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Photogrammetric recording of the archaeological site of Pinchango Alto (Palpa, Peru) using a mini helicopter (UAV)

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ABSTRACT

In this paper we describe a new system for the recording of archaeological sites based on an autonomous UAV (unmanned aerial vehicle) that has recently been employed in the framework of the Nasca-Palpa Archaeological Project on the south coast of Peru. In the vicinity of Palpa, the prehispanic site of Pinchango Alto is an attractive, yet difficult target for archaeological research. On the one hand, its well preserved stone architecture, abundant surface finds, and richly furnished graves dating to the Late Intermediate Period (AD 1000-1400) offer many opportunities to study this still poorly understood pre-Incaic period. On the other hand, access to and working on the site is rather difficult. The recording of the preserved surface remains therefore required a highly mobile and flexible documentation system. In the 2004 field campaign we used a model helicopter carrying a CMOS camera to acquire a series of vertical aerial images for a photogrammetric recording and 3D modeling of the site and the surrounding terrain. The system used in Pinchango Alto is based on a commercial low cost model helicopter. It features an integrated GPS/INS based stabilizer. While the GPS/INS unit enables semiautomated navigation along a predefined flight path, the stabilizer ensures a stable flight attitude and thus a highly reliable image acquisition. The processing and analysis of the acquired images encompassed image pre-processing, semiautomatic triangulation, and DTM generation. A virtual 3D model of the site was produced and visualized. In this paper we present the first results of our ongoing work in Pinchango Alto and discuss the strengths and weaknesses of the UAV-based documentation system for archaeological research.

1. INTRODUCTION

1.1 PINCHANGO ALTO

Archaeologically, the south coast of Peru is mainly known for the fancy ceramics and famous geoglyphs of the Nasca culture (200 BC – 650 AD), whereas earlier and later phases of pre-hispanic cultural history are less well studied. The Late Intermediate Period (LIP, AD 1000-1400), preceding the incorporation of the Nasca region into the Inka empire, is marked by high population density, Ica-style ceramics, and a distinctive settlement pattern (Reindel *et al.*, 1999; Conlee, 2003). In contrast to earlier times, LIP sites tend to be situated on hillsides, ridges, and even hilltops. They are rather large and apparently removed from water and arable land. This pattern may be explained on the one hand by more humid climatic conditions (Eitel *et al.*, 2005) and on the other hand by possible mining activities among the hills (Reindel, 2002). (Fig. 1)

Pinchango Alto is the largest LIP site in the Palpa area (Fig. 1) and has recently been studied in the framework of the long-term Nasca-Palpa Archaeological Project (Reindel, Isla, 2000; Reindel, Gruen, 2005). The site is located about 3 km north of the modern town of Palpa on an elongated rocky spur on the western slope of Cerro Pinchango. It is framed by deep ravines on three sides, making access from both Río Grande (to the north) and Río Palpa (to the south) difficult. The central part of the site covers an area of roughly 3 ha on the flat ridge of the spur. The ruins are composed of partially collapsed double-faced walls built of unworked stones, today preserved to a maximum height of about 1.5 m (Fig. 2). These walls once formed agglutinated rooms, enclosures, corridors, and several large plazas. In general, the site is quite well preserved, the southwestern and northeastern sections being in a better shape, allowing to recognize e.g. doorways in the walls. Due to its hidden location, the site has suffered less looting than most other sites in the region of Palpa and Nasca. (Fig. 2)

1.2 PROJECT GOALS

Because of its state of preservation, Pinchango Alto is well suited to study a typical LIP site in detail. However, the rugged topography renders access to and working on the site very difficult. During the annual field campaigns in the Palpa region time and manpower available for site surveying are limited. A series of vertical aerial images of the region taken in the framework of a geoglyph survey (Lambers, 2004) did not provide enough detail for a photogrammetric survey. Thus, a highly mobile, flexible, and efficient recording system was needed to record the preserved architecture, as well as the terrain. The documentation of Pinchango Alto was also intended to show the potential of modern surveying techniques in archaeological research in terms of accuracy, efficiency, and detail.

Many recording efforts in archaeology are still based on classic surveying techniques like tape measurements, single point determination using total stations, or leveling. These measurement techniques may be accurate, but are quite time consuming, especially on large sites. It is often desirable to do the surveying of archaeological sites in a rather short time. Furthermore, the recording system employed should be easily transportable, easy to use, and able to handle big datasets. Thanks to funding provided by the German Ministry of Education and Research (BMBF, Bonn) in the framework of its research program NTG ("New Methods and Technologies in the Humanities") we were able to employ two new systems for the recording of Pinchango Alto during the September 2004 field campaign.

