Diversity of Flight Strategies in UAV Recording

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Abstract: Archaeology has been greatly benefiting from hardware evolution in UAVs and cameras. In keeping with the spirit of preferring low-cost and open technologies, many archaeologists are turning to free and open source software for data processing. Low-cost UAVs in combination with small action cameras are being employed by a diversity of archaeological users. Over the last three years, a broad range of sites and areas were UAV-recorded within the scope of the project “Archaeocopter”. These were selected not only for their historical relevance but also to explore the limits of technical and practical feasibility. This contribution focuses on the role of flight strategies for successful recording with UAVs. Prior to designing a flight strategy, it is reasonable to make oneself familiar with the complexity and diversity of excavation areas and archaeological sites. We define three main classes of sites/areas and matching flight strategies. One of the most important aspects is operational safety. As practical tools, we use instruction cards and software for android devices that take into account the different experience levels of the operators. In addition, we created training scenarios to improve staff experience levels.

Keywords: UAV, Flight strategies, Classification, Training

Introduction and Motivation

Archaeologists have come to expect the presentation of ancient artefacts as digital 3D models in museums or at exhibitions. But the 3D documentation of archaeological excavations has also become increasingly important. In this context, 3D recording is not only used to digitise objects or areas once, but at several stages throughout the excavation, as a means of supporting interpretation and decision making in the field (e.g. DE REU 2013).

Digital photogrammetry is an easy-to-use alternative to traditional spatial sensing methods like laser scanning. To derive full 3D models from single-shot image sequences, Structure from Motion has emerged as the most popular photogrammetric technique (SfM; e.g. HARTLEY 2004).

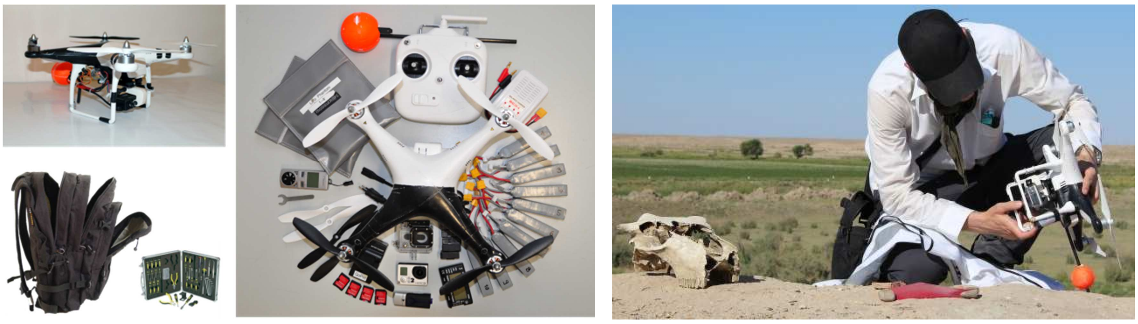

Fig. 1 – Left: One of our extended UAV "survival kits" used for documenting archaeological sites. The kit is based on a Phantom I with a GoPro Hero 3 BE and includes additional LiPo battery packs, an anemometer and several batteries for the GoPro Hero 3, for a full day's recording work. The customized camera mount allows us to record parallel to the ground plane while the emphasis lies in the centre. With systematic packing, it is possible to put everything, including several spare parts, into one knapsack. Right: Work under severe conditions in Bukhara (Uzbekistan), at a temperature of more than 40°C, where the Phantom I kit was successfully applied.

Over the past few years, archaeology has profited from the enormous speed of hardware evolution of UAVs and cameras. Documentation in 3D makes it possible to create objective records of physical properties such as volume and texture (REMONDINO 2014). Low-cost UAVs in combination with small action cameras (Fig. 1, left) are frequently applied on excavation sites (LORENZON 2013, THEMISTOCLEOUS 2014, SCHUBERT 2014).

Several archaeological sites and areas with a broad range of features and monuments were documented within the scope of the project "Archaeocopter"[1] over the last three years (Fig. 1, right). These areas were selected not only for their historical relevance, but also to answer questions about the limitations of technical feasibility. For flexibility, we put together a system that fits into carry-on hand luggage. Moving and reflecting elements are the most challenging for SfM. For that reason, water surfaces present the worst case.

