Highly Detailed 3D Modelling of Mayan Cultural Heritage Using an UAV

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Key words: cultural heritage, SfM-MVS, UAV, virtual reality, 3D modelling

SUMMARY

Highly detailed and highly accurate 3D models are indispensable tools for the management of cultural heritage, as well as for archaeological and anthropological research. Moreover, these digital 3D models should be combined with high resolution texture maps to facilitate the understanding of the heritage sites or parts of the heritage. The construction of these models requires the deliberate selection of a data acquisition platform and spatial measurement instruments. Different considerations on these issues are discussed in this paper, based on a case study at the site of Edzná, Mexico.

This project focuses on the virtual 3D reconstruction of the different structures and artefacts on the site. The project is a collaboration between Ghent University (Belgium), INAH Mexico and UNESCO. On Mayan sites, Unmanned Aerial Vehicles (UAV) are exceptionally useful tools for data gathering. These devices allow image acquisition with high resolution and under various incidence angles. Moreover, the platform can be compact and light weight, so it allows a flexible deployment. In this sense, flexibility means both the ability to make the platform easily transportable and the possibility to manoeuvre both on high elevations and in narrow spaces. High elevations are required to position the modelled structure in a wider spatial context. The ability to manoeuvre in narrow spaces is needed to operate in forested areas and to avoid self-occlusion in the model. Images taken with the UAV are combined with terrestrial images of the site, resulting in a full coverage with significant overlap between consecutive images. The entire data set is processed with various levels of details (LoD) in an image based virtual reconstruction process, resulting in digital elevation models, orthophotos, textured 3D models and other derivatives. Absolute referencing is based on a series of GNSS measurements and densified with total station measurements. Working with different LoDs allows the smooth implementation of the models in a 3D geographic information system (GIS) and in on-line interactive 3D viewers. Semantic data can be assigned to different geometric features within the project and the models can be used for online consultation and visualisation systems.

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1. INTRODUCTION

Research on highly accurate and highly detailed 3D modelling is still constantly developing. The importance of 3D modelling has penetrated a lot of scientific disciplines and applications. DEMs and 3D city models play an indisputable role in environmental research (Dubovyk et al., 2011; Werbrouck et al., 2011), spatial planning and management (Kolbe et al., 2005; Smart et al., 2011), architectural documentation (Becker, 2009; Murphy et al., 2013) or archaeology and cultural heritage (Koller et al., 2009; Remondino, 2011). Especially since the last decade, the introduction of innovative 3D measurement techniques such as laser scanning and image based modelling resulted in an increasing efficiency of 3D data collection. This efficient data recording is necessary to meet the growing demand for accurate and dense 3D data, 3D models and other derivatives, which can be quickly produced for e.g. 3D architectural structures, building block inventory and facility management systems, both indoor and outdoor.

For the documentation of cultural heritage, like archaeological sites, both Airborne Laser Scanning (ALS, (Coluzzi et al., 2011)) and Terrestrial Laser Scanning (TLS, (Pesci et al., 2012)) are frequently used 3D data acquisition techniques. These techniques enable the construction of dense point clouds with a high geometric accuracy, but with no or limited radiometric information. Moreover, the initial costs to acquire data using laser scanning are relatively high, especially in remote areas. Recent developments in the field of computer vision have enabled the generation of photo-realistic 3D models using series of images. These images can be taken with a consumer digital camera. Consequently, image-based 3D modelling is increasingly applied in cultural heritage studies (e.g. (Koutsoudis et al., 2013; Plets et al., 2012). In order to generate such photorealistic 3D models based on imagery, Structure from Motion (SfM) and Multi-View Stereo (MVS) are frequently used. SfM-MVS is a technique to reconstruct the camera acquisition parameters and a sparse point cloud of the scene (SfM), as well as a technique to calculate a dense point cloud and to acquire the 3D geometry of an object or surface (MVS), using a series of 2D images (Lourakis and Argyros, 2009). The process results in a 3D mesh with photorealistic texture maps.