On the one hand, a Riegl LMS-Z420i laser scanner kindly provided by Riegl GmbH, Horn, Austria, was used to scan the whole area in 5 days. Using laser scanning, large sites can be surveyed in a short time with high point density. The Riegl scanner was mainly chosen for its long scanning range of 800 m and the combination with a digital still-video camera (Gaisecker, 2005; Riegl, 2005). Data acquisition and processing with the Riegl scanner and software, as well as the combination of laser data with aerial images will be described elsewhere.

On the other hand, we used a model helicopter from weControl / Helicam carrying a CMOS camera to acquire a series of aerial images suited for photogrammetric analysis (Helicam, 2005; WeControl, 2005). This part of the work is the focus of the present paper.

1.3 THE UAV SYSTEM

For the production of high resolution orthoimages large scale images are required. High resolution is essential for interpretation, detection and measurement of small archaeological features. Ground based image acquisition is limited concerning its perspective. Aerial images, on the other hand, are a common starting point in archaeological research to document a given site. They may be used as base data for orthophoto and DSM generation as well as for map production. However, aerial images are usually taken from airplanes and in some cases from helicopters or balloons. Their limited maneuverability is a disadvantage of these platforms. They are furthermore mainly suited to obtain nadir images at a rather large scale.

Model helicopters, in contrast, are able to operate rather close to the object. They are highly flexible in navigation and may be used with variable viewing directions. Hitherto, in archaeology model helicopters have been used without GPS/INS based navigation (global positioning system / inertial navigation system). New technologies now allow low-cost navigation systems to be integrated in model helicopters, enabling the system to fly autonomously. This kind of mini model helicopters is called mini UAV system (unmanned aerial vehicle: Figure 3; Eisenbeiss, 2004; UVS, 2005).

Using a mini UAV with GPS/INS based stabilizer it is easy to fly precisely along a predefined flight path and to change the different viewing directions for image acquisition. In Pinchango Alto, we used a model helicopter developed by weControl (Fig. 3) featuring the following characteristics: the wePilot1000 system, a flight control system for UAVs consisting of a GPS/INS system, altimeter and stabilizer, a laptop with monitoring software (weGCS), ground support and control equipment, handling and storage equipment, a Canon D60 still video camera with various lenses (14, 28-200 and 50 mm), communication links, power supply, video link (incl. video camera) as visual control for monitoring image overlap, and transport equipment. (Fig. 3)

Depending on requirements for specific tasks the camera system may be changed to medium format analog cameras or still video cameras with higher or lower resolution and comparable payload. In its current state of development, the UAV system used in Pinchango Alto has an airborne operation time of 15 to 25 minutes, depending on payload and altitude. In Pinchango Alto a rather small gas tank was chosen, since a bigger tank would have reduced the payload of the helicopter.

2. DATA ACQUISITION

2.1 FLIGHT PLANNING

The GPS/INS navigation system and the autonomous flight capabilities of the weControl UAV allow a detailed and precise flight planning prior to fieldwork, defining acquisition points and certain parameters of the helicopter according to the project requirements (Fig. 4). In order to determine the flight path the following parameters are needed: desired image scale, focal length, sensor size and pixel elements of the camera, along and across track image overlap, corner points of the area, average terrain height or an elevation model, and velocity parameters of the helicopter between acquisition points (velocity for forward, side, climb and heading). (Fig. 4)

The flight was planned using software developed at IGP (Eisenbeiss, 2004). In a first step the area of interest has to be defined depending on the features to be recorded. For this purpose, either an existing map is required or a single image acquired from the model helicopter from high altitude and four control points on the corners. With the aid of an orthophoto and an elevation model derived from aerial images at a scale of 1:7000 (Sauerbier, Lambers, 2003) and based on the predefined parameters, a terrain dependent flight was planned, aiming to get the same image scale of 1:4000 in all helicopter images (Fig. 5). Because of the low flight altitude over ground in comparison to the normal aerial case, the fleight height was defined individually for each acquisition point, averaging 56 m. As input for weGCS (weControl grond control station software) a text file with 3D coordinates of the acquisition points, parameters for flying velocity and the definition of point status (stop, crossing or turning point) was generated. The velocity of the helicopter had to be limited to 2 m/s because of the short distances between acquisition points where the helicopter had to stop. (Fig. 5)