This paper is structured as follows: First, Section 2 introduces in theory and related work with the focus on flight strategies in context of photogrammetry and the 3D reconstruction process itself. Section 3 presents the diversity of different documentation areas we determined from several case studies. The Section also discusses the resulting flight strategies due to the classification and some derived flight experience level depending on concrete training scenarios. Then, Section 4 presents a selected collection of achieved results and discusses some useful tools for documenting different kind of sites, i.e. handy instruction cards and our app for android devices, each taking into account the different experience levels. Finally, conclusion and future work are drawn in the last Section 5.

[1] Archaeocopter: www.archaeocopter.de

Theory and Related Work

As an alternative to proprietary software packages such as AgiSoft PhotoScan[2], aSPECT 3D[3] or Pix4D[4], it is possible to combine and use different well-working and freely available programs. Several options exist with VisualSFM[5], MicMac (DESEILLIGNY 2011), OpenMVG (MOULON 2013) and Bundler (SNAVELY 2006) to perform the sparse reconstruction step (pose estimation). After this, dense reconstruction with CMVS and PMVS (FURUKAWA 2010) in combination with Poisson reconstruction (KAZHDAN 2006) is commonly used to produce textured meshes (YANG 2013). As an alternative to the dense reconstruction step, methods based on semi-global matching are used in CMPMVS (JANCOSEK 2011) and SURE (ROTHERMEL 2012). DroneMapper[6] gives information about Aerial Data Collection Guidelines and Flight Planning with Sony NEX-5 as an example camera. They present flight pattern like Grid Flight Plan, Double Grid Flight Plan and Transect Single Pass Flight Plan.

Structure from Motion (SfM) is a popular and accurate way to derive 3D structures from image sequences. It is in the mathematical nature of SfM that careful planning is required for taking the individual images and obtaining complete photographic coverage (MALLISON 2014). It is often not feasible to acquire additional images at a later point in time. Therefore, there is a substantial risk of producing incomplete 3D models that require manual improvement and hole-filling (POLLEFEYS 2008).

In contrast to similar projects, we use a videogrammetric (BRILAKIS 2011, GREENWOOD 1999, PAPPA 2003, POLLEFEYS 2004, NISTÈR 2004) instead of the more common photogrammetric approach (WEI 2013). Videogrammetry offers cost-effective and fault-tolerant data recording, allowing the UAV to capture data while moving, at relatively low resolution but with enormous numbers of strongly overlapping frames. This approach is inspired by real-time robotics and has the potential to be a first step towards real-time 3D processing and for providing at least reduced detail 3D models immediately after data capture. This will make it possible to verify on site, that the recorded material is adequate for reconstructing connected and gapless 3D site models. Higher quality and more detailed models can be obtained in the post-processing stage, in the office.

In remote sensing, software to plan flight paths commonly produces 2D GPS routes for planning single shots at constant altitude, taking into account camera properties and required accuracy (TORRES-SÁNCHEZ 2013). Such flight planning software is of limited use for recording complex excavations, due to the fact that recording from a bird's eye view only produces data suitable for the derivation of digital elevation models (DEM), not for full 360° 3D models (AXELSSON 1999). Great efforts in planning single image shots and

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[2] AgiSoft PhotoScan: http://www.agisoft.ru/products/photoscan/

[3] aSPECT 3D: http://www.arctron.de

[4] Pix4Dmapper: http://pix4d.com/

[5] VisualSFM: http://ccwu.me/vsfm/

[6] DroneMapper: https://dronemapper.com

recording different models[7] (which can be later combined) are mandatory to document complex objects with UAVs, like the Christ the Redeemer statue of Rio de Janeiro and Corcovado peak.
To georeference the models, markers (ground control points, GCP) are placed into the areas to be recorded and their coordinates are taken with a total station (Fig. 2). To assess the accuracy of the georeferencing, at least ten GCPs are used and their mean square errors (RMSE) are computed after an affine transformation (usually iterative closest point, ICP) from model space to real world coordinates. Assigning coordinates to markers can be done in the images prior to computing camera reconstruction/pose estimation (e.g. using VisualSFM) or by locating them in the sparse (VisualSFM) or dense (e.g. MeshLab) point clouds. When generating 2D orthorectified images from the 3D model, it is also possible to use a desktop GIS, (such as QGIS[8]) for georeferencing and transformation.

