D compass, a Garmin GPS (global navigation system), and a Nikon D100 digital SLR (single-lens reflex) camera. The results in this study showed already the potential of the spatial detail contained in the 3D point cloud for urban and natural terrain. However, the determination of an accurate position and orientation of the flight trajectory was not focus of this work. In 2004, at the ISPRS congress, Nagai, et al., (2004) proposed a system which integrates a LiDAR system and CCD-cameras with GPS/INS data for digital surface model generation. The system used a Subaru helicopter with a payload of 100 kg and a main rotor diameter of 4.8 m. The workflow for the geoprocessing and the first results generated from LiDAR data were presented at the ISPRS congress in Beijing (Nagai, 2008). The geoprocessing was done using a “hybrid IMU” which combines the GPS/IMU data, using the image orientation resulting from bundle block adjustment with a Kalman Filter. These studies show the problematic of getting accurate position and orientation of the flight trajectory with high frequency using low-cost sensors. The integration of tactical and navigation grade IMUs, which would deliver sufficient accuracy for the orientation, are limited by the payload constraints of UAVs and cost factors. In contrast to airborne LiDAR systems, image-based systems only need the position and orientation at the time, where the image was acquired. Furthermore, it is still possible to georeference images with the indirect georeferencing method (bundle adjustment) using GCPs (Ground Control Points). However, current developments in the field of UAV mapping focus also on the improvement of the GNSS and INS data by using DGPS (differential GPS; Bláha, 2011) and vision based navigation combined with inertial sensors, visual odometer and registration of a UAV on-board video (Conte and Doherty, 2008). The results of these studies are promising. But, this topic is emphasized in current and future investigation focusing on the determination of an accurate UAV trajectory for mapping applications.

In the past the majority of the UAV mapping projects and investigations was done related to vegetation monitoring and archaeological applications. Thus, in the following literature review the focus lies on these topics.

The use of UAVs for archaeological applications has increased in the last years. Particularly, due to the budget limitations in archaeological projects, low-cost systems such as balloons (Verhoeven, 2009), blimps (Gomez-Lahoz and Gonzalez-Aguilera, 2009) and more sophisticated systems such as manually controlled model helicopters (Zischinsky et al., 2000) and autonomous navigation systems (Lambers et al., 2007) were used. A detailed literature review on blimps and balloons used in archaeology is given in Verhoeven (2009) and further examples for model helicopter based systems are shown in Eisenbeiss (2009) and Chiabrando et al. (2011).

The potential of slow-flying fixed-wing UAVs equipped with imaging cameras for agricultural surveillance was shown in Herwitz et al. (2004). Furthermore, several research groups focused on applications using rotary and fixed-wing UAVs for natural resource management and monitoring

(Horcher and Visser, 2004), on the use of stereo images for the generation of crop maps (Kise, et al., 2005, Rovira-Más, et al., 2005), vegetation monitoring (Sugiura, et al., 2005), classification of hyperspectral UAV imagery (Laliberte, et al., 2007), integration of light-weight multispectral sensor for micro UAVs (Nebiker, et al., 2008), precision farming (Reidelstuerz, et al., 2007) and rangeland monitoring (Slaughter et al., 2008). An overview of the potential of several low-cost UAVs in forestry and agriculture was given in Grenzdörffer, et al., 2008. Eisenbeiss (2009) generated dense elevation models of maize fields, which were used for GIS-based analysis of the pollen dispersal in maize.

The chapters of this paper are structured as follows: Chapter 2 categorizes UAV photogrammetry in the context of aerial and terrestrial photogrammetry and gives an overview on UAVs which can be used for mapping. Chapter 3 focuses on the acquisition and processing workflow of the UAV data and comprises two case studies for UAV mapping. The last chapter 4 a summary and an outlook is given.

## **2. OVERVIEW OF UAV SYSTEMS**

Major advantages of UAVs compared to manned systems are that UAVs can fly in inaccessible areas, such as mountainous, volcanic, earthquake and desert areas, flood plains and scenes of accidents. Furthermore, most systems available on the market are stabilized and can operate autonomously. These systems are mainly low-cost systems, and thus a major advantage of UAVs is the cost factor, as UAVs are less expensive and have lower operating costs than manned aircrafts have.

In contrast to the advantages, UAVs are mainly limited by the payload. Thus, low weight sensors like small or medium format amateur cameras and LiDAR systems have to be selected as photogrammetric measurement systems. Furthermore, quite often UAVs are equipped with low-cost sensors, which implicit reduced quality in the mapping data and the observed orientation and position of the systems. Due to the small weight of many UAVs, the platforms are highly dependent on environmental conditions, such as wind.