2.2 CONTROL POINT MEASUREMENT USING DIFFERENTIAL GPS

During fieldwork we determined the positions of 80 signalized control points (CPs) to be used for both laser scan data and UAV image orientation. The CPs was regularly distributed over the site. Retro-reflecting cylinders (standard cylinders by Riegl GmbH) were mounted on circular white cardboard discs and affixed to stones with a special glue easily removable without traces (Fig. 6). While the reflectors were clearly marked in the laser scan point clouds, the cardboard discs were discernable in the aerial images. The CPs were measured with RTK-DGPS (real time kinematic differential global positioning system) in the WGS84 system with a 3D accuracy of 2 to 3 cm. The resulting coordinates were then transformed to UTM coordinates. (Fig. 6)

2.3 ACQUISITION OF UAV IMAGES

The helicopter flight was navigated both by an operator and a pilot. While take off and landing were controlled by the pilot due to the difficult terrain on the site, the actual flight mission was then controlled by the operator via the control system installed on a laptop (Fig. 7). The helicopter started from and landed on a white tarpaulin to prevent the raise of dust. Once the helicopter reached the predefined elevation above ground the pilot turned the control over to the operator while still being able to intervene if necessary. The operator then sent a navigation command to the helicopter to fly to the first crossing point, thus putting it on the predefined flight path. The next point along the course was the first acquisition point and therefore defined as stop point. Here the operator controlled the position on the monitor (position and image wise) and acquired the first image by triggering the shutter via radiolink. Then the helicopter moved on to the next predefined point. The weGCS software interface enabled the control of parameters like position, altitude, speed etc. while the helicopter was airborne. (Fig. 7)

During one flight 20 to 30 images corresponding to 1 to 1.5 strips could be captured. Then the helicopter had to land to refill gasoline and to recharge the batteries. Due to the high temperatures during our field campaign battery recharging took 1 to 2 hours. Therefore, on the first day only 5 out of 8 predefined strips could be flown, acquiring a total of 85 images. On the morning of the second day, dusted petrol and sand in the engine caused the helicopter to crash before reaching its normal flight height. Due to time constraints it was not possible to repair and relaunch the damaged system. However, 95% of the site had already been covered on the first day by images suitable for stereoscopic post processing thanks to the precisely predefined flight path, the GPS/INS based stabilizer and the considerable overlap between the image strips. Thus, in spite of the mentioned serious problems, the system generally proved to be highly operable. The main project parameters are summarized in Table 1.

Table 1 – Main project parameters for flight planning and post processing

Project parameters Pinchango Alto	
Average flight height above ground	56 m
Velocity	2 m/s
Acquired images	85
Image scale	1: 4000
Ground resolution	3 cm
Image overlap along / across track	75% / 75%
Images used for DSM generation	70
Images used for orthophoto generation	26

3. DATA PROCESSING

For 3D building reconstruction, helicopter images have up to now only been used in addition to images taken from the ground (e.g. Zischinsky *et al.*, 2000). In contrast, in Pinchango Alto the whole data processing was done using only the images taken from the mini helicopter. Three different software systems were employed for photogrammetric image processing: the commercial software package LPS (Leica Photogrammetry Suite, Leica Geosystems) and the inhouse programmes BUN and SAT-PP.

3.1 TRIANGULATION

LPS offers the functionality required to accomplish the complete photogrammetric working process from project definition and interior orientation to measurements of tie points (either in manual or automated mode), manual measurement of control points, bundle adjustment, and finally to DSM generation and orthophoto production. (Figure 8)

The automatic measurement of tie points in LPS turned out to be time consuming and error prone as LPS is designed for the standard aerial case, implying the use of calibrated aerial cameras. In Pinchango Alto we used instead an uncalibrated CMOS camera with a wide angle lens. These special conditions, in combination with considerably varying terrain elevation not accounted for by the software, change of light conditions, as well as strong shadows in the images, caused the automatic tie point measurement tool to produce a lot of blunders. Therefore we decided to initially measure at least 6 points per image pair manually and then to run the automatic tie point measurement tool. This procedure still yielded a lot of blunders in mountainous areas. These were removed using LPS and BUN, at which BUN detected more blunders than LPS. In addition to the mentioned problems of tie point measurement, certain control points were marked as blunders as well. These points were not used in the bundle adjustment. Due to these problems control points were not optimally distributed.

Using LPS for bundle adjustment we achieved an RMSE value of 2 pixels. With BUN and doing the self calibration of selected parameters following Brown's model (without share factor and parameters for tangential distortion) we obtained an RMSE value of 1/3 pixel.