Fig. 2 – Left: A marker of with dimensions 20x20 cm, placed on the Huaztec temple in Mexico. All markers' colours feature strong contrast with the background. The centre of the cross is measured with a total station. Right: To stand out from to the beige colours of the fortresses in Uzbekistan, we chose red markers.

Hand-held Recording Strategies

Current practice shows two diverging trends that result in different flight strategies. On the one hand, there are experts in remote sensing with very high-quality but heavy cameras. To get these cameras airborne, they need expensive UAVs with sufficient pay-load capacities and battery life. Flight planning software is used to set GPS waypoints for sufficient coverage and overlap of individual, high-resolution images. In such cases, the camera is mounted with its lens perpendicular to the ground. Perfect weather conditions without wind are needed to acquire usable images.
On the other hand, we see low-cost UAVs in combination with small action cameras being employed by a diverse range of archaeological users. These small UAVs can be used to record areas of up to 10 hectares and more per day without using planning software. Moreover, when understanding and taking into account

[7] Projeto Redentor. White Paper: https://pix4d.com/wp-content/uploads/2013/04/Projeto_Redentor_Pix4D_AeryonLabs_Whitepaper_2015.pdf

[8] QuantumGIS: http://www.qgis.org

the natural environment, especially wind patterns, image quality can be improved. Here, a parallel camera plane is not needed, and the best angle of view depends on the characteristics of the area to record. In keeping with the spirit of preferring low-cost and open technologies, many archaeologists (in particular from countries without "western" infrastructure and budgets) are turning to free and open source software for data processing. The cost aspect is central when introducing new technologies and methods for documenting cultural heritage to local stakeholders.

For reasons of capacity development, we focus on manual recording strategies and remote-controlled UAVs flights to document archaeological sites. Before delving into different flight strategies, it is reasonable to make oneself familiar with the complexities and diversities of excavation areas and documentation areas in general. We are also interested in making the increasing use of UAVs in archaeology more safe.

Archaeologist are full-time employed to document the progress of an excavation or the excavation itself. Why shouldn't a multicopter assist them? Pen and paper documentation is a time consuming process, and even more so is the digitisation of the former, post-excavation. If the process of documentation is digital by nature, then the additional costs (time and other resources) can be reduced dramatically. Furthermore, the use of consumer grade UAVs incurs no extra costs for hiring expensive experts.

For this purpose, we designed small "cheat sheet" cards with outlines of flight strategies and matching applications for android devices, taking different personal flight experience levels into account. The cards are available for free on the Archaeocopter project page. In addition, training scenarios to improve flight experience levels are provided.

Diversity of Documentation Areas

As a starting point, we examined several published remote sensing case studies with a focus on archaeological excavations and UAVs. To this we added our own project work of the last three years, including collaborations with the German Archaeological Institute, the Archaeological Heritage Office in Saxony and other international partners. From the resulting knowledge base, we determined three main classes of sites/areas and matching flight strategies for each of them. Intuitively, the identified main classes are flat areas, free-standing and deep structures (Fig. 3).

Fig. 3 – Three different classes of documentation areas: The left picture is an example for a free standing structure and shows an huastec temple in Tamtoc (Mexico). The image in the middle was recorded near Leipzig (Germany) and stands for the flat area characteristics. Here the primary focus was on the texture of the ground than the reconstruction in 3D. Therefore, the structural complexity of this scenario is really small and also the cost of time. The right image recorded in Dresden (Germany) and stands in opposite to the middle one for complexity of the structure. The deep structure based on walls from old cellars witch left over are more intricate as the other representations.

