3D DOCUMENTATION USING TERRESTRIAL LASER SCANNING OF THE REMAINS OF THE JESUIT MISSION IN THE REGION OF LAKE TANA, ETHIOPIA

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Between 1603 and 1633, the religious order of the Jesuits managed to establish Catholicism as official religion in Ethiopia, period in which land grants were conceded, associated to a considerable “foreign” building activity. Nowadays, most of the remains are badly preserved and situated in remote sites, causing problems concerning documentation, conservation and research on that particular cultural heritage. In the present work, terrestrial middle range laser scanning was applied to produce three dimensional digital models of Jesuit remains in the northwestern region of Lake Tana. An overview about the sites history, the instrumentation used and the workflow in data evaluation is given, followed by five practical examples covering all the Jesuit remains in the mentioned region. A special focus is dedicated to the possibility to obtain reflectographic data and to the importance of integrating into such models information achieved by other techniques, such as ground penetrating radar.

Introduction

Historical background

During his second attempt to enter Ethiopia in 1603, the Madrilenian Jesuit Pedro Páez Jaramillo finally managed to reach the mission base established in Fremona, situated in the northern region of Tigray. From there he headed south, entering the Amhara region where soon he got into contact with the Abyssinian king Za Dengel, who invited him to join his court in Dänqáz. Driven by intrigues of other Ethiopian aristocrats against him and also impressed by both language skills and knowledge of local customs of the missionary, Za Dengel converted from Ethiopian Orthodox Tewahido Church to Catholicism. This decision resulted not too fortunate and soon afterwards, after intending to change some religious rules, a civil war broke out in which course the sovereign was killed in 1604, while Páez retired to Fremona.

When Susenyos defeated Za Dengel´s successor Yaqob in the battle of Gol in 1606 and assumed the throne a year later, Páez reestablished contact with the king, who not only kept Catholicism as official religion and tolerated the Jesuit Missions, but became a personal friend of the Jesuit, again inviting him to Dänqáz. In between the results of the king´s favors were an important number of land grants to the Jesuits, the most significant one in Gorgora Nova, located on a peninsula on the northern shore of Lake Tana, the country’s largest lake and a preferred site to establish summer residences of the Ethiopian kings. At this site, first a royal residence and later, in 1626, after Páez´s death, a Jesuit church with various annexing buildings were constructed. King Susenyos had his residence there between 1611 and 1618 (whose ruins have disappeared, possibly because the buildings were made with dry stone without mortar) and converted to Latin faith in an official ceremony in 1621, most probably to reinforce his political power and his independence from the influential Orthodox clergy. In that period, another palace and a Royal bath (water pool) were built in Azäzö, where also, during 1621-1628, the Jesuits further constructed a wall fortified church and residence buildings aside.

When Pedro Páez died in 1622, he was replaced by Afonso Mendez, who is thought to be responsible for the decline of the relations between the governing party and the Catholic Church, causing such social unrest that Susenyos had to resign in favor of his son Fasilidas. The latter expelled the Jesuits in 1633 and restored the Orthodox Church,
with which the 30 years time span of Jesuit influence in the country came to an end. Close to the complex of Azazê, Fasilidas founded in 1635 the administrative and imperial capital of Ethiopia for the next century and half in Gondar.

Since that period, the sites with Jesuit remains were progressively abandoned, suffered earthquakes, fire, disintegration and invasions from neighboring Muslim Sudan and are nowadays in a very deteriorated state, also partly because they are located in remote areas of rather difficult access. In 2006, 400 years after the entry of Pedro Páez, and following an application of the Complutense University of Madrid, the Ethiopian government officially launched archaeological investigations on the Jesuit Mission in the region of Lake Tana, basically centered on identification, designation and consolidation of sites of interest, photographic and topographic documentation and test and open-area excavations. During various campaigns [1-3] carried out between 2006 and 2012, it became evident that the fade-out of the above ground remains is rapidly ongoing, for example most of the east wall the church in Gorgora Nova still wearing the commencement of its original arched structure, collapsed in 1995, leaving intact only a small portion at the eastern end of the structure.