3.2 DSM GENERATION

For DSM generation from the helicopter images we used the inhouse software SAT-PP (Zhang, Gruen, 2004; Zhang, 2005), adapting it such that it was capable to handle still video camera imagery. Thanks to the large overlap of 75% in flight direction three images could be used for matching. The matching approach used a coarse-to-fine hierarchical solution with a combination of multi image matching algorithms and automatic quality control. After pre-processing of the original images and production of image pyramids, the matches of three kinds of features (feature points, grid points and edges) on the original resolution image were found, progressively starting from low-density features on the low resolution level of the image pyramid. A TIN of the DSM was reconstructed from the matched features on each level of the image pyramid by using the constrained Delanuey triangulation method. This TIN in turn was used in the subsequent pyramid level for approximations and adaptive computation of the matching parameters. Least squares matching methods were used to achieve more precise matches for all the matched features and for the identification of some false matches (Zhang, 2005). Finally, we derived an interpolated regular DSM from the matching results (Fig. 9).

3.3 ORTHOPHOTO PRODUCTION

Using the software package LPS the following versions of orthophotos of Pinchango Alto were produced:

- One orthophoto covering the whole site with a ground resolution of 5 cm based on the helicopter images and a DEM with 2 m grid size derived from Zeiss RMK aerial images (Sauerbier, Lambers, 2003).
- Another orthophoto covering the whole site with a ground resolution of 5 cm based on the helicopter images and a laser DSM with 20 cm grid size.
- Yet another orthophoto of the whole site with a ground resolution of 3 cm based on the helicopter images and the DSM produced out of them with 20 cm grid size.
- One orthophoto of the best preserved northeastern part of the site with a ground resolution of 5 cm based on the helicopter images and a laser DSM with 10 cm grid size.

The orthophotos were generated from the helicopter images of the first, third and fifth strip. From each strip we selected every other image, resulting in a total of 26 images used for ortophoto production (Table 1). Cutlines between images were calculated using the weighted cutline function in LPS. In the process of producing the final orthophoto with 3 and 5 cm ground resolution, respectively, we applied color balancing and feathering by a distance of three times the pixel size. The processing time for the complete area, about 300 m by 200 m, was approximately 20 min on a 2.8 GHz two-processor machine. Verifying check points for accuracy analysis we achieved an RMSE value of 5 to 10 cm in 3D for the whole area of Pinchango Alto.

3.4 3D VISUALIZATION

For 3D visualization we used in a first step the orthophoto generated out of the laser DSM and the helicopter images. This orthophoto is appropriate only as texture for the laser DSM due to deviations between the different DSM datasets. In a second step, a 3D visualization was generated from the orthomosaic and the DSM both based on the helicopter images. ArcScene allowed us to combine the different datasets and to navigate in near real-time through the textured 3D model. In order to generate a virtual flight through the model we employed Maya. For this purpose the image file was converted from TIFF to GIF format. In Maya the file was then converted to a block ordered texture format with hierachical structure (LoD). This procedure caused a loss of image resolution. Nevertheless, Maya enabled us to produce flyovers with smooth flight trajectories and high texture quality (Fig. 10).

Thus far, only the orthomosaic derived from the UAV images was used for texturing. Due to the vertical perspective of the aerial images it is mainly suited for the horizontal surfaces of Pinchango Alto. In order to texture vertical surfaces like wall facades, oblique photos acquired by the camera mounted on the laser scanner would be more suitable. Up to now we did use them for this purpose but will do so later on. Alternatively, images could be taken from the UAV with an oblique viewing angle of the camera. Further steps intended for future work include the joint orientation of both the helicopter images and those taken from the camera mounted on the laser scanner. The aim is to produce a 3D model with optimized textures for each viewing angle (view dependent texture mapping).

4. CONCLUSIONS

The autonomous UAV system used in Pinchango Alto generally met the high expectations. It acquired images according to specific project requirements that did not allow us to use a different platform. The GPS/INS unit in conjunction with the control software enabled a detailed flight planning exactly tailored to the specific needs on the site. The stabilizer absorbed vibrations and ensured very precise image acquisition at each stop point. The system worked in a very fast, efficient and accurate way, such that 95% of the site could be recorded in just one day. Image processing could be accomplished to a certain degree in automated mode.