In many cases there is no simple correlation between area class, required resources and optimal flight strategy. The question is how to deal with variables such as time pressure, changing weather conditions, flight experience levels and accuracy requirements when setting priorities to determine suitable flight strategies.
There are often situations when UAV-based recording is not enough, such as overhanging structures or extremely complex elements. In such cases, additional images and strategies for obtaining them are required. Fortunately, SfM is robust enough to handle "mixed" cases, where different cameras with different resolutions and lenses, terrestrial and aerial imagery are combined.
The example of Abu-Muslim-tepa (Uzbekistan) shows a part of a defensive citadel (Fig. 4 left). In this case we have all three types with different dimensions (Fig. 4 right). This is the reason for a different grading with the focus on the occurrence. The diversity is also very simple and based on three grades predominantly (O), partially (o) and not present (_). The classification for Abu-Muslim-tepa, based on our scheme, is “Ooo”.

Fig. 4 – Left: Citadel in Bukhara (Uzbekistan) with a mix off all three classes of areas. Right: Estimated structural map (depending on the three classes) of the existing map material.

As regards resource estimation, an overview of different characteristics and their cost weights are shown in Tab. 1. We want to estimate the required cost (time) for recording one hectare, depending on the site’s class.

class	p1	p2	p3
OOO	0.34	0.33	0.33
OOo	0.4	0.4	0.2
OO_	0.5	0.5	0
Ooo	0.6	0.2	0.2
Oo_	0.75	0.25	0
O__	1	0	0

Tab. 1 – Time cost estimation: Different characteristics with correspondent weights.

The influence of structural complexity on the classification is reflected by the estimated time cost. A flat area requires about 10 minutes, for a free standing structure we calculate 15 minutes and a deep structure has the highest time cost per hectar with 20 minutes. A realistic flight plan includes a variable delta which stands for the time between flights. This includes finding a new position for the next start and the preparation times between landings and take-offs.

Deriving Flight Strategies

For the reconstruction process it is very important that parallel flight tracks overlap sufficiently. Good SfM results require that a real-world feature needs to be visible on a minimum of three images. To prevent degenerated models resulting from divergent flight tracks, we suggest a minimum overlap of 30 to 40% (NEUMANN 2003); excessive overlap (e.g. 90%) is not required and will only increase time cost.
Flat areas are the easiest to document, because they can be recorded at constant altitude. There are different options here, catering to the flight experience level of the UAV operator and time limits. One obvious flight strategy, similarly used in remote sensing, is the orthographic grid flight (Fig. 5 left).

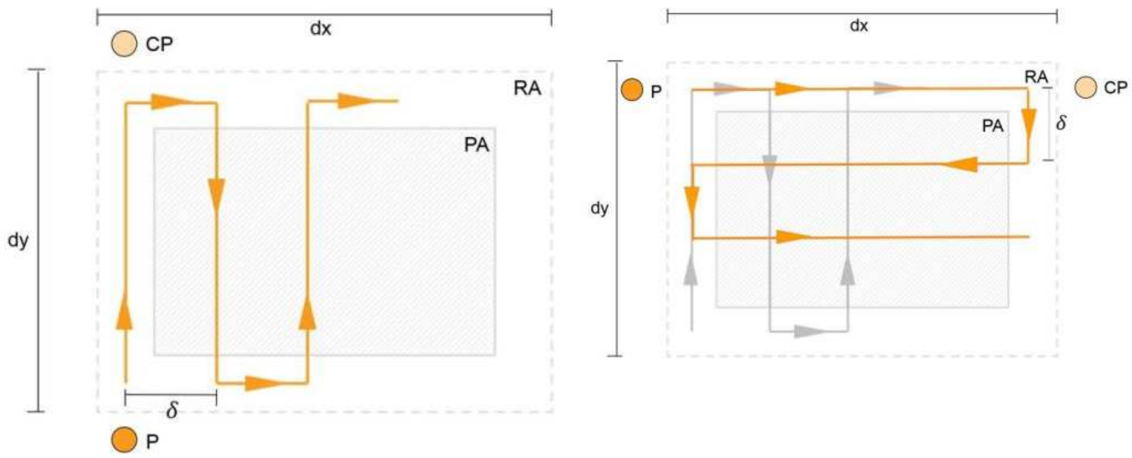

Fig. 5 – Orthographic grid flights with a camera perpendicular to the surface (left) and orthographic double grid flights with a second 90 degree rotated recording scheme (right).

