

3D MODELLING OF HERITAGE SITES IN AFRICA. A CASE STUDY IN THE WORLD HERITAGE SITE OF KILWA KISIWANI, TANZANIA.

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ABSTRACT:

No metrically correct 3D documentation exists for the UNESCO World Heritage Site of Kilwa Kisiwani and Songo Mnara, once one of the most important African trading centres in the Indian Ocean region. Modern technology makes it possible to create such documentation and develop an integrated information system for the site. This paper describes an ongoing research project on the documentation of two of Kilwa's remaining structures, the fortress, known as Gereza, and the Great Mosque on Kilwa Kisiwani. The project forms part of the development of a methodology for the digital recording of African heritage sites and the design of a database as part of an integrated information system for African heritage sites. The Kilwa documentation is a pilot- and case study within this larger framework. It focuses on the development of appropriate methods, procedures and techniques, recognizing the technical, economical and physical limitations of documentation work in an African environment. Specifically, the project looks at the smooth transfer of photogrammetrically acquired point clouds into CAD programmes. The photogrammetry-to-CAD transfer is addressed through the development of a data structure, which is employed to systematically code photogrammetrically acquired points on features of interest. An interpreter is then used to translate the labels of the feature points and their coordinates into an AutoLisp feature file, which in turn can be 'understood' by the CAD system and plotted. The resulting 3D wireframe model forms a basis for the creation of surface and/or solid models that are subsequently draped with real texture for realistic representation of the site. The paper also reports on first experiences with a laser scanner and attempts a comparison of laser scanning and close-range photogrammetry.

1. INTRODUCTION

1.1 Back ground and motivation

The coast of East Africa, from Mogadishu to Mozambique has several small offshore islands and mainland settlements with a history dating back to early medieval times. It is important for indigenous people of East Africa to realise, that the popular theory, that these ruins are exclusively of Arabic origin, is erroneous and possibly a deliberate attempt to obscure the predominant East African element in the history of the region. The structures are understood today as the relics of earlier Swahili settlements, and not those of foreign migrants or invaders ('Arabs', 'Shirazi' and others), as often maintained. Although the mosques and tombs are by definition Islamic, they are not direct transplants from Arabia or the Persian Gulf. Instead, their architectural style has developed locally and is unique to the Swahili coast in both forms and coral masonry techniques (J.E.G. Sutton, 1998).

The ruins of Kilwa are the remnants of a once prominent trading centre in East Africa, with links to Sofala and Zimbabwe, to the South, and Arabia and the Far East to the North and East. Its merchants traded gold, silver, ivory, pearls, perfumes, Arabian crockery, Persian earthenware and Chinese porcelain. In recognition of its importance, UNESCO declared Kilwa a World Heritage Site in 1981 and the site also appears in a list of the 100 World's Most Endangered Heritage Sites. The site comprises a number of buildings distributed over two islands, Kilwa Kisiwani and Songo Mnara. The Gereza, a

fortress, (Figure 1) and the Great Mosque of Kilwa (Figure 2), two of the most prominent buildings of the site and the objects of the documentation, are located on Kilwa Kisiwani, in sight of the coast of Southern Tanzania. Ground plans of the Gereza and the Mosque have been published before, but no metrically accurate 3D documentation of the Kilwa ruins exists. It was therefore decided to include Kilwa into the African Heritage Database.

The digital documentation of the Gereza, including 3D models, database and GIS is designed to

- create a permanent digital record of the Kilwa ruins
- provide metric data for ongoing restoration work
- provide data for education and research
- generate awareness of African Heritage in Africa
- support initiatives towards the development of tourism
- contribute to the development of an appropriate methodology for African heritage recording, with the aim of creating an African (architectural) Heritage Database and Information System (R ther, 2002).

In developing the documentation a number of factors specific to Kilwa and Africa had to be considered:

- the extent of deterioration of the Gereza is such that most of the building has been reduced to an open structure with a number of freestanding walls without a roof, while about 50% of the mosque is roofless. The top sections of the freestanding walls are badly broken and highly irregular

and difficult to record and represent in diagrams and models.

- the walls, built of coral rag and covered with lime mortar, display highly eroded, undulating surfaces that pose a major challenge to automated and visual edge detection and line drawing.
- the technical and economic limitations of an African environment render some of the methods and approaches applied elsewhere in documentation, impractical or entirely impossible.