The research presented in this paper covers the 3D documentation of different structures at the Mayan site of Edzná (Campeche, Mexico, Figure 1). During a two-week field campaign in November 2013, data for an image based 3D reconstruction of the site were acquired. After comparative studies on the quality of image based modelling in airborne (Stal et al., 2012b) and terrestrial (Stal et al., 2012a) applications, it was decided to create airborne-based textured 3D models using images acquired with an Unmanned Aerial Vehicle (UAV). Previous research has already demonstrated the potential of UAVs for 3D modelling (Hendrickx et al., 2011). During the project, a large series of terrestrial and airborne images were taken during this campaign. Although the use of the UAV was preferred for the image acquisition, a platform configuration with helium balloons was also operationalized. This alternative platform could be used in case of difficulties with the UAV and increases the flexibility and efficiency of the data acquisition, in terms of optimal use of hardware and human-ware. The images were processed in a semi-automatic workflow and resulted in 3D models with a high radiometric and geometric accuracy. The integrated use of different spatial data sources is essential for this project. Thus, Ground Control Points (GCP) were also acquired by topographic measurements, allowing the connection of different modelled features in the model, as well as the absolute positioning of the site. A total station and handheld GNSS receiver were used for these measurements. The procedure of constructing these models and the temporal results are presented in this paper. Furthermore, an online environment for the presentation of the results is elaborated.

Figure 1: Panoramic overview of the archaeological site of Edzná (Campeche, Mexico), taken from the upper 'Temple of the five Stories'

2. STUDY AREA

The Mayan site of Edzná, (meaning either 'House of the Itzaes' or 'House of the Grimace'), is situated on the Yucatán Peninsula in the state of Campeche (Mexico, Figure 2, left). The city of Campeche and the coast are approximately 50 km away from the site. The old Mayan city was founded around 600 BC and abandoned in 1450 AD, but flourished between 600 and 800 AD. In this period, the city had over 25 000 inhabitants and different large structures like the 'Temple of the Nohochna' or the 'Temple of the Five Stories' ('Edificio de los Cinco Pisos') were constructed. From an architectural point of view, the latter is very interesting for its combined use of 'Puuc' and 'Petén' styles: the upper floor of the structure, which is the actual temple and four underlying spaces are in the 'Puuc' style; a pyramid inside the temple is constructed in the 'Petén' style.

At the site as it is known today, sixteen large structures are excavated and exposed, spread over an area of a few hectares. However, with an estimated size of 18 km^2, the full extent is expected to be significantly larger. The current archaeological area is limited by the 'Platform of Knives' in the north, the 'Great Acropolis' in the east, the 'Temple of the Masks' in the south and the 'Nohochna' in the west. Next to the 'Great Acropolis', a smaller acropolis is situated (Figure 2, right).

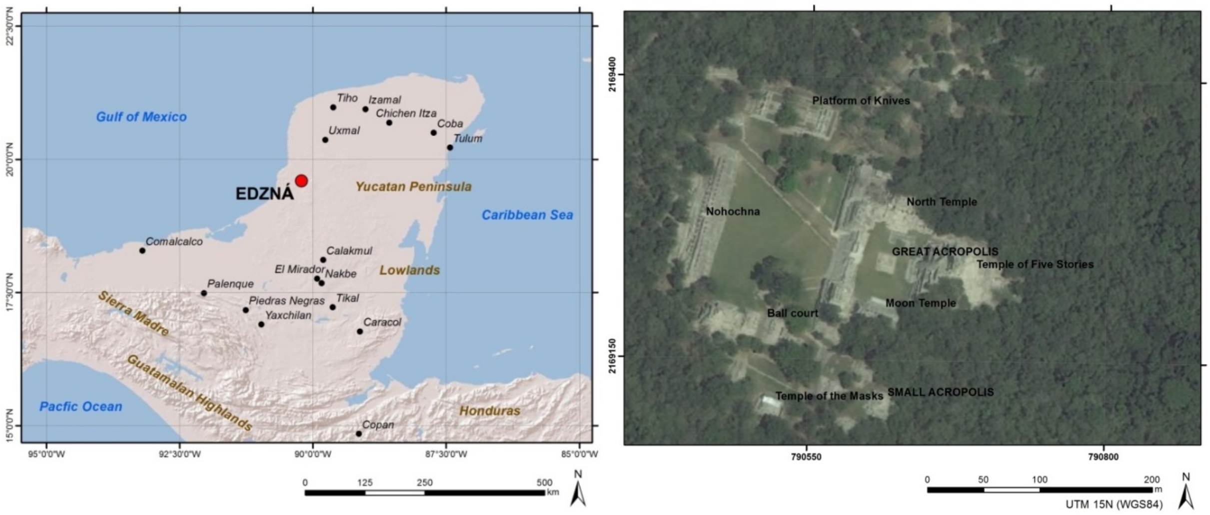

Figure 2: Situation of the Mayan city of Edzná and other important sites on the Yucatan Peninsula (left) and overview of the site itself with some large structures (right)

