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PHOTOGRAMMETRIC DOCUMENTATION OF AN ARCHAEOLOGICAL SITE (PALPA, PERU) USING AN AUTONOMOUS MODEL HELICOPTER

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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-Inkaic 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. The inhouse software used for automatic DSM generation is here described in detail. A virtual 3D model of the site was produced and visualized. The resulting data were analyzed concerning in particular the potential of DSM generation from model helicopter images as compared to laser data. 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 Documentation of archaeological sites using UAVs

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 shortcoming 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 potentially provide variable viewing directions. The development of model helicopters and comparable autonomous vehicles is primarily driven by the artificial intelligence community (AAAI, 2005) and the military.
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 them to fly autonomously. This kind of model helicopter is called mini UAV system (unmanned aerial vehicle: Figure 1-1; UVS 2005; Eck 2001; Eisenbeiss 2004). Using a mini UAV with GPS/INS based stabilizer it is easy to fly precisely along a predefined flight path and to capture images from different viewing angles.

Figure 1-1: Mini UAV system from weControl / Helicam.

The model helicopter from weControl used in Pinchango Alto (Figure 1-1) features 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 (for further detail see weControl 2005 and Eisenbeiss et al. 2005).
In our project in Peru we successfully used for the first time an autonomous mini helicopter for archaeological documentation by means of photogrammetric image analysis. The process of photogrammetric flight planning, image acquisition, data processing and visualization is described in the following.

1.2 Pinchango Alto

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 the archaeological site of Pinchango Alto in September 2004.
On the one hand, we used the mentioned UAV system, which is the focus of the present paper. On the other 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 with the Riegl scanner and data processing with the Riegl software, as well as the combination of laser data with aerial images will be described elsewhere.

Figure 1-2: Overview of Pinchango Alto (aerial images of 1997, scale 1:7000); red box marks the ruins on the spur.

Pinchango Alto is the largest Late Intermediate Period (LIP, AD 1000–1400) site in the Palpa area (Figure 1-2) 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 (Figure 1-3). 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. Its state of preservation was one reason for chosing Pinchango Alto for a detailed recording.

Figure 1-3: Pinchango Alto: overview of the stone walls and the structure of the settlement.

2. FLIGHT PLANNING AND IMAGE ACQUISITION

The image-based documentation of Pinchango Alto required a precise flight planning and a careful acquisition of images in order to ensure successful image post processing. Since the GPS/INS system onboard the UAV was used for navigation and as an approximation for bundle adjustment only, it was necessary to measure well distributed control points (CPs) using differential GPS. These points later served to orient the laser data as well (Eisenbeiss et al., 2005).

2.1 Flight planning

The GPS/INS navigation system and the autonomous flight capabilities of the weControl UAV allowed a detailed and precise flight planning prior to fieldwork (Figure 2-1), defining acquisition points and certain parameters of the helicopter according to the project requirements described in Eisenbeiss (2004) and Eisenbeiss et al. (2005).

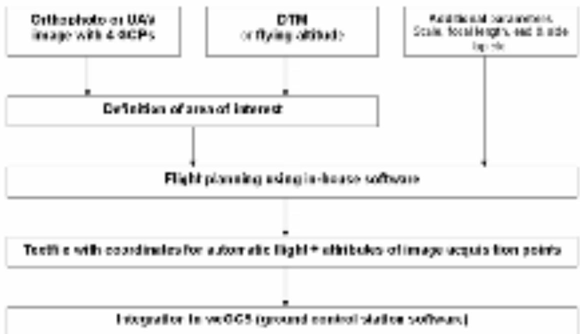

Figure 2-1: Workflow of flight planning.

The result of flight planning was a carefully defined flight path. As input for the helicopter navigation software weGCS (weControl ground control station software) a text file was generated, containing the definition of point status (stop, crossing or turning point), image acquisition point numbers, their coordinates in the WGS 84 coordinate system, as well as parameters for flying velocity.

2.2 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 (Figure 2-2). 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.

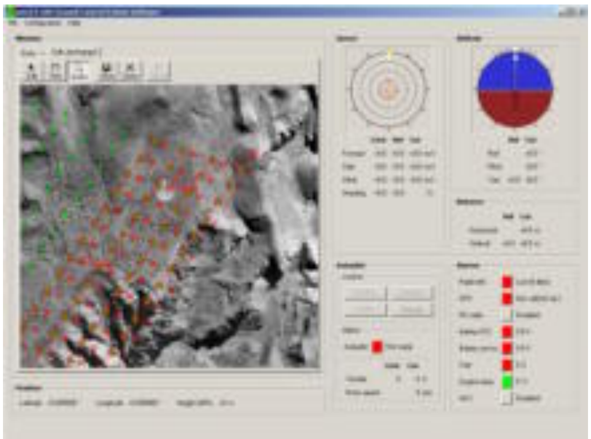

Figure 2-2: User interface of the ground control station software (weGCS) showing the flight plan for the first four strips, start and home point.