When wind impacts the copter, a second grid flight with a 90 degree rotated recording scheme is recommended to guarantee overlapping parts between the tracks (Fig. 5 right).
From a theoretic 3D reconstruction perspective, the use of a camera plane parallel to the ground is good enough as long as perfectly flat areas are recorded. But in reality, small and more complex elements often require attention. The use of an oriented grid flight with a camera pitch of 10 to 45 degrees therefore produces better results (Fig. 6 middle). If weather conditions allow, oriented double grid flights are a good choice.

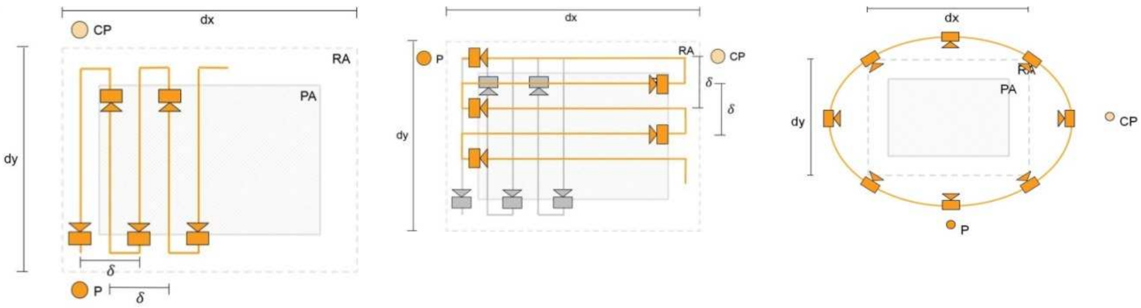

Fig. 6 – Left: Oriented grid flights with camera angles between 10 and 45 degrees. Middle: Oriented grid flights with camera angles between 10 and 45 degrees. Right: Helix flight with camera angles between 10 and 45 degrees.

Free-standing structures require different recording strategies, depending on the complexity and the flight experience level of the operator. The orthographic grid or double grid flights are much easier to apply but oriented grid flights are the better choice here. If the operator is skilled enough to perform a helix flight (Fig. 6 right) at different altitudes, the result of the recorded data will be much better suited for the reconstruction free-standing structures. The corresponding flight strategies are shown in Fig. 8.

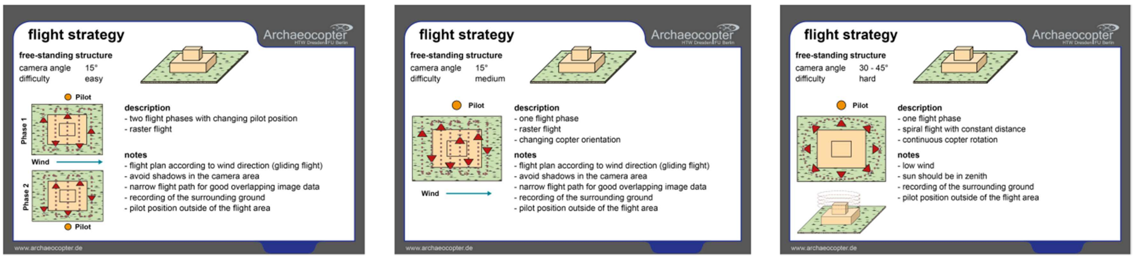

Fig. 7 – Three different flight strategies are shown for the classification free standing structure.

Flight Experience Levels and Training Strategies

We developed and improved different training strategies for us and our partners, suitable for recording different excavation areas. Even from an adventurous archaeologist's point of view, it is desirable to use these "flying robots" in a safe and controllable way. When remote controlling a multicopter for the first time, it is necessary to read all manuals and make oneself familiar with the technique and integrated fail safe scenarios and to find online communities to share experience. It is also advisable to prepare and maintain the hardware setup by oneself to gain awareness of the multicopters functionality. This makes archaeologists more independent from technical experts.

There is no real alternative to learning to fly by hand. Before doing so, especially where expensive equipment is involved, some training sessions with simulation software are recommended. Our proposed training program is divided into seven flight experience level which can be achieved over the course of one week. Every level has a main goal and motivational elements.