3. EQUIPMENT AND DATA ACQUISITION

Motivated by the experience of Hendrickx et al. (2011), it was decided to focus on a lightweight, flexible, compact and relatively low-cost UAV, for which spare parts were expected be available in regular hardware stores, in order to perform repairs after platform break-downs. These requirements enable the easy and fast deployment of the system in more remote areas. Besides, the compactness of the system allows operating even in densely vegetated areas. As a result, a *TSH GAUI 540H* hexagonal UAV (www.gaui.com.tw) with a *Sony Nex 5R* was used (Figure 3). A summary of this platform and other equipment is presented below:

- UAV: *TSH GAUI 540H* (www.gaui.com.tw):
  - *DJI Naza-M* multi-rotor control platform with GNSS antenna and gyroscope;
  - *GAUI GUEC GM-412* brushless motor;
  - IR camera trigger;
  - Two axis stabilising camera gimbal;
  - Live video transmission system.
- Camera: *Sony Nex 5R* (www.sony.com):
  - 16.1 Megapixels;
  - APS-C sensor (25.1 x 16.7 mm);
  - 16-50 mm lens;
  - Time lapse software.
- Total station: *Trimble M3* (www.trimble.com):
  - Distance accuracy: ± (2+2 ppm) mm (prism), ± (3+2 ppm) mm (reflectorless);
  - Angular accuracy: 2”.
- GNSS: *Garmin eTrex 30* (www.garmin.com) with 2 metre accuracy in SBAS

(WAAS) mode.

Figure 3: Close-up of the UAV, equipped with a digital camera aiming downwards and two LiPo batteries mounted on each side of the frame

The UAV was also equipped with two LiPo batteries with a capacity of 4500 mAh (3 cells, 11 V). The mass of the UAV (0.5 kg), the camera (body with lens: 0.5 kg) and batteries (two pieces: 0.7 kg) have a large influence on the operational time, but the flying duration is also depending on the weather conditions. Under normal circumstances (no rain and a wind speed of up to 3 or 4 Bf), the flying duration is approximately 7 to 8 minutes. For the entire site, between 9000 and 10 000 images were taken at a maximum flying height of 100 metre. With angles of view of 55.1° and 76.2°, a maximal image coverage of 104 x 157 m can be estimated.

During the field campaign, the 16 different structures at the site were terrestrially photographed and photographed using the UAV (Figure 4). In order to have a full coverage, the camera was fixed with its optical axis vertically down or under an angle of 30° or 45° for the airborne acquisition. It is important to mention that neither flight control software was used during the acquisition, nor were the images geo-tagged. Next to a constant visual contact with the platform, live video transmission was used estimate the elevation of the UAV and to control the coverage of the images. In order to check the image coverage, a first processing of the images was performed on a daily basis.

Figure 4: Operational UAV near the 'Temple of the Five Stories'

For the referencing of the models, a first order polygonal network was materialized and measured by total station (Figure 5). For the alignment of the 3D models in this network, 25 to 90 Ground Control Points (GCPs) of each structure were measured from second order setups. This large number of GCPs allowed a redundant registration of each structure in the processing software, as well as a profound quality control. Per structure, an equal distribution of the GCPs was respected in both planimetry and altimetry. This meant that points were measured from the basis to the top of each structure. It was decided to use characteristic points on the structures, instead of explicitly materializing points. The 9 points in the first order network were also measured with a handheld GNSS device for the global referencing in WGS84. Consequently, the absolute accuracy is only a few metres, but centimetre accuracy was realized for the local network and ensuing GCP coordinates.

