January 2003 Field Mission
Tomb and Temple of Ramesses II

Interim Report

Kevin CAIN
Director, INSIGHT

2121 Peralta Street, Suite 178
Oakland, CA 94607
510.268.1627 voice
510.268.1661 fax

Philippe MARTINEZ
INSIGHT / Laboratoire d'Archéologie
École normale supérieure

45 Rue d'Ulm
75230 Paris Cedex 05
01 44 32 38 24 (ligne directe)
01 44 32 30 60 (télécopie)

2003 INSIGHT Fieldwork in Thebes - Interim Field Report

Philippe MARTINEZ[*]
École normale supérieure

Kevin CAIN[†]
INSIGHT

Brett BOWMAN[‡]
Bridge Design

Abstract

In this report, we:

1. *Describe the work involved in our 2003 field season.*
2. *Sum up the results of our on-site work with different hardware and software used for 3D scanning of archaeological artifacts*
3. *Suggest a new metric for evaluating the resolution of scan data and propose a new 'polyresolution sampling' methodology for improving speed and accuracy in long-range scanning.*
4. *Discuss current work with Geometry Systems Inc. to develop new software for aligning and merging scan data.*
5. *Propose a calendar for sustained activity leading to publication of 2003 field data.*
6. *Present a practical analysis of portable field scanning.*

CR Categories: K.6.1 [Management of Computing and Information Systems]: Project and People Management -- Life Cycle;
Keywords: archaeological documentation, laser scanning, visual computing

Introduction

This practical preliminary report represents our contribution to a collaborative action agreed on by the EdF R&D department, the Laboratoire d'Archéologie at École normale supérieure and the INSIGHT research group in California. The collaborative action led EdF's R&D department to support INSIGHT's use of a Mensi GS-100 scanner on site in Egypt during our 2003 mission. Preliminarily set for a week, the gracious provision of this scanner was then extended to the full three weeks of our work in Luxor, for which we would like to extend our heartfelt thanks to EdF's R&D Department and Mensi as well.

EdF's generous extension enabled us to do much more than we ever thought possible during such a short mission and to make a thorough trial of a scanner and a software package we were using for the first time. We hope that the technical information we gathered during this period shall prove useful to all the parties involved, contributing to the improvement of a machine that is evolving at a brisk pace. We welcome improvements to methodological approaches that could be used in future efforts in Egypt, as well as in many other fields of archaeological research and industrial applications.

1 2003 Field Season in Thebes, Egypt

The data gathered in January 2003 while the INSIGHT team worked in Thebes, Egypt, forms the basis for this interim report. In the process of working with the data, we have developed several observations about both its quality and the requirements we have for its future development and publication. Here, we informally introduce these ideas and invite our collaborative partners (EdF, Mensi, and GSI) to begin an open discussion around these questions of outstanding research.

In specific, we hope that the concepts of *"polyresolution sampling"* and *"adjusted registration index"* detailed herein will serve as useful common definitions on which further discussion can be predicated. This is a working draft document and we invite your active critiques.

Documentation Goals

Figure 1. The Ramesseum.

Our 2003 field work involved a team of ten. Work was carried out in the Valley of the Kings on the Nile's West bank in Thebes, Egypt, through official invitation of the Egyptian government (Supreme Council of Antiquities) and of Christian Leblanc, Research Director for the CNRS and actual field director of the French archaeological mission in Western Thebes. The main aim was to prepare scientific documents for publication, as well as to guide decisions in the context of current restoration and presentation work.

There are three facets to this documentation effort:

1. **3D Laser Scanning.** During our three weeks of field work, we gathered over half a billion detailed measurements of Ramesses II's tomb and temple, using three laser scanners with standard PCs as control systems.
2. **High-resolution digital photography.** Our professional photographers shot over one thousand documentary images of the tomb during our field work. A laptop was used to preview these high resolution photographs in the tomb, and other systems were used to archive the huge number of images shot with Canon D-60 and Nikon D-100 cameras.
2. **Video Projection in Ramesses II's burial chamber**. Digital artists used a desktop PC to project a digital restoration onto the walls of the tomb's burial chamber. This was the first 'digital restoration' of its kind that we have attempted.

These three facets were led according to two separate but complementary fields of research. In 2002, we were called on site to scan the remnants of a granite colossus of the king that used to stand in front of the second pylon of the Ramesseum. The colossus has rested on its back across the main axis of the temple since the medieval era and plays an active part in the romantic aspect of this ruin. Nevertheless since it is also blocking the main axis of the site, the current state of the colossus prevents visitors from understand the Ramesseum's architecture. In an effort to present and preserve the site in a modern way, the Franco-Egyptian mission working on site was asked to prepare a project for the restoration and re-erection of the colossus. Therefore, the most important fragments were scanned last year with a Mensi SOISIC scanner and a virtual reconstruction was achieved against a template using a 3D scan of the best preserved of the two Memnon colossi. If the results appeared interesting and new, they were not as helpful as first thought in judging the feasibility and interest of a physical reconstruction. The virtual colossus needed to be judged against its real setting and a model of the temple in its actual state was therefore necessary. We thus decided to ask for the help of Mensi and the generosity of EdF to secure the use of a fast 3D long range scanner that would enable us to survey the architectural remnants of the mortuary temple for the King of Kings.

