Mapping Remote Areas with a Portable High-Accuracy Photogrammetric System

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SUMMARY

In the global-village era interests of commercial companies worldwide have become interrelated with the accelerated development of certain countries. As a result the demand for mapping in remote areas has been rapidly increasing. Mapping in such areas may pose some difficulties, due to the lack of geodetic infrastructure such as control networks, control points, and reference GPS stations. Furthermore, the task of allocating a local designated aircraft could prove to be a complicated one; alternatively, attempting to transport such equipment to a target area forces excessive logistic preparation.

In this paper we will present an accurate aerial mapping system that enables a high level of portability and mobility. Due to its small dimensions, it can be packed into a standard size suitcase and delivered via regular commercial flight. The system can be mounted on any type of small airplane through a short and simple installation. Moreover, the system is integrative and includes the entire photogrammetric process: starting with the mission and project planning, through navigation and image acquisition, data processing and ending with the extraction of the final products. The system is designed in a way that will not require proficient operators by incorporating high levels of automation within the different photogrammetric stages. We will present experiments demonstrating the system's accuracy and its suitability to high accuracy mapping. We will discuss, as case study, mapping projects that demonstrate the system's capabilities.

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1. INTRODUCTION

In recent decades a growing body of efforts has been directed towards the challenge of developing a photogrammetric mapping system, which is based on a digital sensor. The basic requirement of such a system is related to the level of accuracy that can be achieved as derived from the sensor dimensions and properties. The required accuracy must be high enough to supply precise mapping products that meet the specification of the mapping project. Moreover, the required accuracy should be comparable with respect to the traditional film-based large format systems (Mcglone, 2004) which are still regarded as the golden standard concerning accuracy.

Petrie and Walker (2007) categorized the available digital photogrammetric systems which are based on pin-hole (namely frame) camera model into two major groups.

- **Medium and small format**. This kind of photogrammetric system basically relies on high-end consumer cameras originally designed for studio and fashion photography. Currently, the most advanced sensor available is 60.5 Mega-Pixel with dimension of 54x40.5 mm. In most of these systems the camera is integrated into an aerial unit containing a GPS and an IMU.
- **Large format**. As mentioned, even the most advanced sensor available today has relatively low resolution and small dimensions. Therefore, in order to meet the required resolution levels, most of the large system manufacturers choose between one of the two options: i) using a set of synchronized cameras in a rigid mount; ii) stepping frames cameras. In either option, the images from the different sensors / positions are stitched together in a post-processing framework. Particularly, in the latter the post-processing relies on the motors' mechanical measurements. Additionally, in this case compensation is required in order to take into account the aircraft’s forward-motion.

Generally, the large format systems are based on a quite complicated integration of technological and mechanical elements. The large format digital systems consist of an assembly of digital sensors with few optical lenses, e.g. four different optical devices in the Intergraph Z\I Imaging RMK-d or eight different sensors assembled together in the Intergraph Z\I DMC (Petrie, 2007). In addition, the sensor head is always mounted on a heavy stabilizer and a large electronic box used for the flight management and storage is commonly attached. Due to the overall weight and dimensions of the aerial unit, in case of a large format system, the utilized aircrafts need to be heavy and designated ones. Generally, large format systems are designed for wide area coverage as part of huge mapping projects in country/state scale. In mapping projects of that scale, the efforts involved in the operation and transportation of such aircrafts are reasonable. On the other hand, for small scale projects or projects in remote areas such as developing countries, the logistics and regularization barriers may be disproportionate to the project's total overhead.