3D Laser Scanning

In this context, a high resolution three dimensional digital model of such sites provides an extraordinary tool for documentation of the degree of conversation of the buildings at a given time [4]. It may further aid planning their consolidation and partly reconstruction and supports a future development and promotion of the region for tourism. Since portable middle range laser scanning devices became available at the beginning of the millennium, these instruments are increasingly used in architecture [5, 6], civil engineering and cultural heritage [7-9]. They also provide 3D models of underground structures such as caves [10, 11]. The instruments are based upon a direct, time-based system of measurement. The most commonly used mechanisms of data capture is the “time-of-flight” approach, were an emitted laser pulse is reflected from the target surface back to a detector, which is measuring the time interval between emission and reception. From the time delay and the speed of light in air, the distance to the target is calculated. With this procedure, ranges of about 100 m and a resolution between 3 and 10 mm are typically achieved at a velocity of 2,000 to 50,000 points per second. The latter can be further enhanced to about 250,000 points per second, using “phase shift” technology. Here, incoherent light modulated in amplitude is emitted. The backscattered reflections are compared by a circuit determining the phase difference between sent and received waveforms, which is also a time delay.

During the measuring of an object, the equipment realizes an automatic scan over its surface, precisely determining the distances following a previously established standard. The polar coordinates with respect to the center of the coordinate system are achieved by codifiers which are determining the horizontal and vertical angles of the pulse projection. With these elements and the measured distance, the spatial coordinates of each point can be defined. The aperture angle of the emitted light beam limits the resolution of the exploration. The resulting non-structured point clouds are subject to subsequent computing allowing to obtain the geometric characteristics which define the three dimensional model. Though, due to the versatility of the technique and multiple possible products, nowadays the majority of the applications of this non-invasive
infrared laser operating at 20 mW (class 3R) with a circular beam diameter at exit of 3.3 mm. Its range is from 0.6 to 76 m, achieving a resolution of 0.6 mm and a measurement speed of 120,000 points per second. The horizontal view is 360° while the vertical view is restricted to 320°, the system is equipped with an inclination sensor and has a built-in Pentium III PC, allowing its remote control via WLAN and external laptop. Further accessories were the Faro LS power base for field operation and carbon fiber tripod. Figure 1 shows an image of the equipment employed.

The color option consists in mounting a digital camera equipped with fisheye lenses onto the scanner using a non-parallax support, after the regular scan the camera is manually placed in the optical path of the laser beam taking a series of images. The scanner software then associates a RGB value to each point of the point cloud; by this a colored 3D model can be achieved. Nonetheless, in the present case the preferred strategy consisted in taking images apart in order to save battery lifetime of the scanner and to apply these later onto the meshed surface of the models during data treatment.

**Methodologies**

**Strategy for data capture**

Prior to data capture, each site had to be cleaned from vegetation and weed blocking the sight on the structure to be scanned, though bigger trees and adult climbing plants often could not be removed. Steep slopes and unevenness of the terrain frequently further hampered the selection of appropriate scan positions. One has to keep in mind that with incrementing distance of the survey technique are centered in the fields of engineering or architecture, its use in archaeology and cultural heritage has experienced an important growth over the last years [12].

**Instrumentation**

The instrument used in the current work was a Faro Photon 80, a compact, accurate and fast middle range scanner making use of phase shift technology. The system is equipped with a 785 nm
scanner to the object, precision of the measurement will decrease, other limitations are due to the minimum distance to the object, field of vision, material properties of the object and incidence angle of the laser to its surface. Then, reference targets have to be distributed in a way that a minimum of three are visible with sufficient resolution in two subsequent scans, otherwise it will be impossible to register them into a unified model. Two different references were employed, 150 mm diameter spherical targets covered by an IR-reflecting paint layer (Faro Reference Sphere Set), these were placed on tripods and homemade checker board targets (27×27 mm), which were stuck to the walls. As compromise conditions between measurement time, data volume and required resolution, a value of 20 mm was considered to be acceptable; this can be achieved by a fraction of a quarter of the instruments maximum resolution which then works with a pulse repetition frequency of 3 Hz and a pulse duration of 0.00190 seconds. Prior to each scan, a low resolution (1/32) 360° scan was taken, from this data the exact area of interest for higher resolution could be defined in terms of the corresponding horizontal and vertical angles. The achieved point clouds were then downloaded to an external PC for post processing.