In spite of these strong points, we encountered major problems as well that will have to be solved in further development stages of the system. Dusty conditions similar to those in Pinchango Alto that finally caused the failure of the system prevail on other potential usage sites as well. A stronger engine and a better filtering system are thus needed. Furthermore, the time needed for battery recharge and the limited capacity of the gas tank caused several long breaks during fieldwork. The major constraint, however, is the fact that take off and landing have so far to be controlled by an experienced pilot for security reasons. While the control software is in principle capable to manage this part of a mission as well, height measurements of the GPS currently mounted on the helicopter are not precise enough to ensure a safe landing. In the future differential GPS will be used to more precisely determine flight positions. In order to do a meaningful flight planning, the operator needs a certain background knowledge of photogrammetric image analysis. Image processing required some manual intervention due to shortcomings of the applied commercial systems.

To sum up, the system proved to be highly promising for fast and efficient site recording. Future work will focus on the robustness of the system. Improvements are aimed at concerning GPS measurements, operation time, and possibly payload. Flight planning has to be further refined. Concerning image processing, we plan to provide downsampled images directly on the site for a quick quality check. Certain capabilities of the system that could not be exploited in Pinchango Alto, like e.g. different viewing angles of the camera, will be tested in future projects as well.

Pinchango Alto, a highly complex archaeological site difficult to access, was recorded in just a week of fieldwork by two new systems that exceed traditional surveying methods by far concerning accuracy, point density, and acquisition time. Data processing allowed the elaboration and visualization of a detailed 3D model that will now serve as starting point for further archaeological research. The UAV system presented here is thus a powerful tool for the recording of other cultural heritage sites as well.

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FIGURES

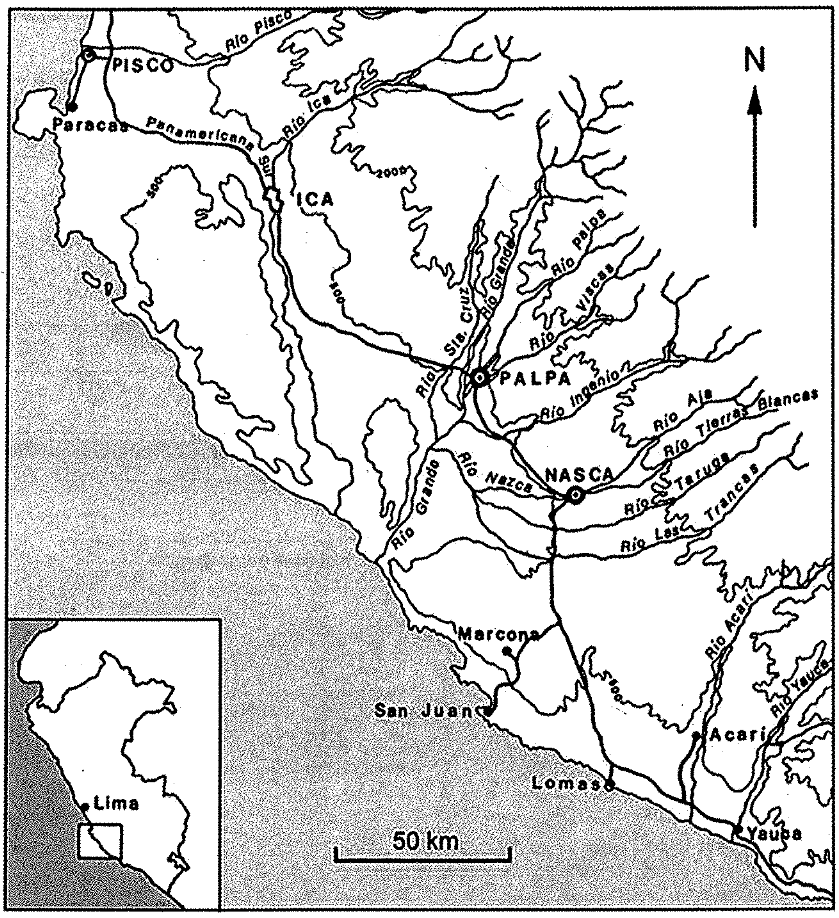

Fig. 1 – The region of Palpa and Nasca in southern Peru.

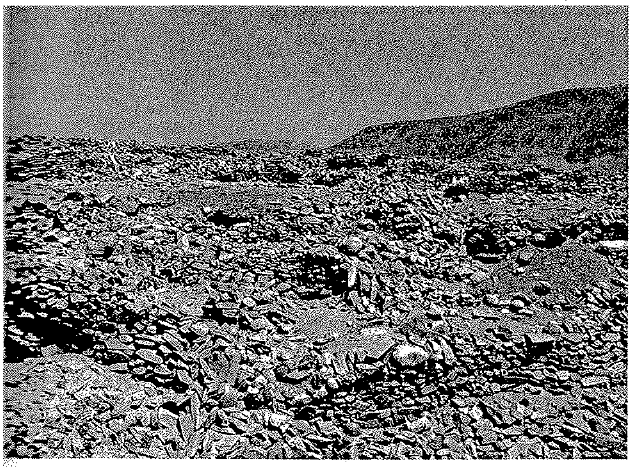

Fig. 2 – Stone walls in the northeastern sector of Pinchango Alto.