In contrast to the large format, the medium and small format systems (e.g., Petrie, 2006; Mostafa, 2004) have relatively compact dimensions and a reasonable weight. Therefore, they can be installed on a relatively small aircraft including single engine airplanes. In these photogrammetric systems, the limitations of a small sensor size on one hand and the relatively low number of pixels on the other impose flights in low altitudes in order to meet the required level of accuracy. Flying in low altitudes while using a small frame format naturally leads to a large number of images per area unit. The large amount of images which have to go through the classic photogrammetric pipeline necessitate teams of skilled operators, plenty of processing time and smart workflow management. In order to avoid the classical photogrammetric processing and particularly the aero-triangulation phase, the current commercial medium format systems (e.g., Petrie, 2006; Mostafa, 2004) use an expensive IMU and accurate GPS to generate telemetric measurements for each image. The telemetric data is assigned as the images' external orientation (i.e., direct geo-referencing) instead of the aerial triangulation results as performed in the classic process.

However, when using this scheme, the entire photogrammetric process relies only on the telemetric data which may lead to several unresolved issues. From a geodetic point of view, the telemetric data may contain some systematic and random errors (Flenniken et al., 2005; Guo et al, 2006). Unfavorable flight conditions can cause IMU malfunctions and data drifts. When using direct geo-referencing, there is no data redundancy and therefore, a low GPS signal directly leads to registration errors. Sometimes, depending on the accuracy specifications of the project, reference GPS stations and/or GPS data post-processing are required. When based only on the telemetric data, no effective quality assurance, fault correction and problem fixing can be performed during the geometric processing, even though this analysis is a common procedure within the aerial triangulation process, For example: generation of relative registration reports; accuracy estimation of each image parameters based on the covariance and interactive improvements of the solution when required. Moreover, the Geometric problems might be discovered in advanced stages of the project and may sometimes even require repeating the flight. From an operational point of view, due to the total dependency of the photogrammetric process on the telemetric data, an accurate and professional installation of the system on the airplane is crucial. Measurements of the relations between the optic head, the IMU unit and the GPS antenna are essential (i.e., sensor alignment), see (Pinto and Forlani, 2002). Therefore, in the most of the medium format systems, as in the case of large frame format systems, a designated aircraft is always used.

In this paper, we focus on the development of a digital photogrammetric mapping system, which is relatively simple to manufacture and assemble. The system has to be easy to operate and offer a fast and simple airborne installation. It has to be flexible enough to be installed on any aircraft including single engine airplanes even without a designated shooting hole. Furthermore, the system will be designed in such a way that it will have a low weight and small dimensions so that it may fit into a standard passenger suitcase and delivered via regular commercial flight to the target area. Our aim is to develop a system that in spite of its simplicity and flexibility it can provide a level of accuracy, which satisfies typical photogrammetric mapping projects requirements. As in all medium format systems, in order to achieve the required level of accuracy, the amount of images that have to be acquired may be quite large. Therefore, we face the challenge of developing a fast, automatic and easy to manage photogrammetric workflow that completes the aerial unit flexibility and simplicity into a comprehensive mapping system.

In order to meet these goals, we use the latest advances in the field of computer vision in order to make the classical photogrammetric process automatic, efficient and fast. Furthermore, we implement an automatic failure analysis and fault detection processes as an integral part of the proposed system. The failures that are detected in the analysis phase are corrected in an automatic manner in order to guarantee successful processing even when large amounts of images are involved. For this purpose, we have developed a photogrammetric workflow management system, which enables a fast, parallel and easy to operate, execution of the process. Finally, integrating the photogrammetric workflow management system with a flexible low weight aerial unit enables the use of regular lightweight aircraft for photogrammetric missions.

2. THE AERIAL UNIT

The design of an effective and simple aerial photogrammetric unit presents a number of challenges. The goal was to develop a generic mount that can be adapted to carry various kinds of cameras with minimal modifications. In order to facilitate the use of an aircraft which does not have a designated photo shooting hole, the system was designed for external installation. The system is divided into two major components; the internal unit is mounted to the airplanes' body while the external unit, which contains the sensor head, can be extended out via sliders when positioned over the target region. Figure 1a shows the aerial unit sketch. Figure 1b shows an installation of the aerial unit on a Cessna-172 single engine airplane. It is shown in open mode (shooting mode) which has its external part pressed along the sliders and positioned outside of the airplane body.