Data processing

For further optimization of the data, first a series of filters were applied to each scan. A filter is a mathematical algorithm allowing to correct or to remove scan points according to a previously selected threshold. Table I summarizes the applied filters and corresponding filter settings.

Figure 2 shows an example of a single scan before and after filtering, in this particular case data volume could be reduced from 120 to 40 MB.

Once done, local references have to be identified in each scan and to be aligned into a global coordinate system, a process known as registering. The search for unequivocal sets of references becomes increasingly difficult with rising number of scans to be registered in a single model. Additional references visible in the scans such as planes, corner points, slabs or similar may be

Table I. Filters and settings applied to the raw data.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Function</th>
<th>Set Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stray</td>
<td>Removes scan points resulting from hitting two objects with the laser spot or by hitting no object at all.</td>
<td>Grid size: 3 pixel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distance threshold: 0.02 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Allocation threshold: 50 %</td>
</tr>
<tr>
<td>Distance</td>
<td>Removes scan points outside a selected distance range from the scanner.</td>
<td>Minimum distance: 0m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum distance: 50 m</td>
</tr>
<tr>
<td>Dark points</td>
<td>Removes points with too much noise based upon the reflective value.</td>
<td>Reflectance threshold: 100</td>
</tr>
<tr>
<td>Smooth</td>
<td>Minimizes noise on surfaces, replacing the measured value of a scan point with the mean value from its surrounding area.</td>
<td>Grid size: 3 pixels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Distance threshold: 0.02 m</td>
</tr>
<tr>
<td>Cut off</td>
<td>Tool to manually cut selected areas</td>
<td>No default value</td>
</tr>
</tbody>
</table>
Figure 2: Original scan data (above) and filtered scan of the entrance tower in Azäzö (below). In the latter, the identified local references are also shown and the grayscale was inverted for better visibility.
also used, nonetheless, from a certain number (about 15) aligned scans onwards registration does not properly work. In these cases, scans are grouped into clusters which are later blockwise registered.

For data capture, Faro Record software was used. Coarse filtering and registration was carried out with Faro Scene v4.7, which also provides 2D and 3D views of the registered models. Point clouds can further be meshed with this program and be exported in various formats. For further filtering and modeling, JRC Reconstructor, AutoCad 2011, Geomagic Studio 10, Adobe Photoshop CS4, Fast Stone Image Viewer and Autodesk 3Ds Max 2010 software packages were employed.

Results and Discussion

In Figure 3, a large scale map containing the surveyed sites in presented.

In the following, a brief description of each prospected site will be given, followed by a description of information related with the data capture and a selection of the elaborated products pinpointing the most relevant aspects documented at each place.

Dänqüz

In this small village (pin 1 in Figure 3), situated at an altitude of 2720 m and not connected to the road network, two of the most important monuments of the of king Susenys reign, the Royal Palace and a cathedral are located [13]. As a passing remark we would like to mention that earlier information concerning the rather hostile habitants of this remote village could be confirmed. The palace complex was formerly surrounded by a now ruined wall with gate. Its northeast face was built close to a scarped canyon, which at some 800 m difference in altitude connects with
the valley of Ghedam Giyorgis. The northeastern part of the building is the best preserved, conserving plaster wearing wall panels up to the height of the disappeared roof. The rest of the structure has been collapsing, leaving only a few meters height of the walls. The debris of the collapse has possibly covered the carved elephants, horses and cavalrymen as well as inscriptions that were found during a visit in the 1830’s [14]. Left of the entrance gate, a cistern supported by 12 arches is built into the ground; access is granted by an internal staircase. With dimensions of approximately 14 × 5.5 × 8.3 m, it is possibly one of the largest antique structures of this type in East Africa.