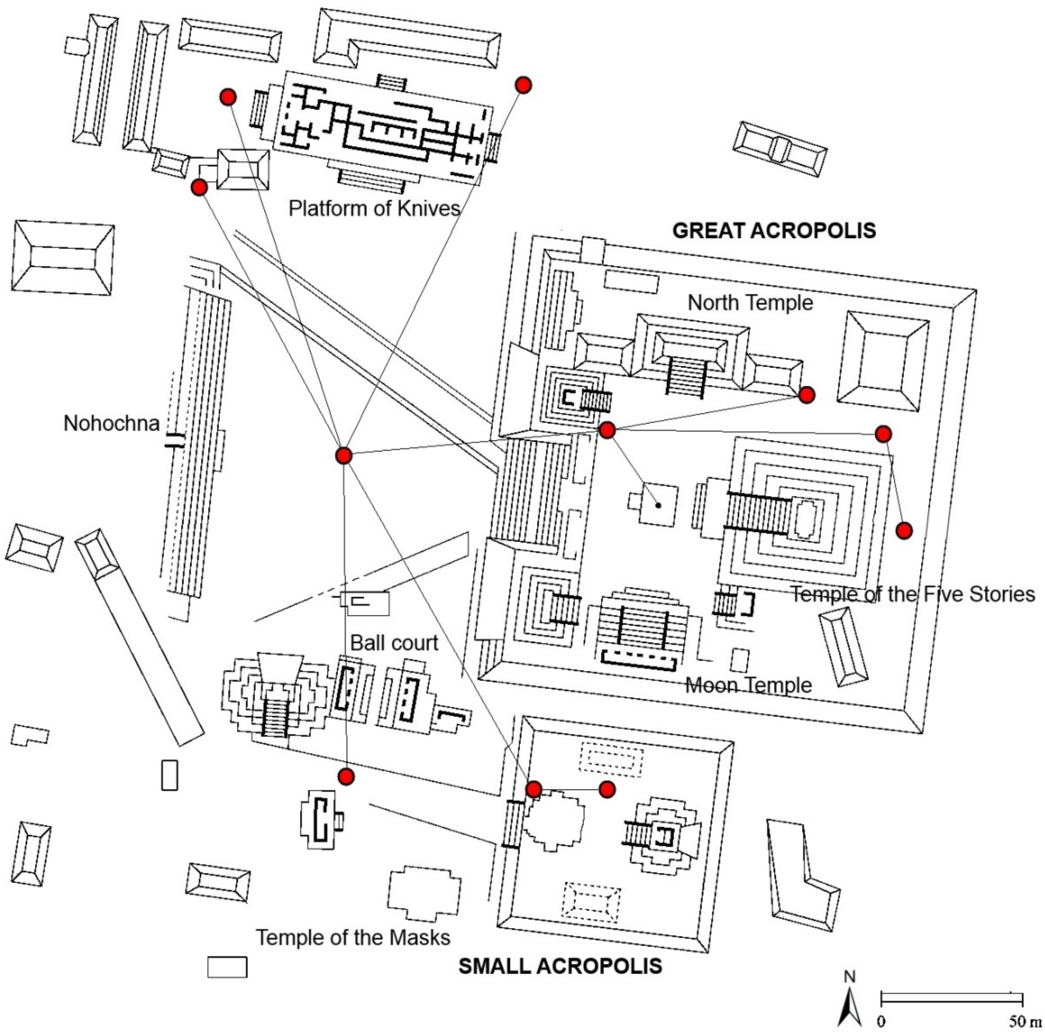

Figure 5: Overview of the site of Edzná and the first order network (modified from Coe (2001))

4. DATA PROCESSING

Agisoft Photoscan Professional (www.agisoft.ru) was used for processing the images. This software uses SfM for the image alignment and MVS for the geometric reconstruction of the object in 3D. SfM-MVS is elaborated by various experts in computer vision, like Lourakis and Argyros (2009), Robertson and Cipolla (2009) or Seitz et al. (2006). For archaeological projects, the technique and accompanying software are also used by various authors, like Verhoeven et al. (2011) or Stal et al. (2014).