We defined three parts with associated training scenarios: Level 1-2 "Basic skills and theory", Level 3-5 "Practical flight strategies" and Level 6-7 "Extended skills". The most important aspect here is for the trainee to be able to master each level at a good pace, but without becoming overly stressed. In the first part focused on "Fundamentals and fail safes" (Fig. 8 left) and "Safety and flying rules", trainees are taught the fundamentals of flight-mechanics and integrated fail safes.

All training scenarios are worked through by a team of two. This is also the recommended smallest team size in real-world field work, due to safety issues. The part “Practical flight strategies” includes three different scenarios focusing on various flight strategies with increasing difficulty. The single procedure of every lecture deals with the practical workflow. The two-directional-grid flight for example is the learning content of Level 4 training (Fig. 8 right). In addition to the flight training itself, planning and discussion are also part of the training.

The final part “Extended skills” is based on two scenarios. The first one deals with the combination of the flight patterns. The last training scenario Level 7 “Flights without GPS” is designed to teach a better feeling for the multicopter.

Level 1 - Training scenarios

1) start and automatically stop copter engine
2) take off one meter then soft landing
3) take off two meters, turn off remote control, fail safe, turn off copter, test batteries
4) take off two meters, test maneuvers like forward, backward, left and right several times with pauses between
5) take off two meters, turn 360 degree around left, turn 360 degree around right
6) take off two meters, turn 90 degree around left, turn 90 degree around right, combine with forward, backward, left and right
7) take off two meters, turn 180 degree around left, turn 180 degree around right, combine with forward, backward, left and right

Level 4 - Training scenario

1) plan the flight exactly and the position, talk about emergency plans and how to communicate
2) make a two-directional-grid flight with a distance of max. 20 meters, 5 meters height
3) discuss about the different point of views, change the pilots, evaluate the photos/video
4) plan the flight exactly and the position, talk about emergency plans and how to communicate
5) make a two-directional-grid flight with a distance of max. 100 meters, 10 meters height
6) discuss about the different point of views, change the pilots, evaluate the photos/video

Fig. 8 – Left: After reading all manuals, the first flight training with easy tasks can be started. Right: Level 4 is more advanced and focuses on different flight strategies.

Selected Presentations of Achieved Results

To give an impression of the results we are able to produce using our workflow, we take a look at three very different scenarios in chronological order. Beside these examples, we discuss some important project decisions and practical solutions.

Reconstruction of an Excavation in Dresden

We documented an excavation close to the Church of Our Lady in Dresden (Germany) at regular intervals between August 2013 and January 2014, in cooperation with the Archaeological Heritage Office in Saxony (Regina Smolnik and Christof Schubert). The excavation commenced on a flat parking area and is a good example for archaeological deep structures.

Several small rooms with complex stone walls and partially occluded elements were uncovered. An overall plan was required to determine a successful combination of recording strategies here. We focused on solutions for deep structures and mainly used inverted oriented helix flights, where the camera has a surround view when flying along the walls (Fig. 9 left).

Fig. 9 – Left: A short sequence of camera pose estimations shows the flight strategy mainly used in this scenario. The complexity of occluded elements called for inverted oriented helix flights. An overall plan worked well here to document several excavation stages. Right: The complexity of the outcome (3D model) of one stage is shown here. The resolution (minimum detail) of the model is approximately 2 cm and the accuracy computed from the RMSEs of 12 GCPs is about 10 cm.

The quality and completeness of the 3D models that we produced over the course of the different excavation stages (Fig. 9 right) support our choice of recording strategies.

Along the documentation stages, we mainly focused on planning appropriate recording strategies, but the managing of data and the comparison of produced 3D models of the same area required something we call "4d modeling". To organize the recording strategies, we developed some useful applications for android devices (Fig. 10)