For documentation of the cistern, three 360° scans from inside the structure were taken. The palace was covered by a total of 16 scans from different angles and positions. Data was separated into two clusters, which were registered making use of circular and checkerboard targets. The two clusters (Figure 4) had to be aligned manually, using the correspondence view function of Faro Scene, because the pixel size of common references was not high enough to be used for that purpose.

Figure 5 presents a cross section through a room in the best preserved part of the palace. The holes where the baulks carrying the three floors of the building, the shape of the different windows as well as the remains of a chimney in the basement can be clearly distinguished.
From the precise geometrical documentation, the maximum volume the cistern once was able to store could be calculated. Taking into account that the cistern was equipped with a spillover situated at the downer end of the arched structure (maximum filling height) and the displacement of the staircase, this volume is about 462 m³, assuring the necessary water supply in an uphill area with no direct access to rivers or creeks nearby.

As can be seen in Figure 6, the scanning resolution was high enough to capture even small graffiti paintings and carvings now present in the plaster covering the staircase which gives access to the cistern. Figure 7 shows a cross section of the whole structure.

In a previous investigation, it could be proven that scan data provided by reflection of infrared laser light is not only useful to record geometric details of the target, but also to exploit the fact that IR light will penetrate more than visible light into a given surface. Analogue to reflectographic techniques, though restricted to a single wavelength, this may help to detect features that are not visible to the human eye, in particular underdrawings in paintings [15]. At a wall situated at the left side of the main exit from the complex, some unique paintings showing two dogs in perspective view are documented [13], though up to date these have been nearly entirely vanished. At first sight, the eye and some lines of the upper dog’s head are the only clearly visible features. In order to check whether the scanner is able to

Figure 5. High resolution 3D view of a room at the north-east end of the palace (left). The right image shows an outside view picture of this part of the palace with the equipment working.
Figure 6. Details of the staircase giving access to the cistern. The left image shows the digital of a contrast enhanced black/white photograph of the lower part of the cistern’s staircase, while the right image is the corresponding section of a 2D view of the scanned model.

Figure 7. Cross section through the 3D model of the cistern. The contribution of one single scan to the overall model is shadowed in yellow.
detect traces of pigments still enclosed in the plaster, the corresponding area was scanned in very high resolution (half of the maximum provided by the instrument).

Unfortunately, the pigments employed in the artwork seemed not to be particularly sensible to infrared radiation, hence the achieved contrast of the high resolution scan shows not substantially more contrast than the corresponding digital image. In the former, the gray scale reflects the measured intensity value for the backscattered 785 nm laser radiation; the latter records color information in the visible region of the electromagnetic spectrum (380-759 nm). In grey scale, the human eye is able to discriminate about forty different tones only; meanwhile about 200 colors can be distinguished. Changing the intensity, about 500 additional brightness values for each color tone can be achieved and, finally, if the white balance is varied, there are another 20 colors per tone, summing up about 20 million colors. This evidently helps when trying to optimize the contrast of desired features in order to make them better visible.

Nonetheless, the 2D view of the scanned area provides valuable additional information. First, a geometrically correct model of exact dimensions can be elaborated; in former attempts, evident distortions were introduced when using non-rectified digital photographs (blue lines in Figure 8). And second, some traces of the drawings (red lines in Figure 8), which were not visible using digital imagery, could be identified using their reflective values in the infrared region of the spectrum.

The remains of the cruciform Catholic church of Dānqāz, which received the distinction of cathedral in Ethiopia, are situated about 300 m south of the Royal Palace, although it is not clear whether the construction was ever finished. It is of pure Portuguese style, cruciform with a nave of about 27 m length and two smaller naves attached perpendicularly. The principal arches as well as a considerable part of the wall structures are still conserved.

Figure 9 shows an orthogonal view onto the model of the cathedral, accurately outlining its ground plan. With the “tomograph” function provided by the Faro Scene software, a model
Figure 9. Orthophoto taken from the registered and filtered model of the Cathedral in Däńqäz.