The image alignment or reconstruction of the image acquisition (SfM) starts with the automatic detection of characteristic points or feature points on each image. Thereafter, a feature matching is performed in order to relate each point with its counterpart in other images. The focal length and image size of each image are slightly adjusted during a maximum likelihood adjustment, which allows an iterative bundle adjustment and the estimation of a sparse point cloud. In this phase, the GCPs are assigned to each image and the scene will be aligned in an absolute 3D coordinate system. The result of this step is a (best-fitting) virtual reconstruction of the image scene and all matched feature points are accurately positioned in this 3D space. An example of the results of this process is given in Figure 6 (left). It is clear that this preliminary result already gives a good impression of the geometrical correctness of the reconstruction. The blue rectangles represent the image recording position of each image used for the reconstruction, numbered by the name of the corresponding image. The numbered dots with flags represent the measured GCPs.

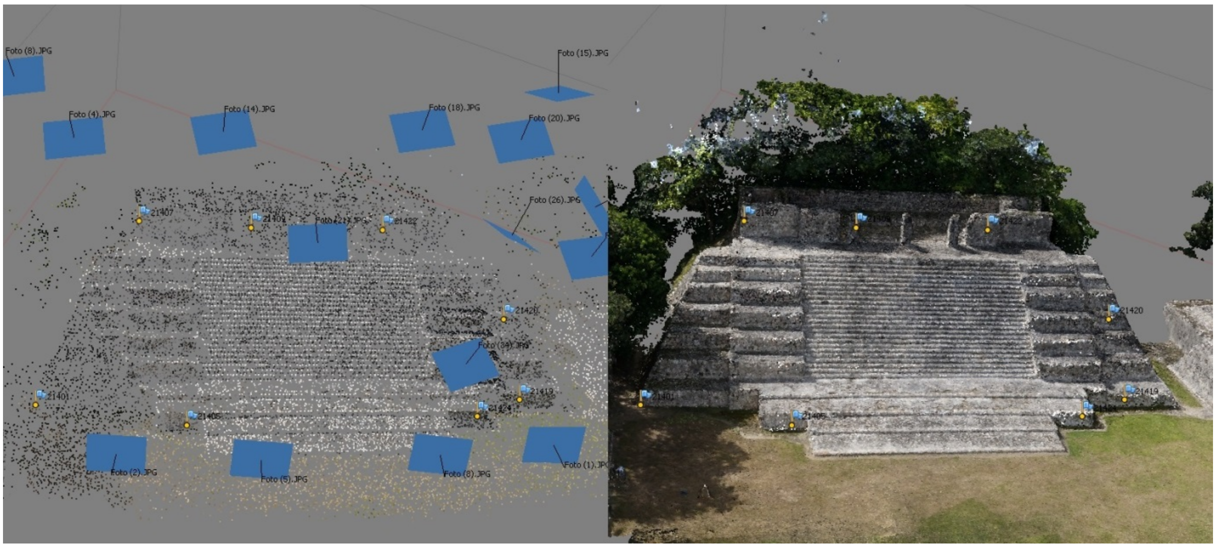

Figure 6: Reconstruction of the image scene with sparse point cloud and positioned and oriented images (left) and the dense point cloud of the same scene (right)

After performing the SfM, the geometry of the object to be modelled is reconstructed using MVS. This actual geometrical reconstruction process is not based on the 3D feature points (i.e. the sparse point cloud), but on a dense point cloud. This new point cloud is generated by projecting the pixels of each aligned image in the 3D space. Using the position, orientation and focal length of each image frame, a depth map is calculated, representing the intersection of the perspective pixel rays with pixel rays from other images. When different depth maps are combined in a single scene, a dense point cloud can be calculated (Figure 6, right). A 3D mesh or triangular model is constructed by the triangulation of this point cloud (Figure 7).