### **2.1. Categorizing of UAVs in the context of photogrammetric data acquisition platforms**

Recent technological improvements of UAVs during the last years emerged to revisit the categorization of photogrammetric platforms.

In the Manual of Photogrammetry Abdulla (2004) presented the existing photogrammetric platforms, such as airborne, satellite and land-based platforms, as well as auxiliary systems. Thereby, the airborne platforms are subdivided in aircraft platforms such as single- and twin-engine aircrafts and other platforms like unmanned surveillance and reconnaissance aircraft systems, helicopters and balloons. The unmanned surveillance and reconnaissance aircrafts are basically UAV systems, but in the context of this categorization only high-altitude and long-endurance UAVs such as the Predator B (United States Air Force) are taken into account. Furthermore, the land-based platforms are partitioned into van-based mobile mapping systems and real-time videogrammetry systems. Looking at aerial based platforms like, for example, kites, model helicopters, quadrotors and terrestrial based systems such as grains, rope-way, well-bucket and base bars, it is clear that not all platforms available for photogrammetric observations can be categorized using this classification. Furthermore, the category auxiliary systems does not represent the non-classified platforms. This group remains for the positioning systems such as GPS, INS and stabilized platforms, as well as aerial survey flight management systems.

Kraus (2007) focused in his book “Photogrammetry: Geometry from images and Laser scans” mainly on aerial photogrammetry. He does not explicitly categorize the platforms used in the aerial case.

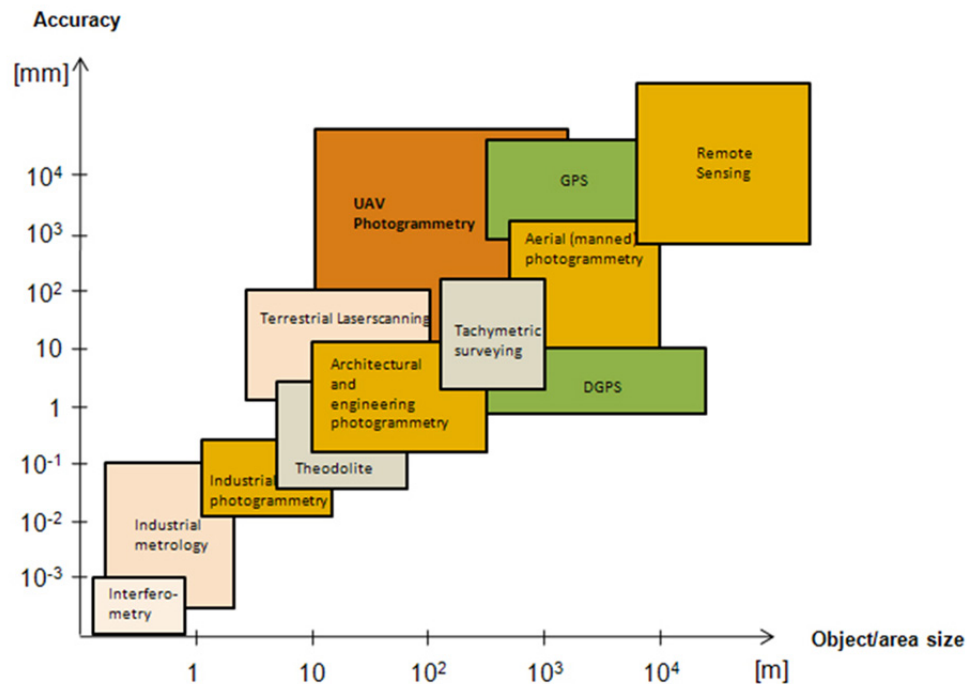


Figure 1: The accuracy of measurement methods in relation to the object/area size. Modified from Fig. 1.4 in Luhmann, et al., 2006, p. 4.

Since UAVs or UAV Photogrammetry are not explicitly defined in the photogrammetry literature, the categorization of measurement methods by Luhmann is used for UAV mapping (UAV photogrammetry). Luhmann, et al., 2006 (p. 4, Figure 1.4) introduced a categorization scheme of measurement techniques, which treated the size of the measured object vs. the required measurement accuracy. This categorization comprises almost all techniques, but the chosen graphical representation does not address the performance of each system at different conditions. Actually, considering the height dimension of an object, some of the presented methods may not cover the entire object with the presented accuracy. Introducing the transition section between aerial and terrestrial based platforms according to Figure 1.4 in Luhmann, et al., 2006, as well as introducing a new category for aerial based platforms operating in the close range and aerial domain without restriction for the viewing angle, leads to a more complete picture. Accordingly, the category “UAV photogrammetry” was added, combining all unmanned aircrafts into a dedicated category, making the classification of photogrammetric platforms more understandable and clearer in the context of the recent developments (see Figure 1). In addition, Eisenbeiss (2009) Appendix Figure A-1 comprises terrestrial, helicopter and airborne laser scanning and radar interferometry to UAV photogrammetry. Thus, UAV Photogrammetry can be understood as method for mapping tasks with different accuracy requirements and areas up to few kilometers.