Setting the Work Agenda

A week before our departure, Christian Leblanc added a specific topic to our schedule. The Supreme Council of Antiquities was now envisioning the dismantlement and reconstruction of the endangered first pylon, a project that had been discussed for the last decade without resolution. With this change and the new focus it brings to the possibility of restoration work on this gigantic structure, the existing documentation that had been gathered looked incomplete and obsolete. Christian Leblanc thus asked us to focus part of our scanning activity on a precise photogrametric survey of this unstable structure, adding to the activity needed on site and forcing us to develop a specific methodology, taking into account the different levels of knowledge to be embedded in the finalized documentation.

The Tomb of Ramesses II

In the study of the tomb of Ramesses II that was originally meant to absorb most of our efforts, the approach was dependent on the physical aspects of the site today. This monument is one of the largest subterranean structures to have been created by the ancient Egyptians and one of the most impressive tombs erected in the Valley of the Kings, a site that has been recognized as World Heritage by UNESCO. It is a site that continues to suffer from its success and the millions of visitors it receives every year. The tomb in its present state brings mixed emotion to its beholder. It was built near the famous tomb of Tutankhamun in a location that was then revealed to be a poor choice in two principal aspects. If it was chosen for the apparent quality of the limestone in this area, the beauty of which is well exemplified by the quality of the carved raised reliefs decorating the outer corridors of the tomb, the workmen of Pharaoh eventually hit a layer of shale that forced them to change the plan of the tomb in search of better material. Secondly, the entrance to the royal tomb had been set a few meters above the ancient ground level of the valley to protect it against eventual flood through torrential rainwater falls. During the centuries that followed the abandonment of the valley as an active burial ground, the valley was filled by mud and debris finally bringing the tomb to be filled in its turn. The structure was thus flooded by a natural watery compound that is now almost as hard as concrete. In the lower parts of the tomb this fluid met with the geologically stressed shale layers, which sucked the water in like a sponge. While expanding, the shale applied extraordinary pressure on the limestone core, provoking the stone structures to literally explode according to their geological conformation.

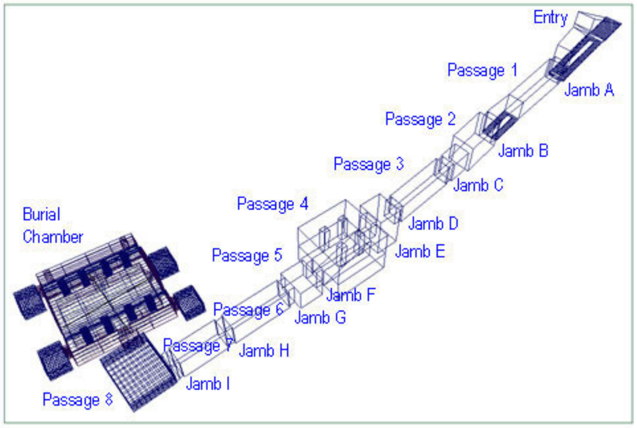

Figure 2. Our Computer Model of KV7.

The exploration of the tomb, which had been thoroughly plundered during antiquity, thus turned into a nightmare, delivering the discovery of interesting but rare artifacts and of an architectural structure that was turned into a threat by its very fragility. The tomb is now almost totally emptied from its muddy encasing and is receiving the focused attention of restorers, in terms of structure as well as decoration. Even at a time when it is not yet open to the public, its location in the neighborhood of the tomb of Tutankhamun and the fact that it is the tomb of Ramesses the Great has turned it into an attraction worth mentioning to the passing groups of tourists. This situation tends to make it clear that once opened it should become one of the highlights of a visit to the Valley.

However, Christian Leblanc is now afraid that in its actual state the monument might belie its ancient glory and deceive its visitors. He thus asked us to join his team keeping in mind three different approaches.

1. Leblanc needed a precise 3D scan of the architecture of the tomb to prepare for its strengthening and restoration. At the same time, it was clear that the preparation of documentation needed for the scientific publication would take another decade, if considered through classical analog techniques. It was thus decided that the remnants of the tomb's very shallow decoration would need to be scanned in a very precise manner. This was envisioned as a first attempt at automated digital epigraphic survey. This novel approach is something that many Egyptologists have been daydreaming of for decades without any real hope of achieving. When discussion began, a 3D scanner able to survey such fine relief did not in fact exist. At the time we began to envision the project we instead were evaluating different approaches, mainly structured light and short range laser scanning. Digital photography was also to be used to survey the actual state of the wall surfaces and be used as realistic textures of the 3D models, to be exploited in the scientific publication of the monument.
2. Apart from this scientific endeavor that would be the logical and necessary output of the decade of hard work already put in the project by Christian Leblanc's team, we were also asked to think about different ways to bring the tomb back to its ancient glory. At the least, we hoped to be able to pass an idea of the complexity and beauty of the tomb's architectural and decorative program as well as of its history and importance to its future visitors.
3. Our work should thus lead to the 2D reconstruction of the polychrome decoration from parallels gathered in contemporaneous nearby tombs, a reconstruction that would not only be shown on screen or paper but that should be projected on the walls of the destroyed burial chamber. In this way, a visit of the tomb would be turned into a three dimensional digital sound and light show, its beholder being plunged into the ancient brilliance of the place after having been turned into the witness of its actual desecrated state, remnant shadows of its ancient glory.