(a) (b)

Figure 1. The aerial unit. a) Design Sketch of the aerial unit. b) The system in shooting mode, installed on Cessna-172 during a mapping mission above Melbourne, Australia.

Furthermore, our aim is to use relatively small aircraft. We also would not like to limit the usage to good weather conditions or to particular flight altitudes. These requirements enforce the use of stabilization and an azimuth correction mechanism. For this goal we develop a three axes controller (for pitch, roll and yaw). The controller has an analog input channel that gets a signal from a two axes gyro and affects the pitch and roll stabilization. The gyro is rigidly fixed to the sensor and therefore delivers reliable vertical angles correction measurements. The gyro measurements are transferred to the controller and the controller corrects the pitch and the roll axes' in a closed-loop form. In order to correct the azimuth we use a GPS receiver with two antennas placed in different positions. This device combines Kalman-filter predictions with the measurement differences taken by the two antennas to produce an accurate flight direction relative to the ground coordinates. The azimuth measurements are submitted to the controller and the controller performs kappa corrections respectively. The three axes correction guarantees not only the vertical (Nadir) view on the scene but also maximum overlap within the flight direction. The use of minimal control equipment and a low weight gyro enables an aerial unit with small dimensions and a low weight that can be installed in a diverse variety of aircraft.

The sensor which is mounted on the aerial unit can be based on any kind of calibrated camera including off-the-shelf consumer cameras. In addition, the adaptations required for the integration of a new camera into the mount are relatively fast and simple. The usage of consumer cameras for aerial photogrammetry has been discussed for a long period among the photogrammetric community. The ongoing research in the field shows that the modern equipment can lead to the required quality from a geometric and radiometric point of view (Läbe and Förstner, 2004; Cronk et al., 2006; Petrie and Walker, 2007). So far, we have installed a range of sensors starting with low cost, consumers, small format cameras and up to high-end medium format cameras equipped with a digital back and advanced optics. In addition, sensors with different kinds of radiometric properties have been utilized (e.g. IR, thermal, CIR etc.). As for calibration, the cameras interior parameters are measured using a calibration-field consisting of ~200 well measured targets. A set of images of the targets (normally 12) are acquired in several poses. The targets are automatically recognized and sampled in the image set by designated software that applies template matching techniques. All of the samples from the various images are entered into a unified adjustment process. The usage of multi-pose images per single calibration process guarantees full coverage of the sensor area and therefore reliable and accurate parameters estimation. Fig. 2 shows typical coverage of the sensor area when using the proposed scheme.

