

AIMING TO GO BEYOND ARCHAEOLOGICAL HORIZONS: 3D DATA OF PYRAMIDS AND THEIR INTERPRETATIONS

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ABSTRACT: Since the 1980's, Ancient Egypt Research Associates Inc. (AERA) led by Dr. Mark Lehner has produced detailed archaeological mappings of the whole Giza plateau in Egypt. In 2006, AERA collaborated with a Japanese consortium to establish the Giza Laser Scanning Survey (GLSS) for the production of detailed 3D models of monuments at Giza for scholarly and scientific studies, recording the current restorations, and monitoring the monuments long term. The GLSS team eventually achieved the production of a 3D model of the tomb of Queen Khentkawes [I] who may have reigned over Egypt around 4,500 BCE. In 2008 according to the request of Dr. Zahi Hawass, the secretary general of Egypt's Supreme Council of Antiquities, AERA formed the Saqqara Laser Scanning Survey (SLSS) team from mainly the GLSS members but additionally recruited 3D laser specialists from DEVELO Solutions of Osaka, Japan in order to conduct of the laser scanning of Egypt's oldest pyramid and first gigantic stone monument for archaeological detailed 3D documentation. The laser survey is part of the salvage archaeology and restoration of the Step Pyramid in the face of threats from centuries of erosion and the fragility of the stone and clay body of the pyramid. The SLSS survey of the Step Pyramid helps commemorate 2008 as the "Japan-Egypt Year of Science."

3D SURVEYS AT MEMPHITE NECROPOLIS

Introduction

Preliminary excavation reports with sections and plans of archaeological sites are generally regarded as original data and the basis for any academic papers. However, they are actually the data interpreted and extracted from only a few aspects of a site. In Egyptian archaeology, the current state of megalithic structures such as pyramids has hardly been recorded at all except for schematic plans and elevations of their architectural elements*.

Any theory of archaeology when it is formed inductively should be checked against primary information, namely sites and findings. However, it is not just impractical but also sometimes actual sites are inaccessible especially to foreign researchers. The result is that some controversial topics, such as the existence of a bearer of Queen Khentkawase (also spelled as Khentkaus) at Giza**, has actually been discussed "from the report" mentioning her relief but not "from the original relief" depicted on a weathered granite block. In other words, theories in archaeology have been constructed on a tacit understanding that excavation reports and line drawings are reliable.

Without clarification of the methodology for data acquisition and also standardization of the recording system, the accumulation of reliable archaeological data is difficult. In fact, there are few reports offering data with an explanation of the methodology. It is therefore significant to discuss how we should record the primary material, sites and findings, in a "one-shot deal" archaeological excavation.

Maps, which are reduced two-dimensional visual information, enable us to comprehend the shape and characteristics of a site and/or landforms but the real world is

three-dimensional. Therefore, the introduction of a 3D measurement is inevitable from the viewpoint of record. Additionally, when megalithic structures are the subject of the investigation, a record with a laser scanner can be useful for work efficiency in a limited time of excavation.

Recently, laser scanners have started to be used in Egyptian archaeology but practical use of the 3D data remains at the experimental stage.

Giza Laser Scanning Survey 2006

Ancient Egypt Research Associates Inc. (AERA) led by Mark Lehner has produced detailed archaeological mappings of the whole Giza plateau, Egypt, to understand how the landform was related to the development of the Giza Necropolis. In 2006, AERA established the Giza Laser Scanning Survey (GLSS) team with Tokyo Institute of Technology, Gangoji Institute, Osaka University, and Tohoku University of Art and Design for a capture of the tomb of Queen Khentkawes [I] "as it really is".

The tomb of Queen Khentkawes [I] appearing as a giant *mastaba**** or step pyramid-like tomb which is composed of two parts; a base which is 45.5 m x 46.50 m and 10.0 m high obtained by cutting into the natural limestone rock, and a superstructure rising in seven courses of limestone blocks to a height of 7.5 m. The tomb is located in the southeast of the Giza plateau roughly between the Central Field of the cemeteries and the Central *Wadi* which once served as a route for hauling non-local materials required for the building of the three main pyramids at Giza.