## 2.2. Systems

The variety of object sizes is compared to other methods quite large, since UAVs not only include VTOL (vertical take-off and landing) systems but also fixed-wing systems, such as model airplanes. Furthermore, UAVs can be categorized using the main characteristics of aircrafts like unpowered or powered, lighter than air or heavier than air and flexible, fixed or rotary wings. Table 2 classifies

systems regarding their range, endurance and weather, wind dependency, maneuverability and payload.

Type of aircraft	Range	Endurance	Weather and wind dependency	Maneuverability	Payload capacity
Balloon	0	++	0	0	+
Airship	++	++	0	+	++
Gliders/Kites	+	0	0	0	0
Fixed wing gliders	++	+	+	+	+
Propeller & Jet engines	++	++	+	+	++
Rotor-kite	++	+	0	+	+
Single rotor (helicopter)	+	+	+	++	+
Coaxial	+	++	+	++	++
Quadrotors	0	0	0	++	0
Multi-copters	+	+	+	++	+

Table 2: Pro and cons of the different types of UAVs (0: Lowest value; +: Middle value; ++: Best).

In contrast to fixed-wings, rotary-wing systems can operate closer to objects and have a larger flexibility in the control of flight maneuvers. On the other hand, fixed wing UAVs are usually able to stay for a longer time in the air, can cover larger areas and are able to enter upper air spaces. In contrast to the rotary-wing and fixed-wing UAVs, the unpowered balloons and gliders are controlled by ropes. This feature means the systems are limited in their flying altitude and distance to the operator, while the horizontal movement of the system corresponds to the walking of the operator or the movement of the car, to which the system is adapted. Moreover, the influence of wind is greater than for the rotary- and fixed-wing UAVs. Compared to the previously mentioned systems, powered airships have the advantage of staying longer in the air than the fixed and rotary

wing platforms due to their uplift. Therefore, these systems can be used for long-term monitoring tasks. Besides of this advantage, powered airships, as well as powered gliders, the drawback of these systems is their dependency on the environmental conditions. In addition the overhead obstructions particularly limit the usage of GPS sensors on these platforms for purpose of navigation.

Additionally, UAV platforms can be classified according to their integrated sensors and real-time capability which directly influence data processing. Low-cost sensors will imply post georeferencing, while high-end sensors, such as DGPS and navigation-grade IMUs have the potential for direct georeferencing. Depending on the implemented sensors and type of processing, specific UAVs will only be suitable for particular applications.

Furthermore, UAVs can be distinguished from each other by commercially available and open source systems. Several open source systems exist on the market. In Europe open source systems like UAVP, Mikrocopter and Paparazzi are common (Eisenbeiss, 2009). Open source systems have a high potential for research projects, while the commercial use of open source systems is limited and thus not practicable for mapping tasks. Furthermore, systems used in commercial applications should have a level of practical reliability and professionalism. Thus, several companies are focusing in the development and production of UAV system, including ground control stations, flight autonomy, back-up systems to overcome system failure, communication through transponder for larger system with the air navigation services and air traffic control units, etc. However, also commercially available system can be divided in two classes, such as low-cost and high-end systems. Low-cost systems are mainly limited by their payload capacities (max. 5 kg), which does not allow the integration of high-end navigation sensors and mapping systems such as LiDAR or medium size camera systems. Furthermore, low-cost systems have less flight endurance (up to 20

min) and flight range (up to 300 m distance to the ground control station). Figure 2 shows a selection of UAVs, which have been used in different projects at the Institute of Geodesy and Photogrammetry (ETH Zurich). The Figure shows examples for low-cost and high-end system, which are on the market or under development. A detailed description of these systems is given in Eisenbeiss (2009).



Figure 2: Selection of UAV systems used at the Institute of Geodesy and Photogrammetry (ETH Zurich) for mapping projects.