Figure 1. Views of the Western wall of the Gereza

1.2 A brief historical account of Kilwa

Kilwa Kisiwani was first settled around 800 AD and by 1320 it had grown into one of the most prominent trading centres of the East African Coast. Its splendid buildings include mosques, palaces and ordinary residential buildings. Kilwa supplied timber, ivory & other African products to Southern Arabia, the Persian Gulf and locations as far as India and China. Kilwa's trade to the North reached Egypt and other Mediterranean countries. For quite some time, Kilwa also controlled the coast to the South as far as Sofala beyond the Zambezi mouth, a harbour from where gold mined in Zimbabwe was exported. Around the 15th Century, Kilwa faced growing competition from Mombassa and Malindi to its North and at the beginning of the 16th Century it was invaded and subdued by the Portuguese who built the Kilwa fortress in 1505 to signify their dominance over the island. When leaving the island after a short occupation the Portuguese reportedly razed most of the original fortress and in its "present form the fortress dates to the period of late Swahili revival and Omani expansion around 1800 AD". First structures of the Great Mosque were built in the 11th century and expanded significantly in subsequent centuries. Other than for some reconstruction in the 15th century, the present mosque has retained its original form (Sutton 1998). After some economic revival in the late 18th Century, Kilwa faced a new period of occupation by Omani rulers based in Zanzibar at the beginning of the 19th Century. In 1840 the last Sultan of Kilwa was deported to Oman, thus ending the dominance of Kilwa. (Chittick 1974).

2. DATA ACQUISITION

Documentation data was acquired in three field campaigns, during which digital imagery, supported by control point surveys, was captured. A Cyrax 2500 laser scanner was available for the last field visit and experimentally employed as an additional documentation tool.

2.1 Photography

Digital imagery was captured using a Kodak DCS 330 camera with 14mm and 28mm lenses. The two camera-lens combinations were pre- and post-calibrated with the lens focusing ring firmly taped down. The repeatability of the camera-lens configurations after removal and re-attachment of the lenses were tested prior to the fieldwork. In a laboratory experiment both lenses were removed ten times each and the camera-lens system was recalibrated after each lens change. The interior orientation parameters proved consistent within the accuracy requirements of the planned documentation. The following requirements were considered in the design of the geometry of the camera stations and the camera orientations:

- Multi-image photography had to be acquired to provide optimal imagery for surface generation by multi-image-geometrically-constrained matching, the mathematical model employed in the in-house software employed for the project.
- Cameras had to be oriented with the image plane parallel to the principal surfaces (walls) to provide optimal data for the generation of ortho- images
- Oblique and rotated photography were required to strengthen the geometry of the photogrammetric triangulation
- Multiple diagonal photography was needed at both convex and concave building corners to provide links between surfaces in rectangular orientation.
- Photography from different elevations had to be captured to obtain texture and detail for the up- and down facing surfaces of ledges, windows and doors.

Photographs were taken, with the camera handheld, from ground positions, elevated positions on the fortress structures and from a six-meter tall ladder. As the site is located between the equator and the Tropic of Capricorn, it was possible to photograph South- and North-facing walls in full sunlight by visiting the site in summer and winter. A total of approximately 1000 photographs of the two structures was acquired, of which some 500 were finally used for the photogrammetric triangulation and the creation of the model. A number of marked control points, distributed over the structure, was surveyed using conventional survey methods.

Figure 2. Entrance area of the Great Mosque



2.2 Laser Scanning

In recent years, laser scanning has found increasing application in 3D documentation (Barber 2001, Boehler 2001 Fangi 2001, Lingua and Rinaudo, 2001). When the opportunity arose to use a laser scanner, it was decided to explore the potential of this technology for documentation in Africa, where access to sites is generally difficult and site condition can be harsh and adverse to the use of sophisticated technology. The Kilwa ruins, for example, are located on an island without access to electricity, and batteries had to be transported by Dhow to the mainland for charging. Further, the delicate and heavy equipment had to be transported over badly pot-holed roads and carried by hand in difficult terrain.



Figure 3 Scan of part of the pillar hall. The pillar scan comprises of 230 000 scan points

The Cyrax 2500 laser scanner, available for the 2003 July field campaign, has a recommended range of 50m but scans up to 100m are possible under good conditions. The system's horizontal and vertical scan-field-of-view is 40° and a maximum of 1000 scan points in each direction can be recorded in one scan. The laser dot size is 6 mm over 50 m. Quoted standard deviations are $\sigma = \pm 6$ mm at a range of 1.5m - 50m. Laboratory testing prior to the fieldwork confirmed this accuracy, with maximum total point error of 11 mm over 20m. Structural detail, edges and targets can be scanned in sub-scans with higher resolution and added into the coordinate system of the master scan. The fortress and mosque were recorded with scan point intervals ranging from 10 mm to 25 mm at distances of 5 m to 15 m from the features scanned, depending on detail of the recorded structural component and spatial constraints.