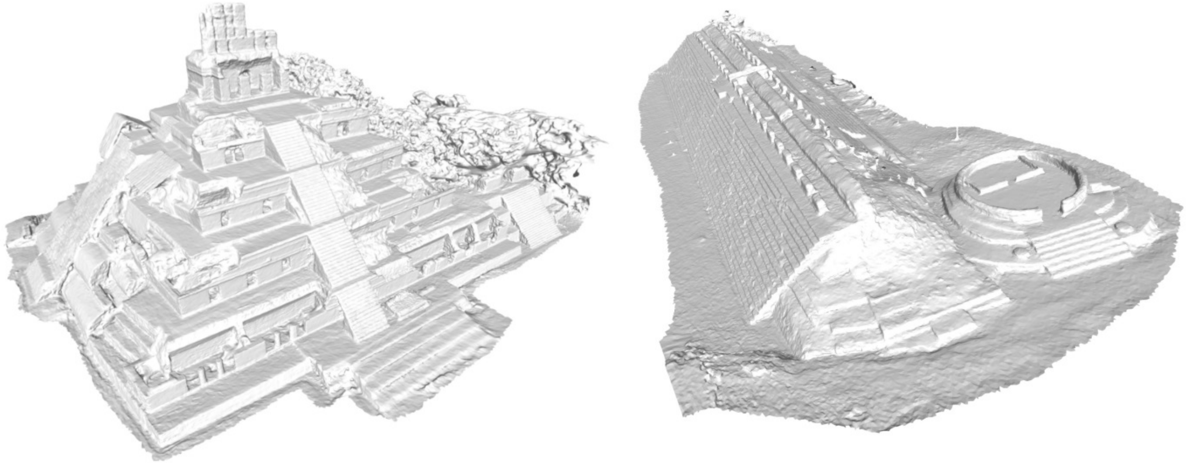

Figure 7: Un-textured 3D mesh of the 'Temple of the Five Stories' (left) and the 'Nohochna' (right)

The final step in the 3D reconstruction process is the projection of a texture map for each model. This texture map allows the photorealistic appearance of the model and it is calculated by projecting original images on the geometric framework of the model. Each pixel in the texture map is the result of a weight distance function of the colour values from different images. The process of assigning a colour value in 2D to a 3D geometry is frequently performed using uv-mapping (Hülksen et al., 2007), where 3D (x,y,z) coordinates of the geometry are linked with 2D (u,v) coordinates in a texture map. Two examples of the final textured 3D models are presented in Figure 8.

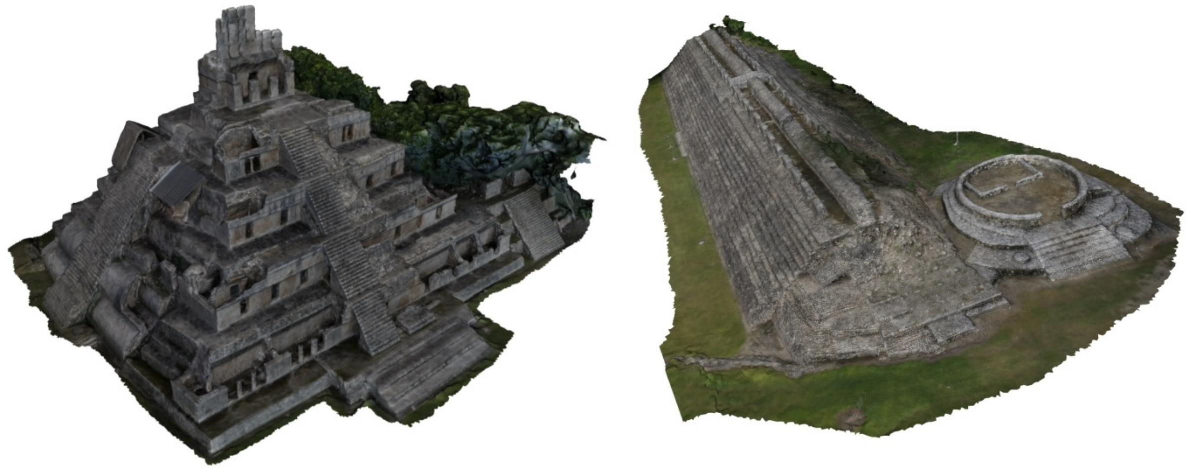

Figure 8: Textured 3D model of the 'Temple of the Five Stories' (left) and the 'Nohochna' (right)

The selection of the different processing parameters is depending on a large number of variables, like the quality of the images, the camera characteristics, the image scale, the size of the object to be modelled, the radiometrical parameters of the object (e.g. ability to detect feature points), the available hardware capacity, the desired properties of the results, and so forth. For this project, the most optimal processing parameters were determined in a trial-and-error procedure. However, the parameters are also based on the required Level of Detail

(LoD) of the models. In the current version of the models, a rough 3D model was generated covering the entire site in situ (LoD-1) and a series of more detailed 3D models were constructed for each separate structure (LoD-2). A third LoD was gained for special features, like masks or frescos. For the LoD-2 models, sub-decimetre accuracy was requested by managers of the archaeological site. After processing all the data, a series of textured 3D models in ascii-based Wavefront Object file format (OBJ) and binary Stanford Triangle file format (PLY) were made available. These models have a full 3D geometry, but 2.5D Digital Elevation Models (DEM) or orthophotos can also be generated.