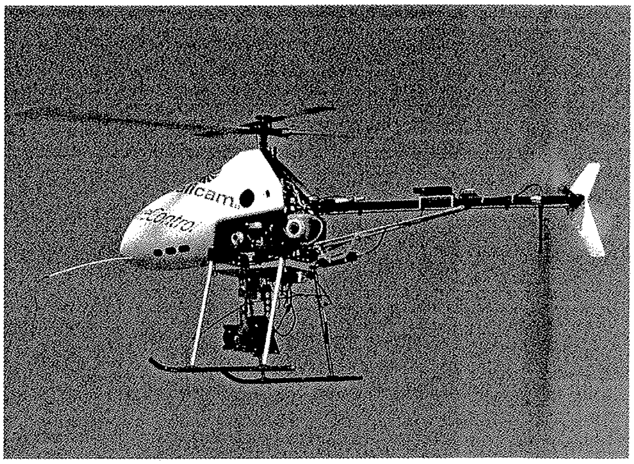

Fig. 3 – Mini UAV system from weControl / Helicam.

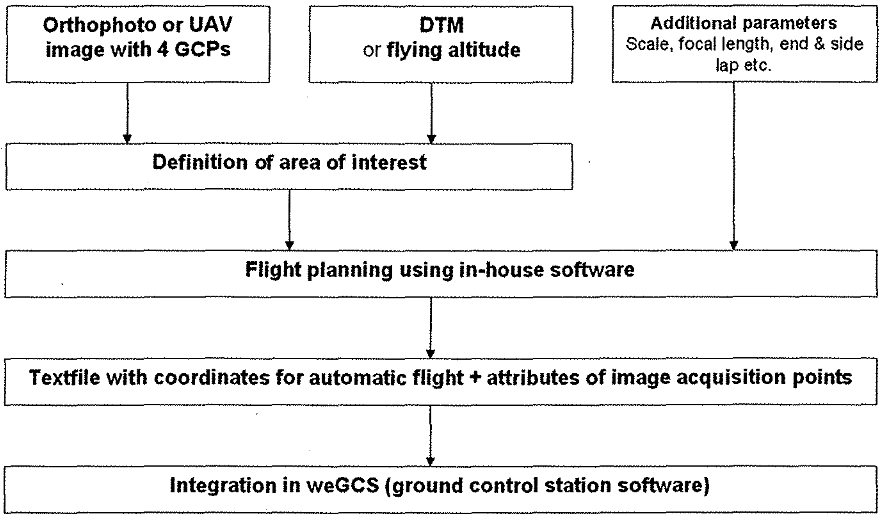

Fig. 4 – Workflow of flight planning.