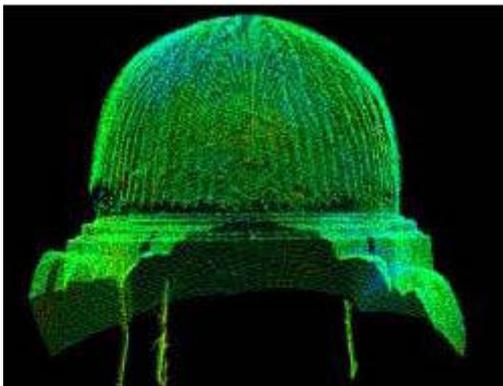


Figure 4. Scan of a dome shaped ceiling inside the Great Mosque of Kilwa. The 2m by 2m by 1.4 m dome was recorded with 130 000 scan points at a 10 mm scan interval.

In six days of scanning, 180 scans were recorded totalling approximately 15 Million scan points or 2.1 Gbytes of data. The number of daily scans was limited by the battery life of the system computer and the need to recharge the battery overnight



Figure 4 . Laser scanning facing the badly damaged inside walls of the Gereza

on the mainland.

In a comparison of laser and close-range photogrammetry techniques, based merely on the experiences of the Kilwa field campaign and a few laboratory tests, one can summarise first impressions as follows (see also Boehler *et al*, 2001).

The principal advantages of laser scanning over close-range photogrammetry emerging from the work on the Kilwa documentation are:

- laser scanning provides direct and immediate access to the scan data making it possible to visually inspect the point cloud in situ and identify possible problem areas in the data sets in the field.
- the point cloud is obtained without any additional processing. Post-processing is similar to that for photogrammetry.
- at an accuracy level of 10 mm, no obvious outliers such as surface spikes, typical for point clouds derived from image matching, were observed in the scan data. This is contrary to experiences with close range scanners reported elsewhere (Lingua and Rinaudo, 2001).
- only one set-up is required for each surface. This saves significantly on planning and execution time and is especially advantageous for complex interior rooms. (In the case of the Kilwa documentation, a hall with some 20 narrowly spaced columns was recorded photogrammetrically in an earlier field campaign. Finding suitable camera positions to capture multiple images for all column surfaces proved extremely difficult and the data acquisition was time consuming. Capturing the same surfaces with the scanner (Figures 3 and 4) required only a fraction of the time and effort compared to the photogrammetric data acquisition.

Close-range photogrammetry on the other hand appeared superior to laser scanning in the following aspects:

- close range photogrammetry provides discreet user-selected points. Vector data, edges, corners and decorative detail can be easier identified and extracted from images than from a point cloud. When using a laser scanner, this can be partly overcome by high-resolution sub-scans of relevant detail.

Algorithms for automated or semi-automated feature extraction from 3D point clouds, combined with appropriate point cloud thinning methods overcome or reduce this shortcoming of the laser scanner.

- photogrammetric point position accuracy is typically higher for targeted natural points at short distances (5m to 15 m). At larger distances the accuracies of photogrammetry and laser scanning become similar and at distances approaching 100 m laser scanning appears to provide slightly higher accuracies.
- cameras are significantly lighter, easier to transport and mechanically more robust than laser scanners.
- photogrammetrically acquired photography provides permanent records, allowing originally unplanned measurements of detail at a later stage
- for highly textured surfaces, point clouds can be generated at higher densities than laser scans. In laser scanning this disadvantage can be overcome by repeat scans with slightly modified orientations.
- at present, photogrammetric equipment is significantly less expensive than laser scanning equipment.
- photogrammetric procedures are designed to provide redundancy (Barber *et al.*, 2001), while the laser might tempt the operator to accept data from a single scan. For the Kilwa documentation redundancy was achieved for the principal surfaces by repeat scanning of the same surface from a different station.

No difficulties were experienced with poor surface reflection. This can be attributed to the homogeneous surface structure of the Kilwa buildings, which consist of well reflecting light coral stones, partly covered with a highly reflecting lime plaster.

At present, the integration of photogrammetry and laser scanning can be seen as a reliable and accurate method of documentation. One can, however, anticipate that the above listed advantages of close range photogrammetry will be equalled by scanners in the near future. One can expect laser scanners to be equipped with fully integrated, stable, high resolution digital cameras, in a configuration which can be calibrated to create a common geometry for the integrated system. One can, indeed, venture to predict that laser scanning will have the same impact on close-range photogrammetry as GPS had on conventional surveying.