Even if the context thus presented is necessary to understand the scope of the ongoing archaeological research that underlies our digital efforts, for the purposes of this interim paper we will concentrate on 3D laser scanning. A full discussion of the photographic and projection projects, including their relation to the laser scan data archive, will be included in the forthcoming "2003 Field Work Final Report" (see schedule in Section 4, below).

NOTE: for an informal day-by-day summary of field work in 2003, see: www.insightdigital.org*; please click on Field Journal 2003*

2. Field Sampling Discussion

Below we would like to consider field sampling issues related to our January 2003 fieldwork, including practical problems and solutions encountered during our laser scanning fieldwork in Egypt. For this work, our team of ten used both the Minolta 900 and Mensi GS-100 laser scanners. A Minolta 700 scanner was also on hand, which was used primarily for testing. For the purposes of this report, after a presentation of our on site test of the GS-100 scanner, we shall concentrate on the use of the Minolta 900 scanner since it is a specific area of interest for EdF's current research carried out by Guillaume Thibaut on digital epigraphic archiving.

Working with the Mensi GS-100 long range scanner

We have been familiar with the use of Mensi's SOISIC scanner and 3Dipsos for a few years now and have been aware of their possibilities as well as their limits. Under the relenting Egyptian sunlight, the major issues in using the SOISIC had been its slowness in acquisition and its inability to function during the day, even when the scanned artifact was protected from direct sunlight. The daylight scanning difficulties led us to ask for night access to the Ramesseum site in 2002 (in order to document a granite colossus). The organization of the work proved to be tedious and diplomatically complicated, leaving us with only a few hours of actual scanning each night. It was thus impossible to plan a full architectural survey of the sacred site.

Figure 3. Dr. Martinez working with the GS-100.

The option of subsequent temple access outside of regular hours has not been improved by the growing political tensions at work right now in the Middle East. Thus, the prospect of using the Mensi GS-100 appeared to be the ultimate solution to our problems. Even if we encountered different problems during our field season, we can acknowledge that our expectations were never disappointed, and we were even surprised by the discovery of new methodological possibilities along the way.

The GS-100 scanner was used mainly at the Ramesseum for a detailed architectural and topographical survey. (We also used the GS-100 in the valley of the Kings for a very quick but important survey of the architecture of the tomb of Ramesses II). The purpose here was to verify the analog plans that had been made available to us and to build a 3D context for the epigraphic laser scan survey and digital photography that was realized by the rest of the Insight team.

Below we offer our team's end-user observations:

At the airport

The GS-100 was easy to handle as carry-on baggage on our flights to and from Egypt and went through the customs in Cairo as a special video camera, its serial number having been written in one of our passports. In its blue backpack it even eluded the attention of the Egyptian custom police and thus entered Egyptian territory without any unnecessary haggling--this was a relief compared to our past custom adventures with the large flights cases needed for the SOISIC.

On Site

The scanner revealed itself to be equally easy to handle on site, where we were able to easily move the scanner around from station to station. A few improvements follow:

Figure 4. GS-100 and Control Computer.

1. We often had to check that the scanner head was correctly engaged on the tripod and found that the process of tightening the tripod took time. However, the relative lightness of the scanner head set on its tripod enabled us to move it as a single unit from station to station, something that turned the whole process into a pretty straightforward operation.

2. It would have been reassuring to have a way to secure the backpack's zippers while taking it up a ladder to the temple's roof, onto scaffolding, et cetera. It was nevertheless possible for a single person to handle the scanner on the ground, and with the help of a second individual the machine was secured in more difficult spots. The setup was easy, even if the ergonomy of the tripod could be discussed, something we shall do in depth later.

3. Following the field work, we learned that Mensi has implemented a full solution for running on portable batteries. This would be an ideal solution except for two flaws: the 5-hour battery limit and their cost. Check below for our proposal on a more robust and better priced solution, which introduces its own limitation: heavy batteries. Still, we believe this solution seems interesting for difficult sites where the electricity is a problem more important than physical access.

   We were able to take advantage of ac-dc outlets available on site. We felt it was necessary to plug the scanner and its controlling laptop into a power conditioner to avoid Luxor's ubiquitous electric irregularities.

Scanner Control

We had initially decided to use one of our own laptops to control the scanner and it unfortunately turned became a problem. The recent laptop that was first scheduled for this use remained in San Francisco with one of our colleagues for a full week after our arrival. Therefore we had to use a slower model with full hard drive. It slowed the acquisition and even brought the whole system to crash. Fortunately the automatic backup file written on disk by the scanning utility was very useful in restoring the lost data file and re-launching the survey but the restoration was very slow and tedious. Also, the actual saving of the completed files took a large amount of time for long scans. We thus lost quite a lot of time as well as some data during our first week, a problem that was partly alleviated by simply making room on the hard drive and defragmenting it. It is clear that the whole ergonomy of the scanning environment would be greatly improved by the use of a dedicated Pocket-PC handheld computer that could be set on the scanner itself without the need of heavy computational equipment on site. This would also avoid the unwanted presence of cables. It is however clear that the control laptop and its connection to the scanner should be thoroughly checked before work to avoid the troubles we ran in on the first days of our work.

Scanner Operation

Following is documentation for a key problem that arose during the scanning operation.