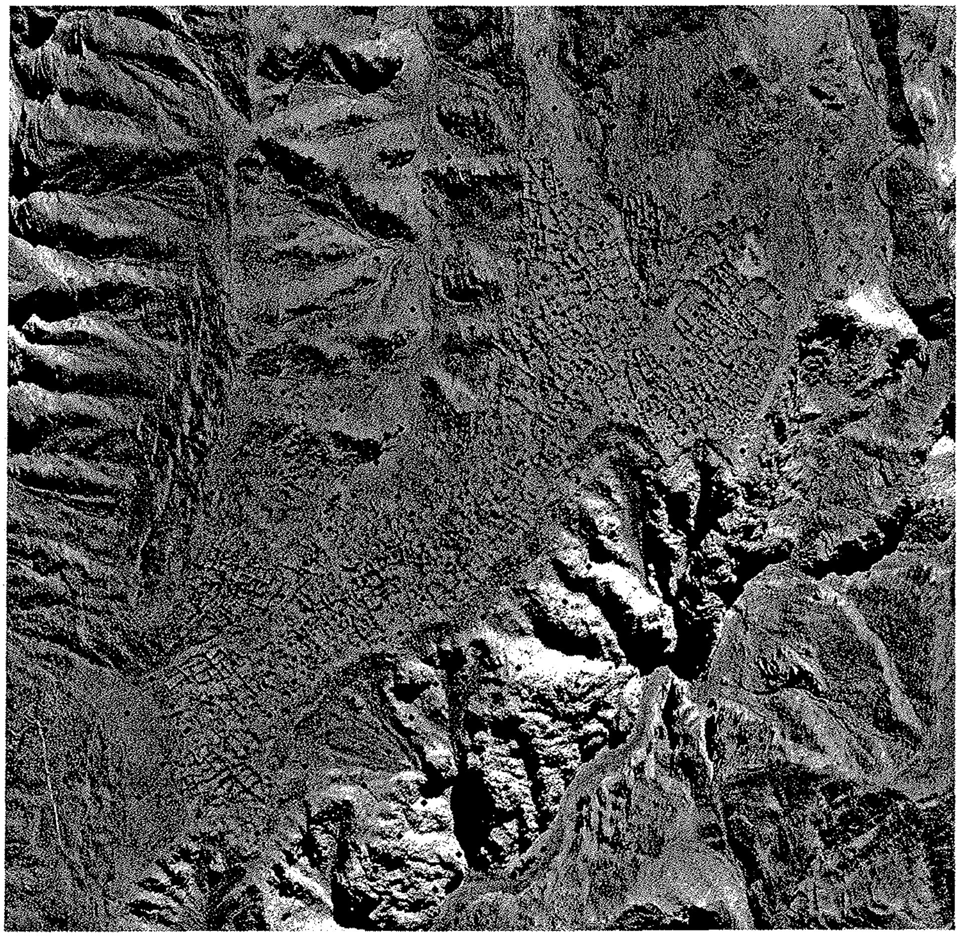

Fig. 5 – Orthoimage overlaid with predefined flight path.

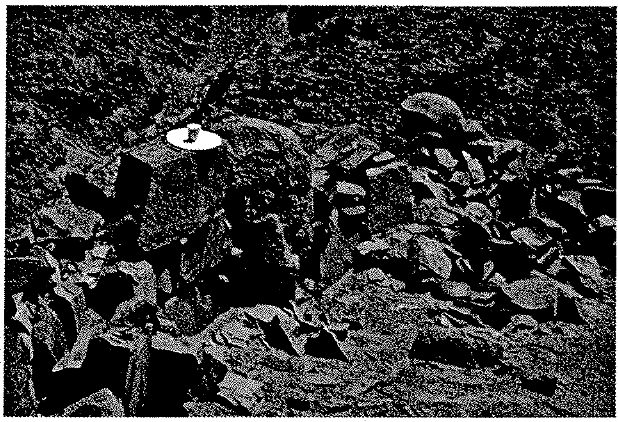

Fig. 6 – Signalized control point for both laser data and UAV image orientation.

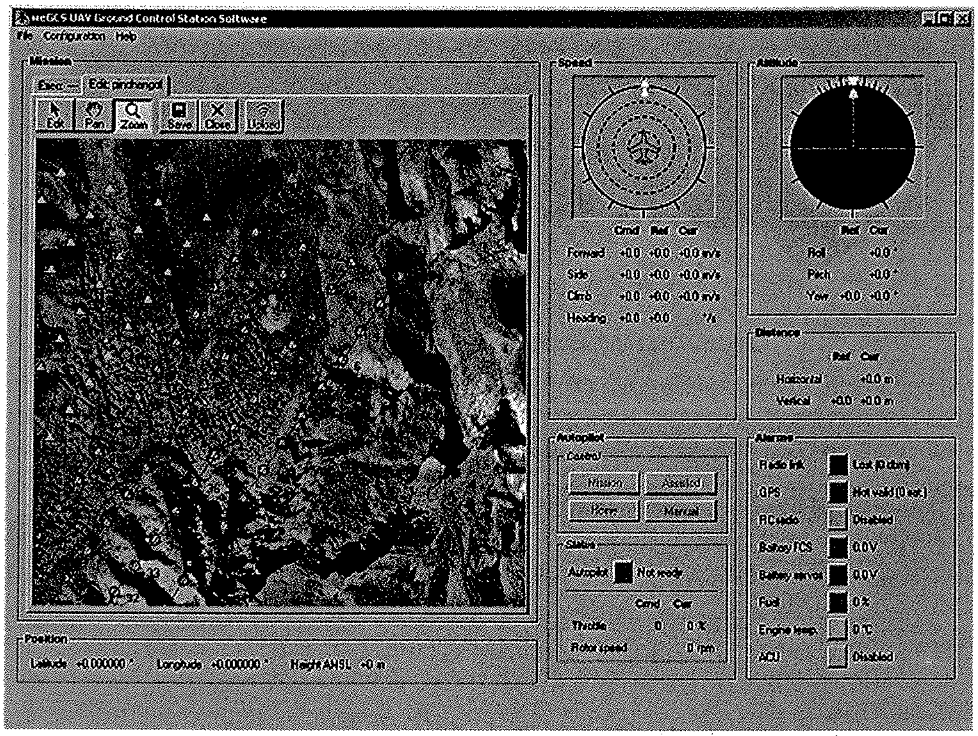

Fig. 7 – WeGCS user interface.