3. DATA PROCESSING

The Kilwa documentation has the dual objective of recording the structures in Kilwa as well as the development of an appropriate methodology suitable for documentation of African heritage sites in general, bearing in mind restrictions in technical and funding resources and limitations due to difficult environments. Three approaches were chosen for processing the acquired imagery and laser scans.

1. Sequential processing -photogrammetry employing a combination of in-house and off-the-shelf software.
2. Integrated processing -photogrammetry employing a stand-alone integrated software programme.
3. Hybrid processing- combination of laser scanning and photogrammetry.

3.1 Sequential Processing

The photogrammetric processing follows standard procedures of photogrammetric triangulation (using Australis software), line drawing (AutoCAD), image matching (in-house software,) ortho-image generation (in-house software) and 3D modelling, as for example described in R ther *et a*, 2001).

3.1.1 Data structure for automated photogrammetry-CAD transfer. A new model for the data acquisition with Australis software was developed with a view to an automated transfer of photogrammetrically digitised feature points into a CAD system. The following workflow was adopted:

- An approximate CAD model was created using tape measurements of the Gereza's ground plan (Figure 5).

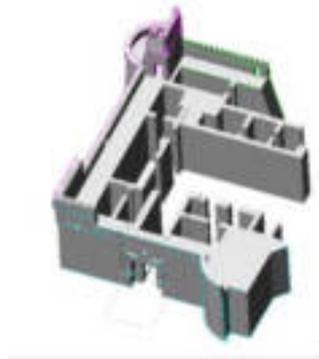


Figure 5. A bird's eye view of Gereza's preliminary solid model designed for planning purposes

- The working model was used to label (code) each point according to its location within the structure, the feature type and the location on the feature, according to a pre-designed data structure; for instance, EGI-1 (Figure 6) refers the first point on the left side of the gate in the East wall, or EWPW1_1 refers to vertex 1 of window 1 on

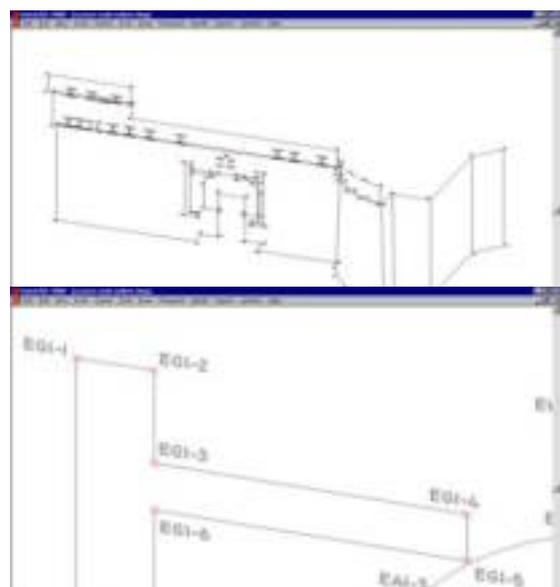


Figure 6. East wall and detail of entrance gate showing an example of the labelling system for automated point identification in CAD

Eastern wall, parapet 1. Further points are labeled in a sequence which follows the outline of the window in clockwise direction, and named EWPW1_2 and so forth. These labels, which identify individual points uniquely, are allocated to points during the 3D digitising with the Australis software. In previous digitising processes, points had only allocated numbers and manually linked in CAD. The identification of individual points in a large densely populated point cloud proved extremely difficult and sometimes impossible. The new coding method combined with automated transfer into CAD, proved a significant improvement on the previous approach and the features of the Gereza's East Wall were successfully plotted on AutoCAD with this method.

- The resultant file of labelled coordinates was then translated into a corresponding Lisp feature file, by means of a program (*Aus2lisp*) for the automatic generation of AutoCAD feature descriptions from an ASCII xyz-file.
- Once imported into the CAD system, the points of a feature are automatically joined with lines according to the number sequence of their labels.

3.1.2 CAD Modelling. CAD environments have become standard platforms for the display of photogrammetric results. Since CAD models conveniently represent photogrammetrically acquired data in a structured form with an unambiguous topology, CAD and photogrammetry naturally blend into a powerful tool for data capture and representation. The challenge in this area is the need to improve the efficiency photogrammetrically acquired data can be transferred into a CAD system for mapping and visualization. The relationship between CAD and photogrammetry and different approaches to their integration are reviewed in Van den Heuvel, (2000). As described above, the CAD model for the Gereza was created by importing the photogrammetrically generated labelled feature points modified with Aus2lisp from the Australis ASCII format into Lisp code. The data structure labels then inform the CAD system on the automatic generation of lines connecting feature points into walls windows and doors.