* Except for drawings in Lehner 1985: 23-56; Lesko 1988: 215-35

** See in "Khentkaus's Problem" (Verner 1995)

*** A style of ancient Egyptian tomb, which resembles the low mud brick *mastaba* (Arabic: "bench")

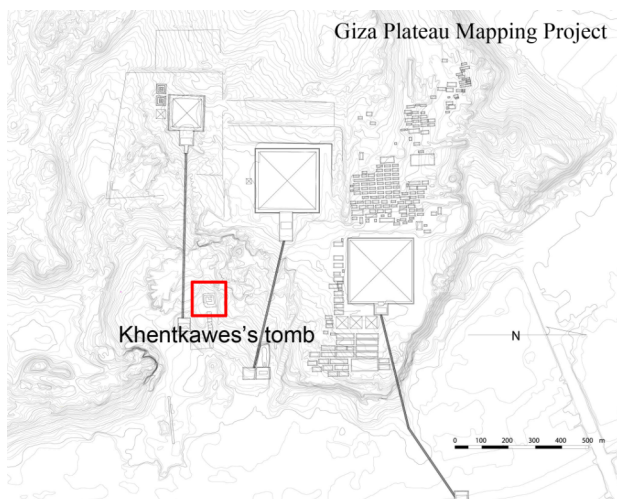


Figure 1. Topographical map of the Giza Plateau © 1999-2009 AERA.

Previous archaeological work on the unusual tomb of Khentkawes [I] and its huge associated settlement was undertaken only by an Egyptian archaeologist Selim Hassan in 1932-1933 (Hassan, 1943). However, Hassan did not accurately map the areas or systematically publish details of cultural remains found in the settlement. In Maragioglio and Rinaldi's comprehensive *L'architettura delle Piramidi Memfite* series, the tomb of Queen Khentkawes [I] was fully studied from an architectural viewpoint. Their plans and east-west and north-south sections of the tomb are the only ones to date showing the architectural elements with measurements including the exterior and interior of the structures of the tomb although they were not produced in facsimile but are more schematic (Maragioglio and Rinaldi, 1967).

The aim of the GLSS in 2006 was to produce a three-dimensional model of the tomb and the topography of the area. Thereby, we attempt to understand the architectural structure of the tomb, and the shape and characteristics of the landforms which host the Khentkawes tomb and town.

Methodology

Atsushi Okamoto (long range laser scanning), Ichiroh Kanaya (middle range laser scanning), and Toshio Tsukamoto (short range laser scanning) respectively used different devices according to the accuracy required and the measurement ranges. Yukinori Kawae then checked all three-dimensional data as point-cloud images. Some scanned areas were re-measured from different positions when necessary. During the laser scanning of the outside of the monument, we marked 37 points on the structure and scanned by laser scanners for locating the points by GPS and also for integration of a separately scanned surface post-processing.

The following equipment was used for positioning and three-dimensional modeling of the monument.

Global Positioning System:

Trimble R7 (U.S.)

Laser Scanners:

Riegl LMS-Z420i laser scanner (Austria), long range laser scanning

- Shape measurement method: laser radar (time of flight)
- Texture scanning method: digital camera (Nikon D100 with 14mm F2.8 Fisheye lens) fixed on top of the scanner
- Measurement range: approx. 2[m] to 1,000[m]

- Maximum resolution: approx. 1[mm] to 10[m] (minimum step of rotation is 0.008[deg], beam diameter is 0.2[mm])
- Range accuracy: 5[mm]

Riegl LPM-25HA laser scanner (Austria), middle range laser scanning

- Shape measurement method: laser radar (time of flight)
- Texture scanning method: built-in color sensor
- Measurement range: approx. 1[m] to 60[m]
- Maximum resolution: 8[mm]
- Range accuracy: approx. 10[mm]

Konica Minolta Vivid 910 laser range finder (Japan), short range laser scanning

- Shape measurement method: laser triangulation with built-in CCD digital camera
- Texture scanning method: built-in CCD digital camera
- Measurement range: approx. 70[mm] to 5[m]
- Maximum resolution: approx. 0.2[mm]
- Range accuracy: approx. 0.1[mm]

With a Riegl LMS-Z420i laser scanner, Okamoto focused on scanning the exterior of the monument from 55 positions and additionally its surrounding landscape between the Maadi Formation and the top of the Member III bedrock outcrop immediately to the north of the masonry superstructure of the Khentkawes tomb. The angle of measurement of the Riegl LMS-Z420i laser scanner was 0.05 degrees or 0.12 degrees as required.