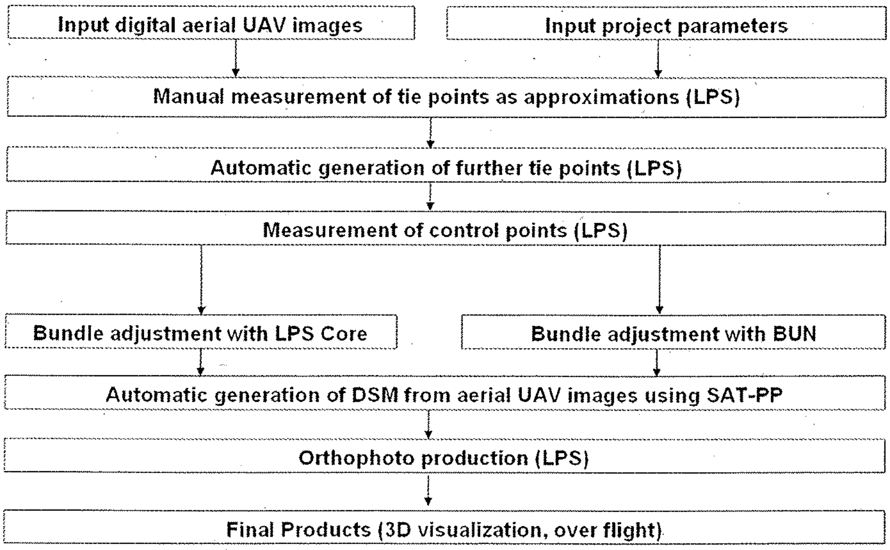

Fig. 8 – Workflow of processing of UAV images.

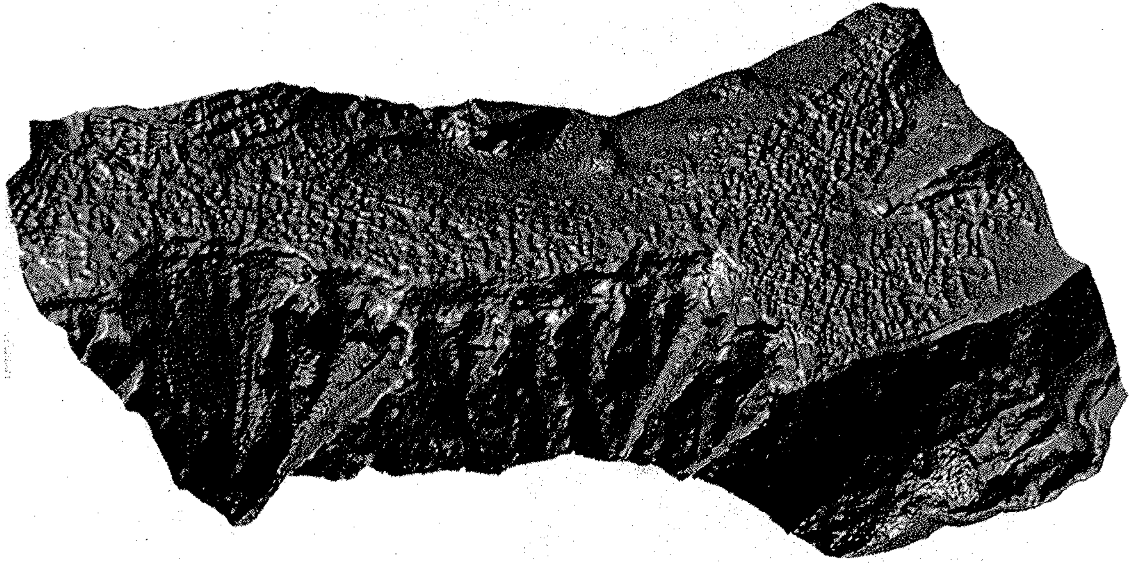

Fig. 9 – DSM of Pinchango Alto generated from UAV images.

Fig. 10 – 3D visualization of the best preserved part of Pinchango Alto generated in Maya.