5. RESULTS

5.1 Accuracy Evaluation

In order to perform an accuracy evaluation of the 3D models, the three largest structures of the 'Great Acropolis', namely the 'Temple of the Five Stories', the 'North Temple' and the 'Moon Temple', are intensively measured using a total station. The measured GCPs were loaded into *Agisoft Photoscan* as discussed earlier and an alignment error was calculated. The values calculated by the software correspond with the averaged triangulation error for each point. It must be mentioned that outliers were removed from this data set. An outlier was detected when the error value is smaller than the lower limit of the first quartile (Q1) minus 1.5 times the Interquartile Range (IQR), or bigger than the upper limit of the third quartile (Q3) plus 1.5 times the IQR. After the outlier removal, the statistics in Table 1 were calculated. The magnitude of the presented errors is very satisfying, given the size of the buildings and the desired sub-decimetre accuracy.

Table 1: Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) of the GCPs

	ΔX		ΔY		ΔZ	
	MAE (m)	**RMSE (m)**	**MAE (m)**	**RMSE (m)**	**MAE (m)**	**RMSE (m)**
'Cinco pisos'	0.016	0.020	0.019	0.023	0.016	0.021
'Moon temple'	0.014	0.017	0.014	0.018	0.012	0.014
'North temple'	0.014	0.019	0.019	0.024	0.015	0.019

5.2 Presentation of the Results

The cultural heritage managers of INAH Campeche, but also archaeological groups working at Edzna will definitely benefit from the work performed during this project. In order to make the results accessible to these institutions and other interested organizations, a web site was developed and hosted at the Department of Geography (Ghent University, Belgium). The internet site is accessible via http://cartogis.ugent.be/edzna/index.html and allowed the visitor to virtually walk through the different 3D models (Figure 9). Interactive 3D visualization was made possible by embedding a *SketchFab* viewer (www.sketchfab.com). Moreover, additional project information was made available for a wider public. Especially this interactive viewer allows non-expert users to get aware of this cultural heritage in a visually attractive way. In order to give an impression of the site of Edzná as seem from the UAV, a video was made available on *Youtube* (http://www.youtube.com/watch?v=GFZhh7h1MiQ).