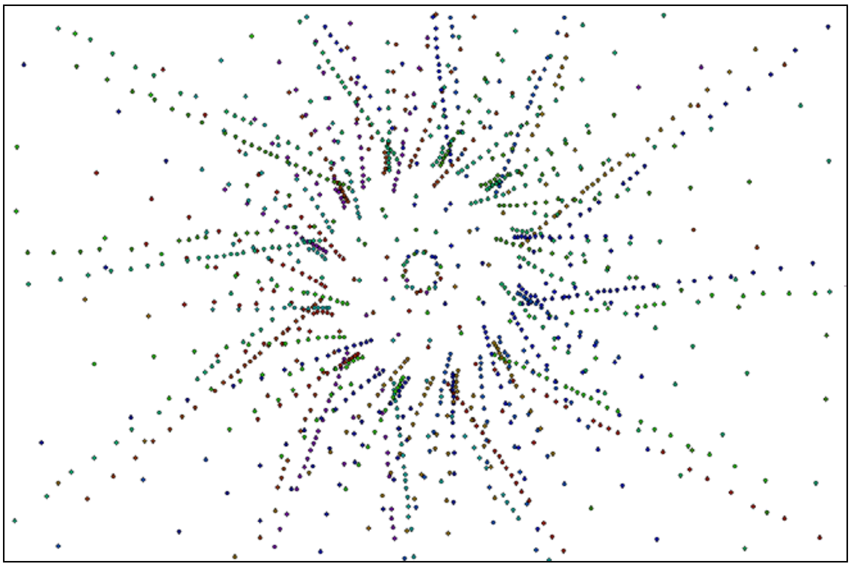
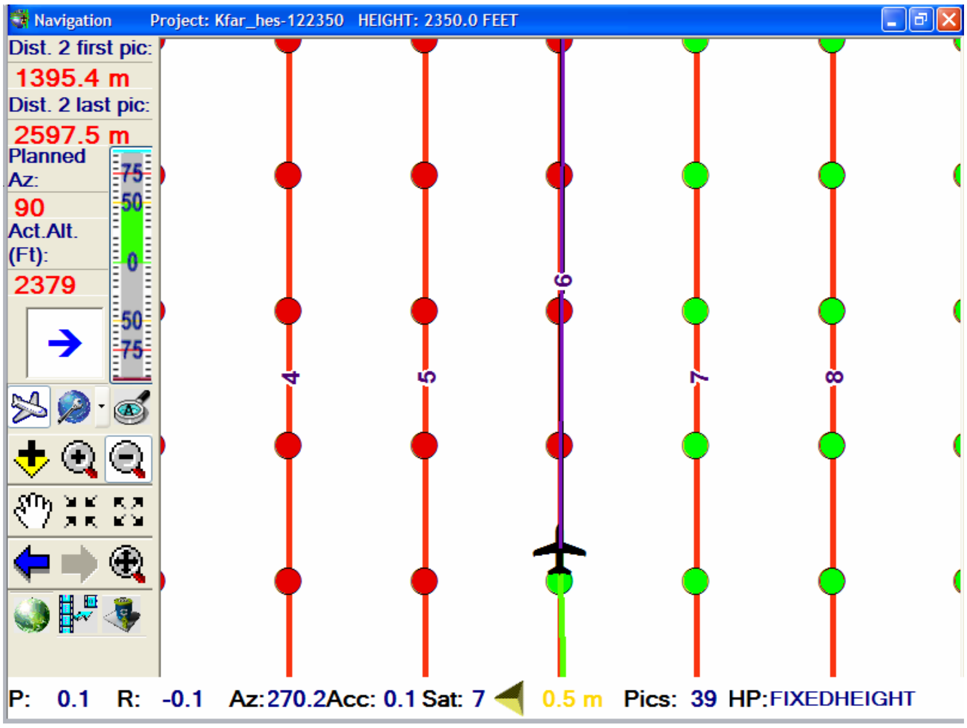


Figure 2. Camera calibration samples taken from 12 images that were taken from different poses created by rotating the camera around its main axis. The dots represent appearance of calibration targets in the acquired images.

For flight management and navigation, we use a computer that does not have any moving parts (e.g. fans, hard-disks). The computer is based on a flash-drive and all the components including the pilot display and the operator screen are cased in protecting shields and have hooks for fast installation. For simplicity, the taken images are stored on a flash memory, which can be replaced from time to time during the flight if necessary. The flight management software shows the flight strips as routes and the planned images as points. The software shows the actual position of the aircraft relative to the mission trail, the required photo-shooting points, etc. When a planned shooting point is reached the navigation software delivers a shooting request to the sensor and the image is captured. Simultaneously, the software records the shooting and navigation parameters and updates the planned image status on the displays. Figure 2 shows a typical view of the operator / pilot display.


Navigation Project: Kfar_hes-122350 HEIGHT: 2350.0 FEET

Dist. 2 first pic: 1395.4 m

Dist. 2 last pic: 2597.5 m

Planned Az: 90

Act.Alt. (Ft): 2379

P: 0.1 R: -0.1 Az:270.2Acc: 0.1 Sat: 7 0.5 m Pics: 39 HP:FIXEDHEIGHT

Figure 3. Typical screen-shot of the flight management software.