1. The estimation of the time necessary for each scan appeared to be faulty. It was clearly estimated before the scan was launched but then the time counter seemed to go crazy, multiplying the scanning time by approximately ten. During the scan, the timer went to zero before the scan was finished and then returned to another crazy display of hundreds of hours before it eventually stopped a few minutes later. Even if the time span that was first displayed was approximately correct, all and all it appeared erroneous and made it difficult for the person in charge of the scanning to precisely plan and schedule the stations that could be scanned in the span of a work day. The end result was that our team ended up with small day-to-day conflicts when the site policemen came to close the temple while a given scan was not yet finished.

Viewpoint Planning

The stations were planned according to two different projects. As explained above, the main project envisioned the scan survey of the whole precinct encompassing the architectural remains of the stone temple as well as the mud-brick structures of its surrounding service area and storerooms. A second but equally important effort concerned a precise survey of the collapsed first pylon. We alternated stations for both projects, accordingly to the position of the sun in the sky. If the ability of the GS-100 scanner to work in the full bright Theban daylight was for us a welcome surprise, we rapidly had to acknowledge the fact that the scanner was blinded when it looked into the general direction of the sun. This was true even when the eye of the scanner was looking at the ground, a fact that might suggest changes need to be considered for the angle of the glass plate protecting the machine. We thus encourage Mensi to consider the use of a lightweight opaque device that could be attached to this plate. We learned that Mensi envisioned the possibility of having this protective plate directly attached to the scanner, thus protecting the lens and CCD from direct or slightly indirect blinding by sunlight.

Performance

At the end of our first week of scan, the scanner range unfortunately dropped in a dramatic way, falling from 100m to about 30m. As the whole site measuring around 300m by 200m, we had to abandon plans to scan the mud-brick service areas to concentrate solely on the stone temple, covering an apprx. 200m x 50m space. We also had to stop launching long range scans running along the area of the ancient surrounding wall that would have covered the whole area, with better measurements on the inner parts where the stone temple lies. Instead, we decided to position our stations around the temple at a distance averaging 15metres, focusing on the stone structure while running faster scans of what could be reached of the service areas from the same spot. It definitely is not a very thorough and evenly planned strategy of scanning and must be seen as a somewhat desperate trial to cover as much terrain as possible. We also have to note that this decreasing range unfortunately happened when we were beginning a series of view points set up from a scaffolding positioned to the north of the temple itself, to try to cover the topographical plan of a late cemetery that lies directly against the precinct to the north and that is actually undergoing thorough archaeological exploration.


Figure 5. Scanning with the GS-100.

It would have been possible, using 360 degrees view points, to connect the Ramesseum with one of the neighbouring funerary temples, dating to the reign of Thutmes IV, now rediscovered by an Italian mission, many of the masonry blocks from this older temple having been reused in the architecture of the Ramesseum. Due to an incident we shall precisely described below, we could not be sure of the technical failure that led to this drop in range. But it clearly looked like the focal point of the laser had dropped from its usual 50meters to a distance of about 5meters.

Suggestions for Improvements

It has thus also to be underlined that the GS-100 scanner we were able to use had a set focal point that enabled us to have very precise measurements only originally at a distance surrounding a range set between 25 and 50 meters. For this reasons trials we made during our first week of scan to have more precise sub-viewpoints concerning for instance parts of the wall decoration or of the statuary failed in giving us usable data. We recently learned that the latest version of PointWorks now enables the viewer to choose between two different modes considering either a set focal mode that is faster but less precise and an autofocus mode where the speed of acquisition drops by half, while each measurement is specifically focused and thus a lot more precise whatever the considered distance, a welcome addition we would have liked to take opportunity to test.

Another issue lies in the framing part of each scan. If framing is conceptually simple in PointWorks, it is too slow. We thus wish that the software could allow high-speed movement of the laser beam in framing mode. For the same reason, it would be interesting to include a “blind” mode for framing, in which the software would not have to display/focus the video camera. This would enable the user to quickly set up a bounding box in framing without being encumbered by camera focusing time. Finally, PointWorks would be also greatly improved by a functionality we could call “frame once, shoot many times”. In connection with the above point, this would allow the user to quickly test a given framing and evaluate the resulting points in 3D before electing to launch a more detailed scan. In other words, it should be possible to perform a quick scan at very low resolution, and then launch successive detailed scans without having to re-frame, the actual framing being kept in memory for a setup that could be duplicated.

We also found it difficult to make use of PointWorks’ standard 360° scans. Due to the disparity of the altitudes of the different parts of the preserved architectures, we would, in almost every station, scan more sky than actual structures and thus lose time in the process. We thus decided to cut the 360 rotations in a varying number of sub-viewpoints that would consider only the different structures, cutting at points where the balance between useful acquisition and useless measuring would become too uneven. It thus generated a specific loss of time. We had to take into account the same aspects during our work in the tomb where the architectural context of a narrow and very long series of corridors meant that for a fixed resolution we would get very dense point clouds in the area of the walls that were near the scanner while on the contrary the density of measurements would decrease along the corridor walls, the further the measured point got from the scanning head. These remarks call for the implementation of non-monotonic vertical-axis rotation for the scanner. For large scenes (like the Ramesseum) the monotonic stepper motor procession necessarily creates considerable disparity in the mean distance between scanned points. For a full discussion, see the "Reverse Decimation" topic later in this report.