Kanaya measured the inside of the tomb with a Riegl LPM-25HA laser scanner. The spaces inside the tomb were suitable for the scanner whose measurement range is from a 1.0 m to 60.0 m. The inner and outer chapel, the sloping passage, the burial chamber, and the magazines (adhering to Selim Hassan's terminology) were scanned without color information. Kanaya's team also took the laser scanner up to the top of the masonry superstructure of the tomb. Later, Okamoto integrated the data from the top of the superstructure into the data of his Riegl LMS-Z420i laser scanner.

Tsukamoto used a Konica Minolta Vivid 910 laser range finder for subjects which required scanning in detail: the famous Khentkawes's title (*mwt-nswy-bitwy* or *nsw-bity mwt-nsw-bity*)* and her image depicted on the pink granite doorjambs and other relieves. Ambient lighting conditions should be 500 lx or less, so the team normally worked during the early morning hours.

All the scanned data were integrated into a single point cloud model on an Intel Core 2 Duo computer with 2GB RAM, Microsoft Windows XP. Positions of each scanned point-clouds were firstly aligned precisely with laser markers distributed on the monument as reference points. Fine tuning of alignment was done by ICP algorithm. Then aligned point-clouds were merged into a single point-cloud model. Duplicated points and noise were eliminated in this process.

Results

Our original aim was to create an image of the Khentkawes tomb as it really is rather than an interpreted line drawing map. Archaeologically detailed, accurate, orthophotographic point cloud images of the exterior of the tomb were produced by a

* Depending on interpretation, means either "mother of two Kings of Upper and Lower Egypt" or "King of Upper and Lower Egypt and mother of the King of Upper and Lower Egypt (see Verner 1995).

Riegl LMS-Z420i. We produced a plan, four cardinal elevations of the tomb and one elevation of the quarry face to immediately north of the tomb.



Figure 2. Orthophotographic plan of the tomb © 2006-2009 GLSS.

Saqqara Laser Scanning Survey 2008

In 2007 an Egyptian construction company under the supervision of Egypt's Supreme Council of Antiquities (SCA) began to restore the inside/outside of Egypt's oldest pyramid, the Djoser Step Pyramid at Saqqara (c. 4700 BCE). Prior to this work, 3D surveys and radar investigations of parts of the area were carried out. However, the 3D products are archaeologically inappropriate since (1) density of the point cloud data is inconsistent, (2) the data from a distance location are less accurate, and more significantly (3) obstacles between the scanner and the target resulted in many shadows.

The restoration of monuments is necessary in site management, yet subtle archaeological features having empirical values often vanish with restoration. It is therefore indispensable to record the present state of the monument in as detailed a manner as possible before any restoration work is carried out.

The attainments of the GLSS 2006 mentioned above prompted Dr. Zahi Hawass, the secretary general of the SCA, to request the GLSS team to take over the previous work of the 3D laser scanning of the Step Pyramid for archaeologically detailed 3D documentation. For this purpose, the SLSS team is formed mainly from GLSS members, but additionally 3D laser specialists from DEVELO Solutions of Osaka, Japan were recruited.

From May 25 to July 19, 2008, the SLSS team investigated the Step Pyramid using two types of unique laser scanners: the "Zoser Scanner" a custom-designed portable scanner developed by Develo Solutions and two of Topcon's latest laser scanners GLS-1000. This joint SCA-American-Japanese project has produced a 3-dimensional map of every millimeter of the Step Pyramid.

The aim of the SLSS in 2008 was to produce a detailed three-dimensional model of the pyramid. The dependable "raw data" is a basis for versatile exploitation in post processing: producing detailed 3D representations and orthophotographs for 2D drawings, recording the current restorations, and allowing the monitoring of long-term deterioration of the pyramid.

Methodology

We applied two types of laser scanning systems to the Step Pyramid. A team from Topcon, Katsunori Tomita and Kazuto Otani, employed conventional ground fixed laser scanners, Topcon GLS-1000, for basic, overall coverage of the pyramid. When we however scan the pyramid from the ground with the commercially available scanners, the laser beams do not get to the topsides of the stones, and when we scan from above, they miss the underside of overhanging masonry, and so each course is left partly in shadow. To avoid such unscanned areas, Takaharu Tomii, CEO of Develo Solutions Inc., designed and manufactured the Zoser Scanner (ZS), which is a portable multiple scanner system that can simultaneously produce laser beams behind small protuberances. Using this method, while surveyors scan and move at a constant speed with the scanner, accurate information for the position and the attitude of the scanner are gained by an automatic target tracking total station with an inertial navigation system (gyroscope).