3. THE PHOTOGRAMMETRIC WORKFLOW

The use of a relatively small sensor directly leads to a large amount of images. Applying the photogrammetric procedures on a large number of images necessitates explicit working methodology. The photogrammetric workflow has three key roles:

- **Workflow management**. The photogrammetric process has to be managed in the production-line sense. Each image has to move through the stations across the photogrammetric pipeline (tie-point extraction, triangulation, DTM extraction, etc.) while maintaining data-integrity and optimizing resource utilization. Due to the large number of images, the amount of input and setting parameters is extremely large, and therefore the use of a photogrammetric workflow management system is essential.
- **The photogrammetric modules**. The workflow consists of the photogrammetric modules that have to be highly interfaced with the management system. Each of the photogrammetric steps has to work in a fully automatic manner.
- **Human interface**. While running all processes in batch mode, problems may rise. The system is required to report problems and errors as fast as possible, provide the operator the maximum information on the problem source and finally offer the user effective tools to solve it. When the problem is solved, the process has to continue from the point where it stopped with minimal effect on the final outcome.

Overall, our aim is to make the photogrammetric workflow fast and effective despite the large number of images.

3.1 Management System

In order to control the large amount of images, a photogrammetric workflow management system was developed. The system conducts a central relational data-base and a central storage unit (i.e. RAID). The acquired images are saved in the storage unit while the images metadata, the division of the images into photogrammetric working units (i.e. blocks, sheets) and the workflow statuses are stored in the central data-base. The system has a geographic display that shows each image as a point and each work-unit as a polygon. The polygons and the points have different symbology, according to their current status. Images' common statuses are: "not yet taken"; "position and orientation were updated"; "the image takes part in orthomosiac" and so on. The photogrammetric unit can hold statuses like: "done", "in process", "not yet started", "error" etc. This display provides the operator with a bird-eye's view of the workflow and the project's current progress.

The work-units have interdependency, for example, a single image that appears in two photogrammetric blocks cannot have two different exterior orientations. The management system makes this interdependency transparent to the operator and manages the conflicts behind the scene in order to make the workflow smooth and more effective. To achieve this goal, the system has an interface to all the photogrammetric tools which are operated from the system and reports back their results back when completed. The results are then analyzed by the system and decisions about changing the status are made according to the system's internal logic. The tools consist of tie-point extraction, aerial triangulation, DTM extraction, Ortho-rectification and mosaic stitching.

3.2 Tie-points Extraction and aerial triangulation

The accuracy of the aerial triangulation process and the accuracy of the final product is highly dependent on the quality and coverage of the extracted tie-points. Late advances in the field of computer vision lead to new extraction and matching schemes (e.g. Mikolajczyk et al. 2005; Lowe, 2004). In addition, some works show the possible use of those schemes in a photogrammetric framework (e.g., Shragai et al., 2005; Nistér et al., 2006). However, these proposed schemes are not efficient and robust enough to guarantee the combination of full image coverage within pixel accuracy in a reasonable timeframe in typical photogrammetric missions. In order to make the process time efficient and accurate, we use an alternate extraction scheme. In the scheme used the extraction phase is performed in the original image scale without any need to downscale the image dimension. We are using a unique descriptor that we found to be more efficient in the case of aerial images. This adaptation leads to a very fast and efficient framework when using a large amount of images in a single matching procedure. Following the extraction and matching of the tie-points a series of geometric filters are applied in order to insure the removal of outliers. Results of the tie-point extraction process are demonstrated in Fig 4. The figure shows a matching example resulting by applying the algorithm two consequential images. One can see that the entire overlap region is covered by correctly matched tie points as the algorithm avoids outliers even though a large part of the overlapping area is covered by clouds. In the photogrammetric workflow, the algorithm is applied on a full block of images and extracts tie-points between all overlapping images. Following the extraction of a huge amount of tie-points in a block mode, only the tie-points with the highest contribution to the block stability from a geometric point of view are used in the aerial triangulation phase.