During one flight 20 to 30 images could be captured, corresponding to 1 to 1.5 strips. 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 of 56 m. 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.

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 (LPS, 2005) offers the functionality required to accomplish the complete photogrammetric working process from project definition and interior orientation to measurement 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 3-1)

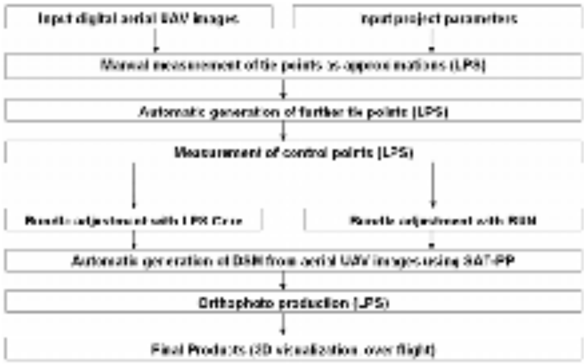

Figure 3-1: Workflow of UAV image processing.

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, and 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 another inhouse software (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 detected, 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). The procedure is characterized by the following aspects:

(a) Multiple image matching: We have developed a new flexible and robust matching algorithm – the Geometrically Constrained Cross-Correlation (GCCC) method - in order to take advantage of multiple images. The algorithm is based on the concept of multi-image matching guided from object space and allows reconstruction of 3D objects by matching all the images at the same time, without having to go through the processing of all individual stereo-pairs and the merging of all stereo-pair results.

(b) Matching with multiple primitives: We have developed more robust hybrid image matching algorithms by taking advantage of both area-based matching and feature-based matching techniques and utilizing both local and global image information.

(c) Self-tuning matching parameters: The adaptive determination of the matching parameters results in a higher success rate and less mismatches.

(d) High matching redundancy: With our matching approach, highly redundant matching results, including points and edges can be generated. Highly redundant matching results are suitable for representing very steep and rough terrain and allow the terrain microstructures and surface discontinuities to be well preserved. Moreover, this high redundancy also allows automatic blunder detection.

(e) Efficient surface modeling: The object surface is modeled by a triangular irregular network (TIN) generated by a constrained Delauney triangulation of the matched points and edges.

(f) Coarse-to-fine hierarchical strategy: The algorithm works in a coarse-to-fine multi-resolution image pyramid structure, and obtains intermediate DSMs at multiple resolutions.

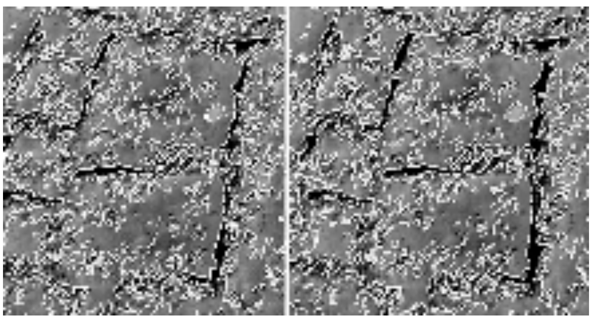

Figure 3-2: Example of edge matching in UAV images.

In order to capture and model the detailed terrain features, our DSM generation approach not only generates a large number of mass points but also produces line features. One example of the edge matching is shown in Figure 3-2. As can be seen in this Figure, even in areas of walls there are many successfully matched line features, which are necessary for the modeling of the area of Pinchango Alto. For details of this matching approach see Zhang (2005).

Finally, we derived an interpolated regular DSM from the matching results (Figure 3-3).

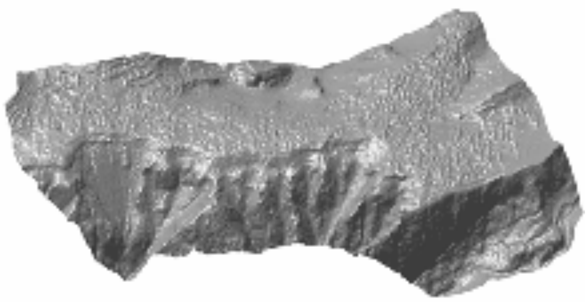

Figure 3-3: DSM of Pinchango Alto generated from UAV images.

3.3 Orthophoto production

Using the LPS software the following versions of orthophotos of Pinchango Alto were produced for data analysis:

(a) An 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.

(b) Another orthophoto of the whole site with a ground resolution of 3 cm based on the helicopter images and the DSM derived from them with 20 cm grid size.

(c) 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 generation of orthophotos is described in Eisenbeiss et al. (2005).

3.4 3D visualization

For 3D visualization we used in a first step the orthophoto derived from the helicopter images and the laser DSM. 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 (Figure 3-4).