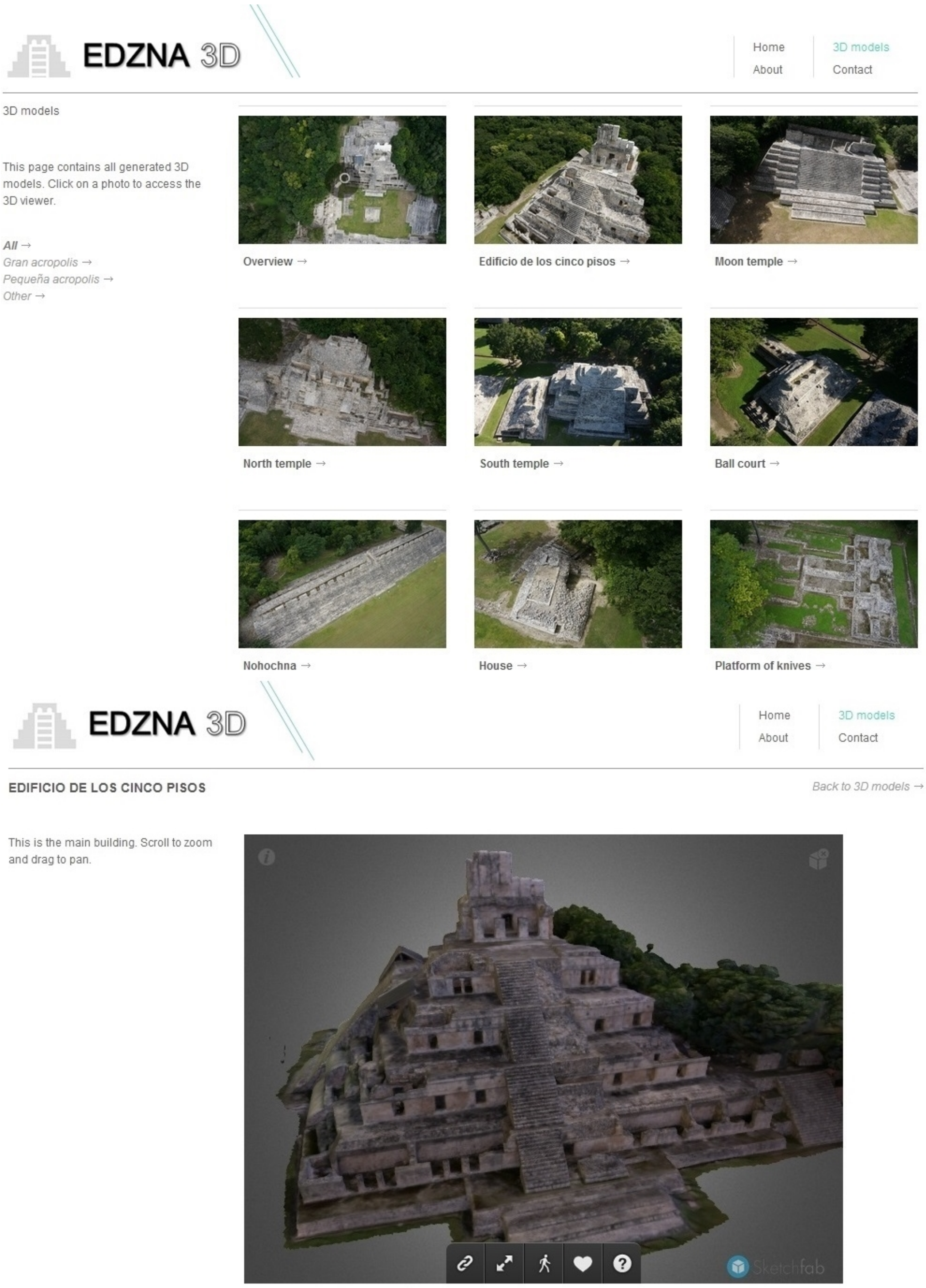

Figure 9: Screenshot of the web site, with an overview of the different 3D models (left) and a 3D model in the SketchFab viewer (right)

Since the project is still on-going, the website is under constant development. It is the ambition to add different other features to the site, with a special focus to GIS-oriented content. The use of conventional DEMs and orthophotos allows the design of a Web Mapping Service (WMS), but this is currently work in progress.

6. CONCLUSIONS AND FUTURE WORK

The construction of 3D models of the archaeological site of Edzná (Mexico) was discussed in this paper. Motivated by the requirement to generate a virtual reconstruction of this Mayan site with sub-decimetre accuracy, a large number of images were taken. These images were taken from the ground and with an airborne UAV. The images were processed in a SfM-MVS-based workflow and GCPs were measured with a total station. This resulted in mean absolute errors between 0.01 and 0.02 m.

Next to the construction of these models, a special focus was the presentation and publication of the results. A website was developed, where information on the project is presented and where the 3D models are made available in an interactive 3D viewer. Further work is required on the design and implementation of GIS-based data in a WMS.

ACKNOWLEDGEMENT

The authors would like to thank the Instituto Nacional de Antropología e Historia (INAH) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) for the logistic and financial support of this project. The Research Foundation Flanders (FWO) is also gratefully acknowledged for funding the research and work presented in this paper. Although the number of authors was limited to five, the authors would like to express their gratitude to MSc. Bart De Wit for his efforts.

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BILBIOGRAPGICAL NOTES

Cornelis Stal (°1985, Waalre, the Netherlands) is a PhD student working on the combination of airborne and terrestrial laser scanning for 3D city modelling. His special interest is in the (automatic) generation of geometric, radiometric and semantic rich 3D models, derived from irregular point sets and other spatial datasets. This means that both laser scanning as a discipline in the land survey and geo-IT (GI-systems, GI-programming, GI-management,...) are important pillars of his research.

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