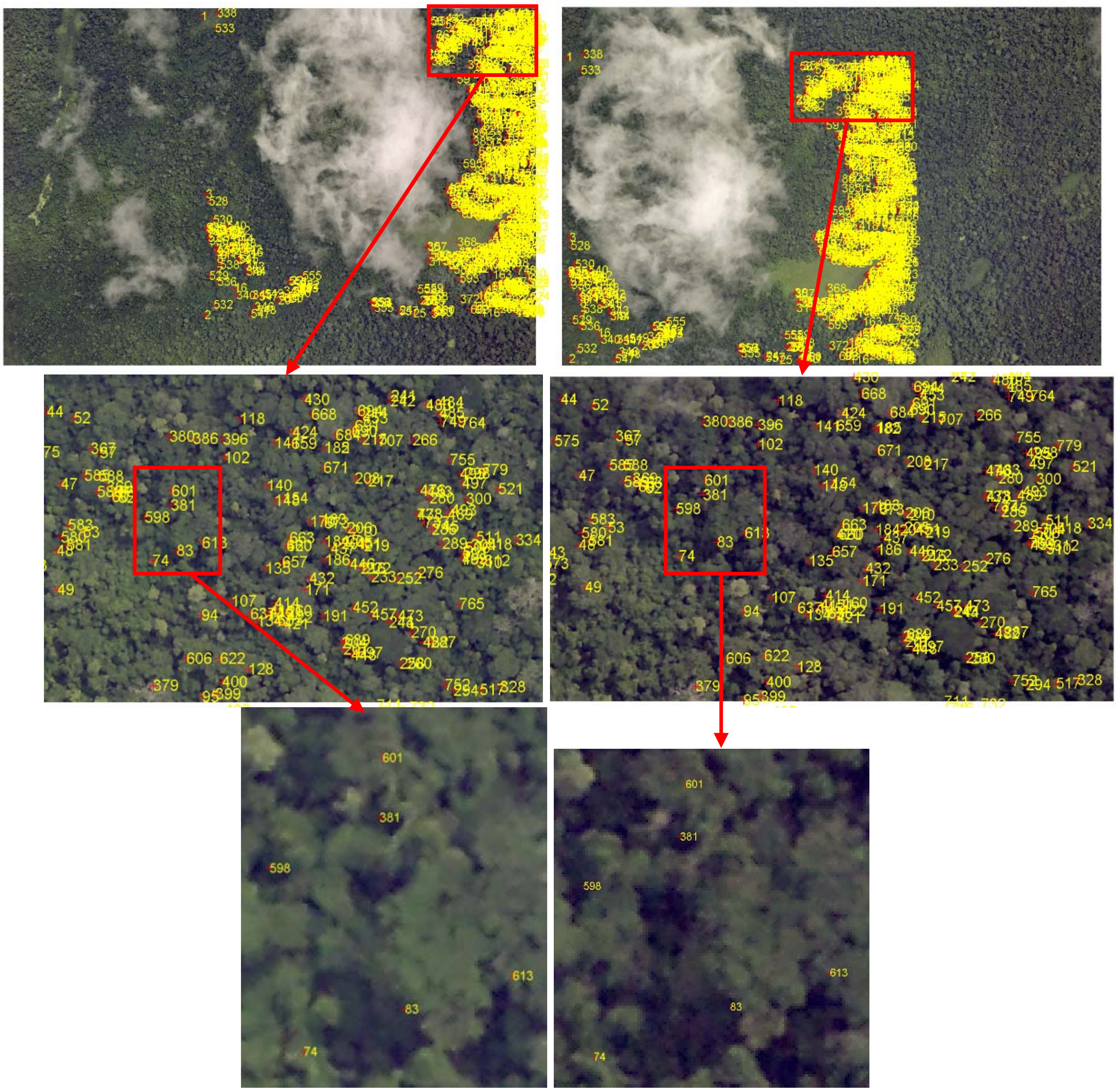


Figure 4. Automatic extraction of tie-points using designated algorithm.