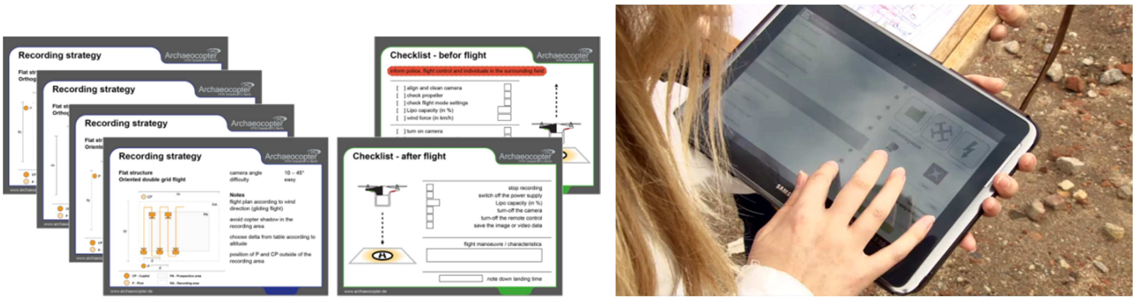

Fig. 10 – Left: Different handy instruction cards were designed to bring the phase of recording into an effective order. Right: As an alternative to the cards, we developed different apps for android devices, each taking into account the different experience levels of the operators.

Reconstruction of a Huastec Temple Site

In October 2013, the project team was invited to document two Precolumbian (Huastec) sites in Mexico within the vicinity of the rural towns Aquismon (site of Tambaque) and Tamuin (the ancient site of Tamtoc). This task was supported and supervised by the Instituto Nacional de Antropologia e Historia (Estela Martinez Mora) and the Universidad Autónoma de San Luis Potosi (Peter Kroefges).

We had two main questions at this early stage in our project's development: First, is it possible to document large sites using low-cost UAVs and GoPros under extreme weather and limited conditions? Second, are the documentation workflow and the identified flight strategies good enough to produce accurate results?

Over the course of three intense working days, we collected video footage of the site's impressive ceremonial center and a number of buildings, as well as some stone reliefs and sculptures. For instance, the ancient plaza of Tamtoc, as a good example for an almost flat structure, calls for orthographic grid flights (Fig. 11 left).

Fig. 11 – Left: Orthographic grid flights were used to document almost flat parts of Tamtoc. The plaza has about one hectare and was recorded with only one flight. Right: The resulting orthoimage of the large 3D model. The area is surrounded by trees, visible on the right edge of the picture. The resolution of the orthoimage is approximately 8 cm. The accuracy computed from the RMSEs of 30 measured GCPs is about 50 cm.

To produce the complete 3D model of the site once back in our office in Germany, several human expert decisions, such as key frame selection, a lot of low-detail model previews and processing time were required. The resulting 3D model has a smallest detail resolution of about 8 cm (Fig. 11 right).
After an evaluation process we decided to develop some useful tools to increase our productivity and the probability of producing connected, gapless 3D models. The software JKeyFramer, an automatic key frame selection tool, was one of the important outcomes. This tool was an important step towards fast 3D reconstruction and that would allow us to render fast preview models on site.

Reconstruction of the Coast in Punta di Zambrone

In April 2014 we started a cooperation with the University of Salzburg (Reinhard Jung) and the University of Naples Federico II (Marco Pacciarelli), to document the coastal area of Punta di Zambrone (Italy) in only three days with low-cost UAVs (BLOCK 2014). The main aim was to combine the terrain model with a part of the water surface to get a coherent model and complete overview of the area.
Due to the complexity of the coast, an accurate planning of several recording strategies was required. The coast can be interpreted as a very big, complex free standing structure and needed several adapted helix flights (Fig. 12 left) in combination with oriented grid-flights.
The point cloud we produced on-site was very useful to verify our data (Fig. 12 right).
After evaluating the workflow in Italy, we came to the conclusion that the laborious process of placing markers for georeferencing in the field (Fig. 13), needs to be streamlined and simplified.