As we knew that looking at the acquired points cloud during the acquisition was slowing the process, we rarely took advantage of this ability to check our 3D measurements in the field. However, we were happy to be able to verify that the scan process was not actually interrupted. We were also able to stay for a few evenings and thus launched long scans—for instance, on the faces of the first pylon. For this structure, about 60 meters wide, we needed to set scan resolution at apprx. 5mms in order to properly capture the details of the masonry and a fair survey of the three-dimensional deformations endangering the structure. Due to a mistake in our licensing file for Mensi's Scanworks Survey software, we were never able to use the registration module of the software, a fact that turned to be a serious handicap as we were unable to check on site during the scanning process how each of our scans was relating to its direct neighbor. In this regard we have to state that we were never able to set registration entities (i.e., spheres) in the scenes we were scanning. We scanned in areas that were totally opened to the public, with hundreds of tourists and workmen passing through. We tried to set spheres during the first days along our acquisition path, meant also as topographical markers, but found they were moved by curious onlookers or careless bystanders. The version of PointWorks we used did not yet include the possibility of using fixed targets that could have been set on the structures instead of on the ground. Thus our registration process is meant to depend heavily one the use of ICP registration algorithms.

Finally we had to deplore a frustrating and devastating incident at the end of our second week of scan. At this stage we were moving steadily in our planned list of scanning stations and were pretty well done with the scans concerning the photogrametric survey of the first pylon, in terms of the points of view that could be scanned from the ground. For the eastern façade of the structure which almost totally collapsed and is now a chaotic field of blocks from the inner masonry filling of the structure, we had to envision points of view where the scanner would be positioned to sweep the same area from above to get a complementary description of the blocks faces that remained hidden from the ground viewpoints. Getting the scanner in position was not easy but also not dangerous either and the points of view we cautiously defined never caused the scanner to look down in an awkward position.

On an early morning the scanner was set in its first position, well positioned on the limestone surface of a block, and very nearly horizontal. The controlling laptop was set nearby in the shadow of the blocks and as usual we checked that the cables would not interfere with the rotation of the scanner. Having double-checked the stability of the machine, we began the scanning process and the scanner rotated to it's 'home' position, a nearly 360 rotation. The rotation went well and the scanner still looked stabile. We then began to frame the area we wanted to scan and it is during the second part of the rotation that the scanner appeared to have lost its balance and fell from its supporting block towards the slope of the destroyed pylon façade, a fall from about 3 meters. One of us reached to grab the falling scanner but our position was somewhat too dangerous it was impossible to block the scanner's fall without tumbling with it. As dismayed as we were by this unfortunate and regrettable event, we have since tried to analyze the reasons that lead to the fall of the GS-100.

At first, we first thought that one of us had made a false move and tripped on one of the wires, a problem we had been aware since the beginning of our work. However, of the three people working with the scanner, none were near the cables.

At the time, the machine was facing west, its excentered back part being turned towards the slope. According to the recent debriefing of the accident with Mensi engineers, we now think that the scanner lost its balance because one of the tripod legs slipped on the stone surface during the rotation of the head. We note the fact that the back of the machine is excentered because the design of the machine rested originally on the idea that the scanner "eye" needed to be positioned exactly at the center of the rotating axis of the machine to avoid calibrating issues that have been solved since. For this reason the gravitational center of the machine is set five centimeters to the rear of its rotation axis. Furthermore, due to the weight of its embarked computer, this gravitional center is in fact set very high. The GS-100 is thus naturally unbalanced, a fact that becomes even more serious when we consider that the gitzo tripod was chosen for its lightness more than its specific sturdiness. The attachment to the scanner consists of a ring with a 10cm diameter. If we consider that the weight of the scanner is already 5cm off its center to the rear, this represents half of the circle of substantiation of the tripod head. This is very clear when the tripod is used in its lowest position: with its short legs the tripod is set on a triangle that barely cover's the scanner's footprint. Ultimately, this seems to result in a system that can very easily get turned upside down by its own excentered weight. For this reason we decided never to use the scanner in this low position, even when this mounting could have afforded us useful points of view in areas like the hypostyle hall. We considered using the scanner without a tripod, but directly set on the ground the scanner was somewhat too low to offer useful angles.

These remarks bring only one conclusion: in difficult surroundings the lightness of the gitzo tripod has unfortunately to be sacrificed to the security of the scanner and of its user. Our discussion with the Mensi engineers lead us to propose that the heavier tripod used with the SOISIC scanner should be adapted to receive the GS-100. The short version can still be handled by one person, while it is far more stable and is stiffened by a metal device joining the three legs. The round plastic feet of the gitzo tripod should also be questioned. In any position, only a small part of their surface is really in contact with the ground. The metallic hinged flat feet of the SOISIC tripod offer more steadiness in many positions and they even can be fitted with pointed feet to better ensure better contact with the ground where the scanner is set, whatever the material considered.

The adaptation of this tripod would have another advantage that has to be considered in turn. The field of view is quite good on the GS-100, but being able to pivot horizontally would obviate the need for unstable "kneeling" tripod setups (i.e., to "look up" or "look down" on the subject). Using the SOISIC short tripod the GS-100 would thus benefit from a possible horizontal-axis rotation that would greatly improve its ergonomy. We were for instance unable to scan the head of a large jackal statue in a tomb because the scanner had to look down at the piece of sculpture from a distance of 5 meters while being set on a short platform that overlooked the funerary shaft. We were never able to set the scanner in a stable position needed for the scan without taking the risk of seeing the machine tumbling down in the darkness--a risk it would unfortunately decide to take on the impulse of its stepper motor a few days later from the heights of the first pylon.