3.3 DTM, Ortho-Rectification, and Mosaic stitching

Following the completion of the aerial triangulation phase, the next stages consist of the extraction of the DTM, ortho-rectification and mosaic stitching. For the DTM extraction we use the same framework described in the tie-point extraction stage. The tie-point extraction framework supplies dense and reliable tie-point coverage of the stereo region. The points are then used as the base for the DTM creation and thus we shorten the runtime relative to classic methods. The ortho-rectification stage is preformed for each image separately based on the extracted DTM. Due to the relatively small frame and the high resolution, the number of images taking part in a normal ortho-photo sheet may be considerably large and respectively the number of seams in a sheet will be high. Therefore, special attention must be given to the mosaic creation. In order to produce smooth and seamless mosaics we perform several consecutive processes:

- Dodging. This process is used to overcome differences in the brightness within a single image, which could result in a mosaic with unbalanced colors. Normally, due to lens effects, the center of the image appears brighter then the rims.
- Seam line extraction. Finding the optimal seam line between a pair of adjacent images. The algorithm finds the constrained shortest path through the overlap region between the two images. The resulting seams avoid image edges and prefer to go through homogenous textured areas.
- Histogram matching. In order to overcome the brightness differences between the images, the algorithm balances all images histograms in a global adjustment scheme. As a result, homogenous brightness levels are reached throughout the entire mosaic.
- Stitching. Finally, the images are stitched together along the seam lines utilizing a feathering algorithm to prevent the seam line from being visible.

Figure 5 shows an example of four images stitched together.

(a) (b)

Figure 5. Example of Four images stitched together using the proposed framework. a) Regions taken from different images are marked in different colors. The horizontal seam line runs along the road in order to avoid cutting through the sidewalk, which would cause the seam line to be noticeable. b) The stitching results.

4. ACCURACY TESTS

In order to test the proposed system a performance evaluation flight was conducted. The test field area is 2 by 3 km and contains 107 Ground Control Points (GCPs). The field is located in a hilly region in which the difference between the lowest and the highest point is about 250 m. the flight altitude was set to 810 m above ground level. In this experiment we used a medium format camera equipped with a 55 mm lens and a 39 mega-pixel digital back. The sensor dimensions are 49.1 x 36.7 mm and each pixel dimension is 6.8 x 6.8 um. The camera was oriented such that its sensor long dimension was parallel to the flight direction. The overlapping percentage was set to 60% along strips and 30% across strips. The expected Ground Sampling Distance (GSD) was ~10 cm. Overall the flight consisted of 66 images arranged in six flight lines. Theoretic altimetric precision was calculated (according to McGlone et al., 2004):

$$\sigma_Z = \frac{Z}{b}\sigma_{Px} = 0.395\ m \tag{1}$$

with

$$\begin{aligned} b &= 0.4 \cdot 49.1 = 19.64\ mm \\ \sigma_x &= \sigma_y = 0.0068\ mm \\ \sigma_{Px} &= \sqrt{\sigma_x^{\ 2} + \sigma_x^{\ 2}} = 0.009617\ mm \end{aligned} \tag{2}$$

Where Z is the flight altitude above ground level, b is the aerial base expressed in image units and σ_{Px} is the measuring accuracy for parallax x. For the calculation σ_x and σ_y namely, the sampling accuracy is assumed to be 1 pixel in each direction. The experiment results are presented in Table 1. The results show that the accuracy reached by the system was slightly better than the expected accuracy (see eq. 1) when using 5 GCPs. When not using GCPs the accuracy is affected by the GPS accuracy, GPS/sensor synchronization and errors in measuring the relative vector between the GPS-antenna and camera position.

Table 1. The results of the performance evaluation.

# control points	σX	σY	σZ	RMSE pix
0	0.499	0.574	0.459	0.373
5	0.191	0.125	0.324	0.423

5. CASE STUDIES

Two case studies will be presented. The former demonstrates the proposed system suitability for photogrammetric projects in remote areas. While the latter shows its benefits for fast response mapping missions.