Figure 10. View into the last room of the central nave, still preserving Rosetta stones. One of the two conserved main arches can also been distinguished.
can be cut into slices of desired orientation and position; these can be exported in different formats, allowing their integration into computer aided design applications such as AutoCad.

Figure 10 gives an example of a 3D look into the preserved smaller nave and the room closing the cruciform structure.

**Gorgora Nova**

The complex of Gorgora Nova, also known as Mariam Ghimb, is possibly the most known legacy of the Jesuit Missions in Ethiopia. Situated about 65 km south of Gondar, close to the north shore of Lake Tana, it comprises a church and an impressive quadrangular building of 35x35 m, terminated with four towers at the edges, two of which are still conserved. In its inner courtyard, the remains of an Orthodox church of later construction can be found. The original Jesuit church was situated at the north end of the complex. It has been entirely collapsed, only some outer wall fragments and a small part of the apse, wearing an impressive decoration of rosette carved stones, are conserved.

Due to the dimensions of the area, its documentation had to be carried out in three subsequent working sessions. The first started at the Eastern tower, following the interior wall until reaching the rests of the Jesuit church with a total of 16 scan positions. The second session started at the
apse of the Jesuit church, following the outer part of the Eastern walls until reaching the tower scanned the day before, with a total of 23 scan positions. The last day, the remaining part of the area was covered, including the western wall structures, the interior of the patio and the zone of the collapsed church, with a total of 10 scan positions. The interior of five of the eight rooms of the building were also scanned during this session. The corresponding data was grouped into three clusters that were then aligned using external references.

Figure 11 gives an east-west view of Gorgora Nova. At the right side of the image, the eight conserved rooms and the two towers closing the building can be seen. In the center of the patio, the remains of the Orthodox church can be distinguished. At the left side, the collapsed Jesuit church with the single arched structure is seen still standing. The black circles are areas of lower data density due to the blind angle beneath each scan position.

A detail of the latter is shown in Figure 12, the metallic and wooden supports constructed in 2008 to maintain the integrity of the structure can also be distinguished. The geometric patterns which can be seen at the wall in the background are due to shadows caused by the supports from this scan position.

**Debsan**

Rather than a church, this building of dimensions of 24 x 8 x 6 m was most probably dedicated to residence and study of a part of the Jesuit community in the region. Its remains are situated on a hill elevated some 80 m above the surrounding ground and at an altitude above sea level of 2100 m. The site can be reached from Gondar following the Road to Bahir Dar for 35 km until the village of Infraz, then heading south for another 2.5 km. The site itself is inaccessible by car. Perfectly defended by the hill and a stone wall surrounding the building, the site is equipped with a 11 x 4 m and 3 m deep water basin, has sight to Lake Tana to the east and to another hill about 3.5 km south, where the castle of Guzara was later constructed.

The building was scanned from a total of 16 scan positions from inside and outside the structure which were then registered into a single model. The open water basin could not be scanned because it was completely overgrown by vegetation. The model was then meshed into 27 aligned fractions, on the surface of these a total of 66 digital photographs were projected. The photos were previously treated in Photoshop in order to achieve uniform color and illumination conditions. In this photogrammetry approach, a minimum of 10 coinciding points in three dimensions had to be defined between the meshed scan and each picture.

Figure 13 shows the eastern storefront of the building. The arched main entrance, two doors corresponding to the first room, other two corresponding to the second and to the last room, respectively and a window of the last room can be seen.

Cut offs at the top right end of the entrance and are zones of dense vegetation of climbing plants that had invaded the wall structure (Figure 1). Their moving leaves inhibited successful correspondence search between pictures and scan data. For the fraction of non-colored ground floor under the entrance, no pictures covering this particular area were available.

In figure 14, three arched door structures built in brick stone are visible. From all the investigated
Jesuit constructions, this single room was the only place were fired clay ceramic was employed in the construction. Due to the scarceness of this building material in Jesuit remains, samples were taken for their ongoing investigation using archeomagnetic techniques.