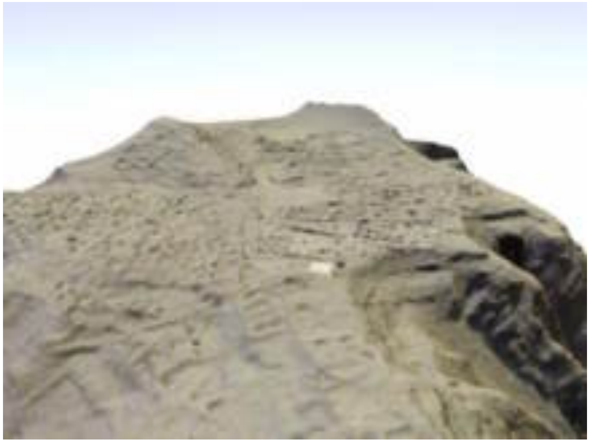

Figure 3-4: Snapshot of a virtual flight over Pinchango Alto generated in Maya using orthophoto and DSM based on UAV images.

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 not 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. ANALYSIS

In the following analysis, firstly the DSM generated from the model helicopter images will be compared to the DSM based on the laser data (Gaisecker 2005). Secondly data visualization and usability for archeological analysis will briefly be reviewed.

The DSMs were imported into Geomagic Studio (Raindrop Geomagic Inc.) to compare them in 3D in order to find deviations. The results are shown in Figure 4-1. Generally a high conformance between the two DSMs can be observed. The mean height difference for the best preserved area is 0.09 m. The maximum height difference for the rocky slopes is less than 1 m. The differences between the datasets are mainly due to occlusions and the different perspectives of laser scanner and helicopter camera. This is especially evident in the case of a series of deep holes or pits distributed over the site (cp. Figure 3-4).

Figure 4-1 indicates that the northern part of the helicopter DSM is generally lower. This may be due to the low number of common control points in this area. A few steps of up to 5 cm can be observed, resulting from the combination of individual elevation models. Comparing the laser and UAV DSMs for the complete area of Pinchango Alto (not just the northeastern part shown in Figure 4-1), the standard deviation turned out to be higher (0.1 to 0.2 m), just like the shift in vertical direction. The difference is probably due to different control points used for absolute orientation of both laser and helicopter data.

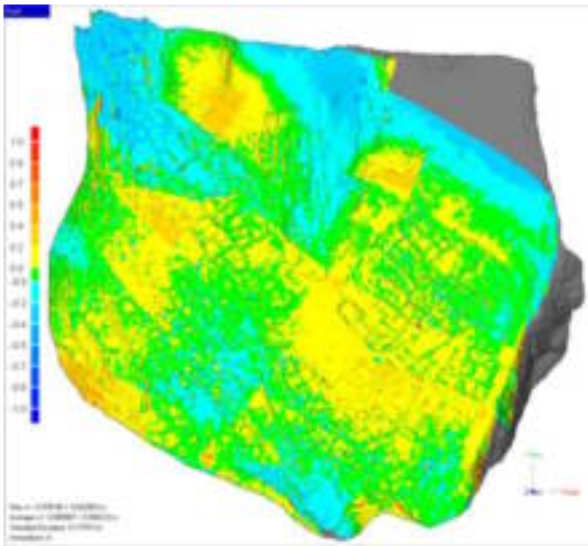

Figure 4-1: 3D comparison of DSMs based on laser data and UAV images, respectively.

Concerning 3D visualization, the available orthophoto (based on UAV images) was draped over both available DSMs (derived from UAV images and from laser data, respectively) in order to find the best match. Both visualizations generally showed comparable results. However, the combination of orthophoto and DSM both derived from UAV images gave a more homogeneous impression as both datasets were based on the same source data. Consequently, for visualization in Maya we used the UAV based orthophoto in conjunction with the DSM derived from the same images. It is planned to further enhance the results in the future by integrating images taken from other perspectives as additional texture.

The different 3D models of Pinchango Alto may be used as a versatile tool for future archaeological research at the site. In the laser DSM, archaeological structures can be detected and analyzed more easily than in the DSM derived from the UAV images due to its higher resolution. Gaisecker (2005) demonstrates how single stones in preserved sections of the walls may be digitized, displaying the results in the point cloud and also in the images taken with the Nikon D100 camera. The high resolution UAV images can be visualized in 3D in the LPS stereo analyst. Starting from the stereopairs or simply from the 2D orthophoto, the internal structure of Pinchango Alto may be analyzed, identifying different area that served e.g. as living quarters, central places, or working areas. The resulting data can be immediately visualized in ArcScene with the orthophoto draped over the DSM.

5. 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, the flight planning and the image processing methods presented here are therefore powerful tools for the recording and modeling of other cultural heritage sites as well.

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