The custom-designed portable scanner, the Zoser Scanner, is equipped with four Develo Scanning Range Finders, four 1/2-inch CCD digital cameras (C mount), a gyroscope, a target for Leica TCRP 1205+ and a table PC.

The Gyroscope of the ZS measures its position, orientation, and velocity at the rate of 100 Hz (100 times per second). The four digital cameras take one photo per second. The body of the ZS is automatically traced by a TCRP 1205+ at the rate of 6-10 Hz. These data are eventually synchronized by a GPS timer.

The accuracy of the gyroscope, depending on the number of satellites and their orbits, needs calibration to raise its precision for at least half an hour when it starts. Once it starts, the device should work with an uninterrupted power supply. Therefore, the ZS without a battery for lighting is connected with a long power cord around the pyramid during the survey. The width of the ZS wings is 2.5 m each. This required that the climbers, Yoshihiko Yamamoto and Risei Sato, rappel each face about 25 times (The Step Pyramid is at 109.02 m north to south by 121 m east to west and 58.63 m high (originally 59.93 m)).

The following are the specifications of the equipment we used:

Develo Zoser Scanner-1

- Inertial Navigation Unit

Yaw	0.01[deg]
Roll/Pitch	0.01[deg]
Rate	100[Hz]
- 3-D Scanner Unit

Range of scanning	60 to 4095[mm]
Angle of scanning	+/-120[deg]
Resolution of scanning	0.36[deg]
Scan rate	100[ms]/line
- Digital Camera Unit

Imager	1/2-inch CCD interlace scanning
Resolution	1392 x 1040 [pix]
Size of pixel	4.65 x 4.65 [micrometer]
Lens mount	C mount

Topcon GLS-1000

System performance:

- Maximum range at specified reflectivity

330m at 90%,	
150m at 18%	
Calculated range at 18%	150m
- Single Point Accuracy

Distance	4mm at 150m
Angle (Vertical)	6"

Angle (Horizontal)	6"
Laser Scanning System:	
• Type	Pulsed
• Colour	Invisible (Eye Safe Laser)
• Laser Class	Class 1
• Scan Rate	3,000
• Colour Digital Imaging	2.0 MP camera

Chief Inspector of Giza Pyramids. We thank Osama El-Shimy, Director of Saqqara; Samir Ghareeb, Supervisor of the Step Pyramid Project; and Affifi Roheim, Chief Inspector of Dahshur and Lisht and supervisor of the Saqqara Laser Scanning Survey. We are grateful to Magdi El-Ghandour, Director of the Foreign Missions Department and Shaban Abe El-Gawad for their assistance.

Results

The scanning of the whole pyramid with the ZS was theoretically supposed to be completed within 14 days but practically some difficulties such as the deterioration of the stones, sending the scanner up to the pyramid, and the requirement of an uninterrupted power supply made us modify the original plan. So, the overall coverage of the pyramid was eventually scanned by GLS-1000, and only the shadow areas such as the top of the pyramid, four ridges of the pyramid, and the area between the southern side of the bottom step and the reconstruction wall to the south were scanned by the ZS. The plan is to integrate this data in the post-processing.

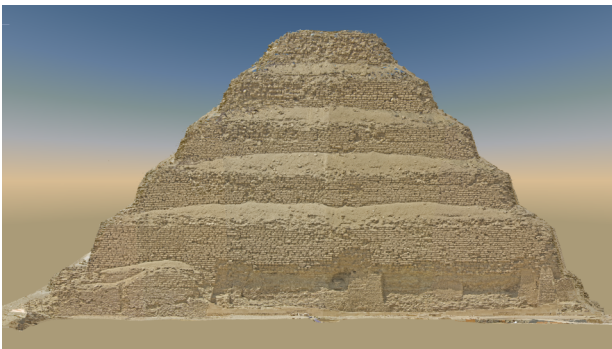


Figure 3. Orthophotographic elevation of the southern face of the pyramid © 2008-2009 SLSS

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