Azäzo

The site of Azäzo-Gännätä Ḥıyäsus (Jesus’ Paradise, or Garden) is situated about 5 km south of Gondar, Ethiopia, just in front of the city’s airport. In 1624, king Susenyo constructed a palace there, which has been already described in literature [16] but whose exact localization nowadays has been lost. The building was associated to a garden and royal bath facilities. During the same period, Jesuits constructed the wall fortified church and residence buildings at the site.

Above ground, remains are nowadays scarce in this vast area and the correct archaeological
Figure 15. Extract from a topographical map of the Azâzê hill area, elaborated by V. del Arco Sanz and E. Martín Agüindez, 2009.

Figure 16. Digital Terrain model of the fortified wall structure including view of the recently unearthed circular tower (downright corner). Scan positions are marked. Overlay with previously achieved GPR data.
interpretation of the different construction phases is still not complete [17]. To support this investigation, a geophysical prospection using Ground Penetrating Radar (GPR) was carried out in 2009, during which a total number of 13 areas of potential archaeological interest could be identified in five different areas, mostly situated in the vicinity of the Jesuit church. The best preserved structures, to which the documentation campaign was limited, are a circular tower with a piece of adjacent wall at the north entrance to the area and the fortified wall structure enclosing the area of the Jesuit church (Figure 15).

The entrance tower, already represented in Figure 2, was scanned at very high resolution (half of the maximum) from seven different positions. The fortified wall and the enclosed area were documented from a total of 31 scan positions, distributed over three daily sessions. During registration of the latter, the south, west and east parts of the wall could be mounted into a single model, but the data did not contain sufficient common references to join the north part as well. Hence this was done manually in the correspondence view screen of the Faro Scene software.

From an orthophoto of this data, a detailed outline of the area could be obtained, including more recently excavated features like another circular tower at the south-east corner of the fortified wall, which can be distinguished in Figure 15.

A very interesting approach is the integration of 3D scan and GPR data. In this way, above ground structures can be documented with high resolution, the surface may be defined by a digital terrain model derived from the point clouds and underground features can be represented as three dimensional time/depth slices of the anomalies detected by the radar. The GPR data shown in Figure 16 represents the projection onto a horizontal plane of data sampled in a depth between 0.3 and 0.6 m. Red or yellow color correspond to high amplitude signals related to the presence of reflectors, while green to white tones are related to weak signals and hence to the absence of reflectors. The previously excavated remains of the church, situated in the white square in the middle of the figure, were not prospected, due to the presence of coarse stones, elevated some decimeters above ground.

This integrated data contains the most complete information which nowadays can be achieved by the application of non-invasive, remote sensing techniques to a given archaeological context. The latter, combined with a very intuitive graphical representation, represents a novel and extremely useful tool for investigation, planning of interventions and divulgation in archaeology and related disciplines.

Conclusions

Four different localizations related to the 17th century Jesuit Missions in the region of Lake Tana, Ethiopia were documented using terrestrial infrared laser scanning with phase shift technology. In only 24 working days, a total of 7 structures or areas of considerable extension were scanned with high precision, covering all the known Jesuit remains in that area. A workflow for data capture and elaboration is proposed. Possible products that can be derived from obtained point cloud data comprise, but are not restricted to, fully measurable 2D and 3D models of the scanned structures, orthophotos, single or multiple slices to produce multiview orthographic projections, meshed models that may be used to apply pictures on their surface, colored point clouds,
digital elevation models and, up to certain extend, reflectographic data. The data can be further exported to be used in other 2D (AutoCad) or 3D (3D StudioMax, JRC Reconstructor, Geomagic) environments to make the model fit for purpose, e.g. measurements or representation.

By the integration of scanning and radar data, hence covering all the potential of two up to date remote sensing techniques, a highly valuable tool can be made available to investigation in archeology.

By further computing in dedicated software, the data may be used for the production of fly through videos, virtual reconstructions, etc., which may then be employed for site promotion, presentation in dedicated museums, investigation and conservation.

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