5.1 Congo project

The project requirements were to produce a 48 cm GSD orthophoto spreading over 2,000 square kilometers. The absolute accuracy specification of the client was ±5 m. the target area had no geodetic infrastructure, such as a control network or GPS reference stations. Due to weather conditions, particularly cloudiness, the available satellite imaging was insufficient.

The project had various logistic obstacles, the required time frame was very short and thus creating an elaborate photogrammetric array was impractical. The proposed solution was to make use of a local standard light aircraft and facilitate it such that it would be used as a photogrammetric platform. The available airplane was a small single engine airplane with no shooting hole (Cessna-206). Other issues included problematic terrain due to recurring floods, absence of paved roads (see Fig. 6.a) and low access to fueling stations and runways (see Fig. 6.b). These obstacles, in addition to cloudiness and no reliable weather forecasts resulted in complicated flight management.

The system arrived on a commercial flight with a team consisting of two operators. The team then went directly to the airport where they met with the local pilot, whom had no prior experience in photogrammetric flights, and started the installation process, which took about an hour (see Fig. 6.c). The first flight was then launched despite the heavy rain and overcast skies. After two weeks of daily flights and over 25 flight hours the area was fully covered. The images were then stored on portable hard-disks and sent via air-mail to the ground team. Due to clouds appearing in some of the images and the variety of flight altitudes (which were required in order to avoid the clouds) the photogrammetric procedures necessitated some manual intervention including picking the best images and engaging the irregular problems that arose during the photogrammetric process. Overall, one month later the final product was delivered (see Fig. 6.d).

5.2 Flights and Orthophoto production in one day

In order to respond to urgent mapping projects we tested the systems' capability to handle the scenario of getting an order in the morning and delivering the products the same day. The project requirements were to produce an orthomosaic of 20 sq KM in 10 cm GSD. The target region was within one hour flight distance from the airport.

Following the recording of the order, a mission planning was made immediately. The target region borders were fed as a polygon into the planning software. The planning software automatically calculated the position of the 100 images and 5 flight lines needed to cover the area in full stereo and exported the data in the format used by the aerial unit. The aerial unit was then taken to the airport and installed on the aircraft, the mission data was then fed into the navigation software of the aerial unit. The flight took about two hours. Upon landing the aerial unit was packed and taken back to the office and the acquired images that were stored on flash cards were imported into the photogrammetric workflow management system. All the photogrammetric stages were automatically performed on the images including: i) automatic tie-points extraction which were not edited nor passed any quality assurance stage; ii) aerial triangulation stage that show sub-pixel convergence iii). Automatic DTM extraction; iv) orthorectification and mosaic stitching. Overall the ground processing took ~4 hours. Fig. 7.a shows the orthomosaic product which was made without any human intervention. In order to examine the radiometric consistency of the orthomosiac product we present in Fig 7.b the product which was made by a common commercial photogrammetric software as a reference. We note that in the commercial results one can see unbalanced brightness levels which have to be corrected manually using graphic editing software (e.g. Photoshop).

(a) (b)

(c) (d)

Figure 6. Mapping mission in Congo. a) Fuelling the airplane. d) Mobility conditions on the ground in the target area. c) Installation of the system on the airplane, Cessna-207. d) The final orthmosiac.

(a) (b)

Image 7. Flight and orthomosaic production in a single day. a) The final product as generated by the proposed system. b) Mosaic results of commercial software.

6. CONCLUDING REMARKS

In this paper we presented a photogrammetric system based on a digital sensor. The system is designed for simplicity and flexibility. It has two complementary parts which are the aerial unit and the ground station that implement the photogrammetric workflow in a unique manner. The system is modular and can be adapted to a variety of schemes which give a solution to a range of requirements including: minimizing flight time, high accuracy, fast processing, challenging weather conditions etc. The aerial unit has small dimensions and low weight which allows it to be sent to remote areas without any special logistic arrangements. The proposed complimentary process makes the photogrammetric workflow automatic and efficient. Overall, the system provides two major advantages, fast and flexible installation on one hand and a high level of accuracy and effective processing on the other. These advantages were demonstrated by accuracy analysis and case studies.

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