Conclusion

Finishing this assessment of our experience with the Mensi GS-100 scanner in Thebes, if we had to stress the negative aspects in order to provide useful clues for a future redesign of the scanner, our view of the machine and of the results we gathered is globally positive. The GS-100 is fast compared to the middle range scanners we have been able to use in the past and retains the precision necessary in the heritage field of interest. It is easy to handle and pretty sturdy, quite fit to use in the difficult surroundings that are most of the time known on archaeological grounds. Though we were not able to fully take advantage of its long range, it is clearly a very useful tool that every surveying team working on archaeological or architectural structure should be able to use in a near future. The trials we did for topographical surveying of an ongoing dig from a scaffold are opening new possibilities in terms of archaeological data management. We really hope to have another opportunity to put it to the test of our ever growing data sets, in an implementation that shall take into account the risks we unfortunately had to meet during this mission.

Scanning with the Minolta 900

Our scanning project in KV7 required optimization for two diametrically opposed factors: quality and speed. The slight reliefs, in many cases sub-millimeter, required high resolution, while the enormous amount of wall space demanded a scanning approach that was fast and simple. Acknowledging the difficulties, the following requirements were laid out.

Acquisition Details & Statistics

Resolution

- In 2002, we carried out a number of trials in KV7 with the Minolta 700, a precursor to the Minolta 900. While results were in some cases quite satisfactory for documenting general epigraphic features, the 200x200 sample resolution was ultimately not sufficient to properly document the small carvings and hieroglyphs present in the tomb.
- Therefore, resolution became a key concern and we became convinced that we required sub-millimeter accuracy throughout our documentation of KV7 in order to capture necessarily details.

Speed of Use

- Since access to the tomb is limited, we were concerned with finding a way to maximize the total wall area we were able to scan during our field work.
- Since the Minolta 900's scan time is fixed, maximizing wall coverage depended mainly on:
  - Using a medium-angle lens
  - While we needed to move the scanner quickly throughout the tomb in order to cover ground efficiently, we also needed to keep the scanner perpendicular to the wall in order to maximize quality (see discussion in Section 2 above).

Therefore:

- We designed and built a simple rig that allowed the scanner to track vertically a set distance from the wall to be scanned—see Section D, "Methods", belowThis approach provided a significant improvement over a tripod mount in being able to maintain a consistent scan angle.

Robustness

- The punishing environment of KV7 is notoriously dusty, hot, and difficult to work in.
- Therefore we needed a scanner that could operate several hours a day in these conditions.

Analysis of the Minolta 900

Our work with the Minolta 900, as described above, allowed us to successfully complete the scope of work we planned. Following is a summary of the machine's performance during our field work:

Advantages:

- The Minolta 900 operated flawlessly in the difficult heat/dust environment of the tomb.
- The portability of the scanner allowed us to set up scan viewpoints reasonably quickly and easily.

Disadvantages:

- The presence of 3D data artifacts (described below) incurred processing time to correct.
- Standard optical triangulation deficiencies (see below) must be taken into consideration, as with any laser scanner that uses this method of 3D range finding.

Figure 6. Working with the Minolta 900.
Note the specially designed transparent plate on the bottom of the scanner—this on-site adjunction proved necessary to provide stability during shooting, the metal base of the scanner not being sturdy enough to avoid transmitting vibration during scanning.

Statistics, timing, efficiency

The Minolta 900 scanner captures:

- 640x480 3D measurements per scan
- Scan time is apprx. 2.5 seconds per scan
- Apprx. 5 second transfer time is needed following scan (either via SCSI or via PCMCIA flashcard)
- Color is captured at the scan resolution of 640x480

Operating Notes:

- The Minolta 900's depth of field is fixed at 200mm—which means it can only record depth readings within a 200mm Z-depth. Points that fall outside of this depth of field are simply discarded.
    - In KV7, the planar nature of the walls posed no problem whatsoever for the limited depth of field in the scanner. However, for more dimensional objects (such as our 2002 field work for the colossus of Ramesses II) the limited depth of field requires careful viewpoint planning in order to capture the entire form.
- The Minolta can be controlled remotely by a computer (via SCSI) or directly from the unit's back panel
    - For our field work, we found it fastest to use the scan controls directly on the back panel. Not only did it speed up the saving of data (which was written to PCMCIA cards) but it obviated the need for a control computer which would have had to move along with the scanner and tripod/rig in very difficult surroundings.

Field Mission Statistics:

- Average number of scans/hour: 14
- Average distance between adjacent points: 0.3 – 0.6 mm
- Total number of scans: 2300+

Techniques—Mounting and Shooting with the Minolta 900

During tests, we mounted the Minolta 900 onto a special tripod, as shown above and below. Tripod setups were the fastest we clocked, but the tilting angles required by the tripod introduced prominent 3D artifacts (the nature of these artifacts is discussed below).

Figure 7. Casondra Sobieralski (above) and Tom Lewis (below) working on a tripod base with the Minolta 900.

For the bulk of the scanning, then, we used a different technique: a specifically designed wooden "ladder" workbench that allowed the scanner to move vertically without having to point the scanner up or down. The ladder was reasonably easy to set up in the tomb, and allowed us to reach areas up to 20' off the ground without having to pivot the scanner.