### 3. WORKFLOW AND CASE STUDIES

#### 3.1. Workflow

The workflow for UAV mapping is similar to the workflow of man-based aerial mapping systems. However, some elements of the workflow are different and thus, have to be extended. The mapping workflow consists of the definition of the preparation phase, flight planning, autonomous flight, quality check of the data, data processing – determination of the flight trajectory (see Figure 3).

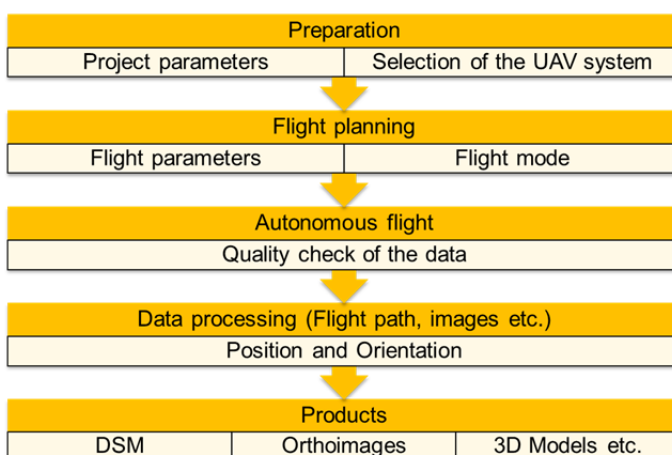


Figure 3: Workflow for UAV data acquisition and processing.

For the automated data acquisition, the flight trajectory of the UAV has to be calculated in advance. Project parameters like object type, output data, camera sensor, type of model helicopter and flight restrictions are standard project parameters. These parameters can vary from one application to another. Therefore, we suggest three scenarios in the flight planning: A) Documentation of a surface with flat or moderate terrain, B) Exposure of a rough/mountainous terrain like hazard areas and C) 3D modeling of buildings and other objects.

For the automated flight the autonomous data triggering, camera viewing angles, the position and orientations of the sensors have to be stored on-board. Furthermore, this data has to be verified, since the data acquisition is often time-limited and a repetition not possible. For quality control the defined and acquired data acquisition points/trajectories as well as the ground coverage have to be compared and validated. The flight or part of the trajectory has to be repeated if the acquired position does not fit to the predefined acquisition point, an image is not acquired or the footprint comparison shows gaps or the required overlapping interval is not fulfilled.

The position and orientation data are generated by the navigation unit of the UAV, which has to be improved by bundle adjustment or direct geo referencing using control points. This process is time consuming depending on the quality and accuracy of the flight trajectory. However, this topic will not be treated in detail in this study. More details for direct geo-referencing can be found in Cramer (2001) and for UAV data processing (Eisenbeiss, 2009).

Finally, out of the acquired raw data products elevation models, orthoimages, 3D models, maps and so forth can be generated. In the following two examples for possible UAV mapping applications will be given.

### 3.2. Cadastre

In cadastral applications tachymeters and GNSS receivers are usually used. These instruments are highly developed in respect of accuracy and performance in surveying tasks. However, these systems are usually applied to measure object points and lines. In contrast to these traditional surveying methods, airborne based mapping is used for creating and updating maps or orthoimages on a larger scale. But airborne images are limited in their use for cadastral surveying, mainly because of the flight altitude, the resulting image resolution and the high expenses. Thus, UAV based mapping could be a perfect alternative or supplement to measurements with tachymeters or GNSS receivers. In a first case study a test area was defined on the Campus Science City ETH Zurich (Hoenggerberg) (Manyoky et al., 2011).



Figure 4: Left: Flight planning of the UAV flight over the test area Campus Science City ETH Zurich (Hoenggerberg). Right: Generated map out of the UAV images.

In Figure 4 (left) the predefined image acquisition points are shown for the flight in test area. In order to gain data by UAV, control points from the Swiss cadastral survey have to be marked with field targets in the test areas. In a further step these targets are used to preserve the national coordinate reference system within the acquired data. Moreover, the flight plan was prepared for autonomous flights to fly on predefined routes taking UAV images. In a second turn the camera on the UAV was tilted, flying around the building complexes to gain images from the facades of the buildings.

The acquired UAV image data were oriented using the flight trajectory as initial value for the bundle adjustment. After image orientation the object structures and geometries were manually stereoscopically measured in the images. Similar to the workflow of the tachymetry + GNSS method, the surveyed structures have to be classified in order to generate a map. Finally, a plan for the surveyed area was developed (Figure 4, right).