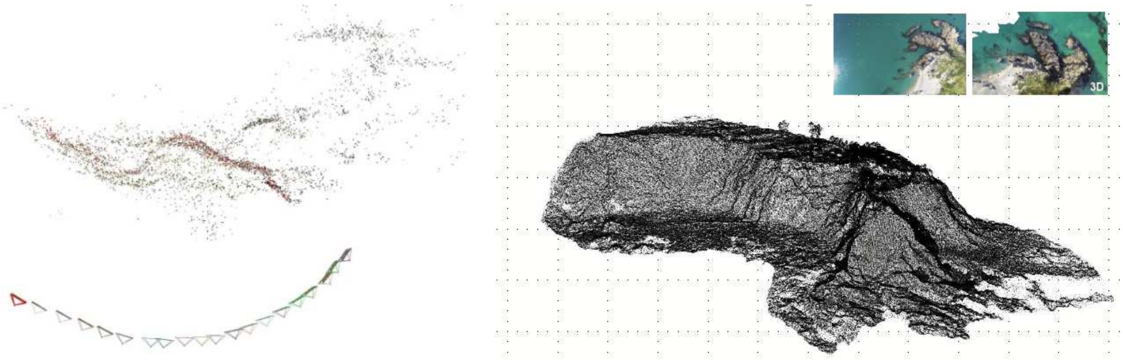

Fig. 12 – The left picture shows an adapted helix flight near to the coast. We used also previews of point clouds to verify our data on-site, which is shown on the right image.

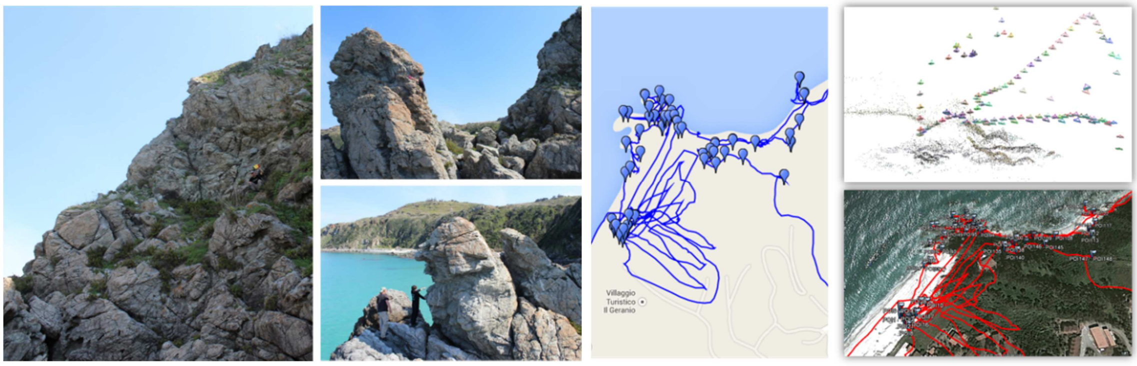

Fig. 13 – Placing well-visible markers at the coast of Punta di Zambrone was a challenge. Right: The GPS data recorded by different sensors prospectively allows us to georeference 3D models automatically without using markers.

We decided to develop an automatic georeferencing tool, using different, low-cost GPS sensors. This is a still ongoing task.

Conclusions and Future Work

This contribution was intended to demonstrate the viability of using inexpensive UAVs for archaeological documentation. Our project is now in its fourth year and has matured to a point where we feel comfortable to share some useful experience and practical guidance. The numbers that we have provided, concerning cost, time overhead and accuracy, are the result of extensive experience from recording a multitude of sites of diverse character around the globe. Ours is a not-for-profit project and we do not have access to expensive high-end equipment. Therefore, we cannot provide comparative data for the latter as regards performance and accuracy. However, we believe that expensive high-end drones are not a requirement in the majority of cases, and that the capabilities of much cheaper technology will meet the needs of most field archaeologists. Far from being experimental, current consumer grade UAVs provide flexibility, robustness and a learning curve that will suite most field archaeologists with an interest in modern technology, drastically driving down the total cost of operation.

Prior to designing different flight strategies, it is reasonable to make oneself familiar with the complexity and diversity of excavation areas and archaeological sites. As a starting point, we examined published remote sensing case studies with a focus on archaeological excavations using UAVs. To this we added our own project work of the last three years, including collaborations with the German Archaeological Institute, the Archaeological Heritage Office in Saxony and other national and international partners. From the resulting knowledge base, we determined three main classes of sites/areas due to three years of our own project work and several published remote sending case studies and matching flight strategies for each them. As practical tools, we created handy instruction cards and an app for android devices, each taking into account the different experience levels of the operators. Additionally, training scenarios to improve experience levels are provided. The presented workflow is still in progress. All current versions of checklists, apps and flight experience level and training strategies will be made freely available on the Archaeocopter project's webpages.

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