3.2 Integrated processing

In order to evaluate different processing techniques for use in the recording of African heritage sites, images were processed with PhotomodelerPro40, an integrated stand-alone modelling software programme. This approach has the advantage that relatively little skill is required to produce a surface model, a fact which can lead to the well-known 'black box' phenomenon. A non-expert operator may well ignore basic photogrammetric principles, accept poor image acquisition geometry and be unable to interpret accuracy information correctly. As a result of this, a model may well be accepted on the basis of its appearance rather than its metric accuracy. An experienced operator, on the other hand, can generate an acceptable line model and, with some reservations, a texture model. The author's experience with such integrated software showed that good result can be achieved in cases where the physical environment allowed the acquisition of images in normal orientation (optical axis at right angle to surface) supported by a significant number of oblique images. In this configuration, the normal case images provide the texture for the ortho images, and the oblique images robustness and accuracy for the photogrammetric triangulation. In all cases, where PhotoModeler was employed by the authors for texture modelling, a small section of the surface texture had a distorted,

"smeared", appearance in spite of extensive attempts to improve the model by adding surface points and selecting different images for the areas in question.

In the opinion of the authors, programmes such as PhotoModeler have an important role to play in heritage documentation, especially in environments with limited resources, but can generally not be seen as equivalent to full digital photogrammetry work stations.

3.3 Hybrid processing

First experiments with a combination of laser scans and photogrammetry are promising and it is planned to adopt this approach as a principal modelling method for the project. The laser scan point clouds were exported from the scanning software in ASCII and dxf-format and these formats were imported into CAD software without complication. Point clouds can be rendered in AutoCAD and models can be created. Problems encountered with the Kilwa scan data arise primarily from the difficulty of merging scans in areas without transfer targets or well defined feature points, which can be used for the 3D transformations of scans into a single model. A further complication arises from the difficulty of working with the large data sets, generated by laser scanning, on standard desktop computers.

4 ONGOING AND FUTURE RESEARCH

Present research within the project is directed at three aspects of laser scanning, namely:

- optimisation of the merging of separate scans into a single model
- development of algorithms to semi automatically generate edges and features from point clouds
- generation of ortho images through the combination of
 - camera position and orientation from photogrammetric triangulation
 - point clouds DSMs generated by the laser scanner.
 - feature vector data semi automatically extracted from the point cloud
- developments of algorithms for data thinning

Laser scanning software does include functions for the above tasks; however, present cost of such software make it prohibitive for use in the limited-resources environment of Africa. The authors also believe that there is scope to improve some of the existing 3D feature extraction algorithms and to add new ones. It is also planned to further explore 3D modelling approaches and to extend the project to the neighbouring Songo Mnara. Finally a Historical Information System will be developed and populated with relevant historical, environmental and site management data for the entire Kilwa complex.

4. AFRICAN HERITAGE DATABASE

The Kilwa project is part of the larger initiative of creating an African Architectural Heritage Database (Rüther, 2002). The

population of Africa is largely unaware of the significance of African heritage sites and generally not in a position to visit any but those in their immediate vicinity. It is therefore planned to record and document the historically most relevant of these sites using state-of-the-art digital photogrammetry and laser scanning, as well as visualisation, GIS and database technology. The digital documentation will consist of metrically correct 3D computer models, 3D interactive visualisations, GIS coverages and databases of varying extent, which will contain site related textual, spatial and image data. This documentation can serve for restoration, documentation for the future, scientific research and, in CD or Web page format, for education and the promotion of tourism. The documentation of the 3.5 million year old petrified hominid footprints of Laetoli, Tanzania have already been completed as a Getty Conservation Institute project (Rüther, 1998), the rock churches of Lalibela in Ethiopia are partly documented (Rüther *et al*, 2001) and the Kilwa project, described in this paper, is underway. The three sites have been chosen as pilot projects for the African Heritage Database as they differ in their nature and require different recording and documentation techniques. The project is partly funded by UNESCO.

5. CONCLUDING REMARKS

There can be no doubt regarding the need to record African heritage in order to preserve it for future generations and make the present population of Africa aware of its rich heritage. Documentation should go beyond pure metric recording and an integrated database and Information System should be established for each site, combining metric data in a structured form with data on history, excavation reports, site conditions, vegetation, geology, site management, tourist activities and relevant site information. The problem of transferring data from photogrammetrically digitised coordinate data into a CAD system was successfully addressed by the design of a data structure which conveyed feature position and topology information to the CAD system for automated drawing. Laser scanning proved to be a valuable addition to the documentation toolbox and can be expected to play a significant role.

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