Both methods (tachymetry/GNSS and UAV) deliver comparable results in the process duration for acquiring and evaluating the data. With the tachymetry/GNSS method only the surveyed points in field can be mapped, whereas the products of the UAV methods depend on the preferred level of detail. However, if area types like land use or vegetation have to be documented in the map, the UAV method is much more efficient due to the additional points which can be measured very fast without an a new flight, even in a post-processing step. The achieved accuracy of the UAV based map fulfills the requirements (3.5 cm for land ownership and 10 cm for land cover and single points in build-up areas and construction zones) of the Swiss cadastral survey (Manyoky et al., 2011).

### 3.3. Gravel pits

Gravel pits are a typical example for a UAV mapping application. The situation at a gravel pit is changing quite a lot over time. 3D models are a useful information source to calculate the volume changes over time and thus to estimate the volume of the gravel elements, which have been carried to end. The classical measurement methods such as leveling and field surveys are time consuming and not so accurate. Image data from satellite or airborne may meet the criteria of the precise modeling of the gravel pits but acquiring of the satellite data may not be available for the desired time of the measurement and the aerial images are not always updated. UAVs are good data sources for such applications, and the data can be acquired frequently and precisely.

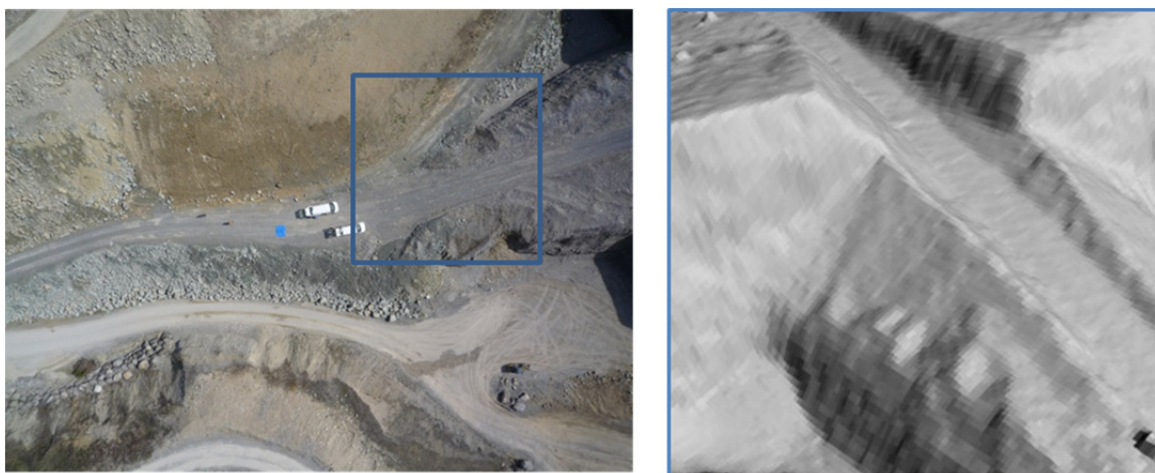


Figure 5: Left: UAV image showing part of a gravel pit. Right: DSM generated from the UAV images.



The processing of the data includes image orientation and digital surface model (DSM) extraction using multi image matching. The quality of the extracted DSM varies enormously depending on the used matching software and method (see Figure 5). Under optimal conditions, an accuracy of 2 pixels in height can be expected for the generated DSM of the bare ground, while in steep areas the accuracy can go up to 5-8 pixel. Typical ground resolutions of one pixel in gravel pit areas are 1-3 cm. Therefore, for the steep areas, additional stereo pairs have to be processed. The results can then be integrated into the surface model and the viewing angle for the data acquisition has to be adapted accordingly. Alternatively to the DSM generation from images, UAVs can be equipped by light weight airborne laser scanner systems (Eisenbeiss, 2009).

#### 4. SUMMARY AND OUTLOOK

As examples for the suitability of UAVs for a wide range of mapping applications, two examples for cadaster application and mapping of gravel pits were given in this paper. Based on the general overview of UAV mapping and the two examples presented here, in future projects it can be envisaged to use a laser scanner and a camera mounted on UAVs, such as high-end UAV, for most applications which require high resolution and accuracy. Exploiting the advantages of both sensors, a combined approach will yield more precise elevation models: The laser scanner creates highly dense point clouds in areas with low texture, while image data is advantageous for edge measurement and texture mapping. The most important factor for the combination of image and LiDAR data is the improvement of the accuracy of the flight trajectory of an UAV, which would lead to the real-time capability of data processing of such UAV platforms and the combined processing of the data.

Finally, it can be stated that more UAVs will fly autonomously in the future, the 3D trajectory can be generated with higher accuracy and more systems will be stabilized. These improvements will turn into more mapping applications based on UAVs.

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