Though we were generally able to cover the entire length of the wall without pivoting the scanner, the wall sections joining the floor had to be shot by slightly raising the sensor. As shown below, we found for example that a simple dustpan allowed us to quickly position, and re-position, scans where horizontal rotation was needed.

Figure 8. The Minolta 900 on a specially built rig allowing the scanner to remain perpendicular to the scanned surface (i.e., parallel with the surface normal of the resulting model).

Analysis of Data Quality

1. Consideration of Intrinsic Surface Qualities

Intrinsic surface qualities matter a great deal when considering the quality of optical triangulation scanning. Because of this, wall surfaces like those in KV7 are nearly ideal for many practical reasons we shall explore below.

In order to quantify the basic quality of the data, we will consider two main sources of error:

- errors derived from the object being scanned
- errors derived from the scanner itself.

We will treat the former first, since it applies to all optical triangulation scanning. Issues relating to the Minolta 900 itself will be explored in the following section.

First, we will reference an independent assessment of scan error from which to view our data in KV7. Brian Curless and Marc Levoy [1995] have identified four primary sources of error in laser scanning. These four error sources are listed below, with specific notes on KV7 indented.

- Varying surface reflection
    - KV7 is extremely isotropic in terms of surface reflection—there is very little variance in the intrinsic reflectivity of the wall surfaces throughout the tomb.
- Surface topology that diverges from planarity
    - Unlike most subjects for 3D scanning, the walls of KV7 are essentially planar, which greatly limits the impact of optical triangulation error.
- Occlusion of light paths to the sensor
    - Again, since KV7's wall are essentially planar, occlusion is not an issue.
- Incidence of laser speckle from sufficiently rough surfaces
    - The roughness of KV7's wall do not scatter laser light.

These four special cases are considered in the following figure:

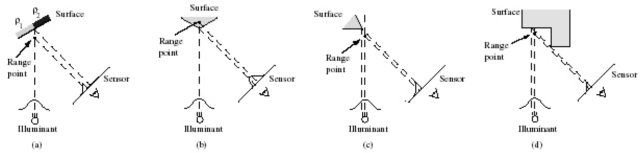

Figure 9. Marc Levoy and Brian Curless' examples of cases in which surface characteristics lead to errors in optical triangulation.

The effect of these errors is artifacts in the resulting 3D data. For instance, optical triangulation will incorrectly infer changes in reflectance as actual geometry, as shown below. A flat piece of paper with the word *"reflectance"* printed on it (a) is interpreted as an embossed 3D surface (b) in the resulting Cyberware laser scan data. The bottom panel (c) shows the results of Levoy/Curless Spacetime Analysis on the data in (b), effectively removing most of the erroneous geometry.

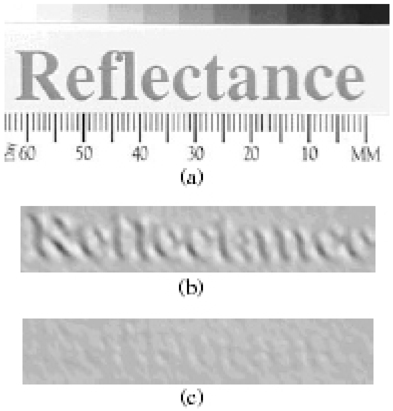

Figure 10. Levoy/Curless' example of optical triangulation error stemming from changes in surface reflectance.

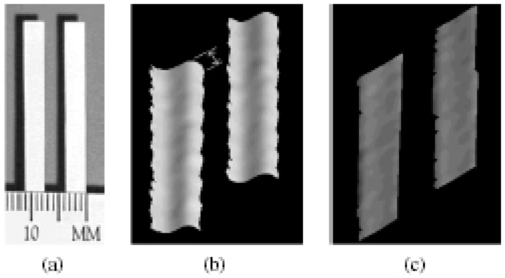

Figure 11. Another Levoy/Curless example of optical triangulation error, in this case showing a scan of two flat features that are incorrectly interpreted as curved surfaces.

Here we have briefly established that intrinsic surface characteristics matter a great deal in optical triangulation range finding. Viewed in these terms, the walls of KV7 are excellent for laser scanning. In fact, this is borne out in our data, where we see:

- low noise
- high resolution and clarity
- excellent dimensional fidelity.

The following figure shows a meshed view of 3D data (approximately 0.25 square meter) in KV7:

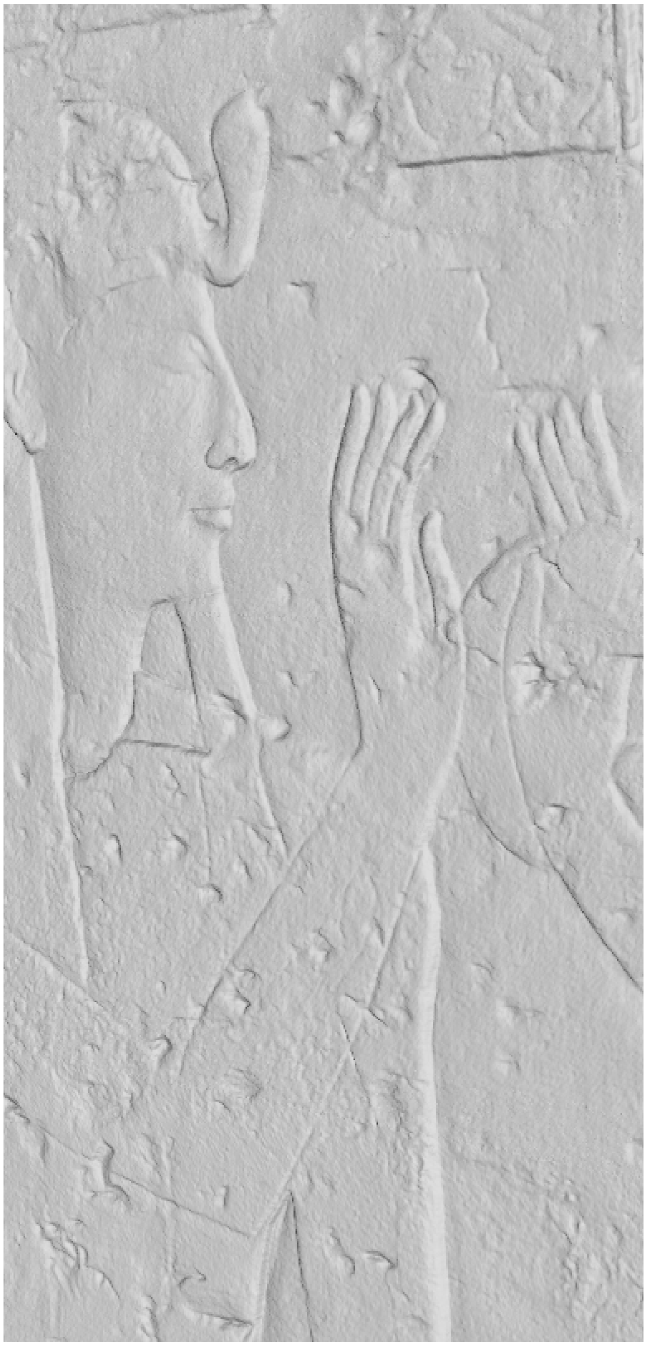

Figure 12. Sub-millimeter detail captured by the Minolta 900.
Note the sensitive detection of the faint scored lines that compose the arm in the center of the frame.

The preceding and following images show how, in general, we were able to acquire clean, artifact-free data. Below, note the exceptional detailing present in the salt-damaged areas to the right of the frame. In these areas it is easily possible to resolve sub-millimeter details.

Figure 13. Example of data quality.
The ideal surface characteristics of the KV7 walls allow clean, accurate optical triangulation data to be taken.

2. Artifacts in the data & computational solutions

Above we have detailed how surfaces must be considered when evaluating laser scan quality. We have also mentioned that there can be other sources of error—those introduced by optical triangulation. Levoy and Curless have identified several common limitations to laser scanners themselves. These limitations include:

- CCD noise Finite sensor resolution
- Optical blurring and electronic filtering
- Quantization errors
- Calibration errors
- Surface-surface inter-reflections

These kinds of errors are common to all optical triangulation systems. However, we will now explore errors specific to the Minolta 900, and briefly discuss algorithmic solutions for these artifacts.

The following figure shows a clearly visible scanner artifact.

Figure 14. Minolta 900 data artifacts.
Note repeating scan artifact that brings a textural quality to a flat surface.

Through experiment, we determined that these regular line patterns arise as a result of two combined factors:

- Scanner placement
  - Through testing we determined that the Minolta 900 performs best when the sensor is placed perpendicular to the scanned surface. When deflected by more than 15 degrees from the normal of the surface, scanner artifacts can be seen.
  - Laser strength
  - The Minolta 900 automatically samples the target surface before each scan, in order to determine the needed laser strength. Higher laser strengths introduce greater distortions but are needed if the CCD cannot read the laser due to high ambient lighting (i.e., sunlight) or if the surface is too dark for the CCD to properly track the laser beam.

With GSI, we have explored different ways to quantify these artifacts. Visualization data was added for Minolta data within GSI's software in order to see vertex and face normals. When displayed:

- Face normals from the Minolta data appear to vary ~15 degrees, which in turn causes vertex normal problems.
  - Vertex normals are more accurate than face normals, since they are averaged around the incident faces.

The apparent difficulty with face normals seems to account for the presence of these artifacts. The above description also suggests computational solutions:

- Global smoothing of vertex normals (without modifying the underlying geometry) remove the artifact
- A very light smoothing algorithm could be used to detect and erase these signature artifacts where present. Further work is in progress regarding implementation of this approach.

3. ***Consideration of other error sources***

In addition to the above, there are other sources of error deserving of consideration.

- Inverse-square law effects
  - Since light falls off at the square of its distance from a given object, this basic property of physics has an effect on the return of the laser light to the CCD. However, since the Minolta 900 operates at short distances from the subject of the scan, these effects are not significant for this scanner.
- Meshing errors
  - Creating a 3D mesh from a point cloud requires specific information about the viewpoint from which a scan was taken. Even when this information is known, there are a variety of approaches for generating surface meshes, and each can be considered to contribute its own unique errors.

3. Improving Speed and Accuracy in Optical Triangulation Scanning through 'Subdivision Scanning'

In the following section, we present a method for evaluating scan resolution and propose a technique for improving speed and accuracy that is based on our field experience with the Mensi GS-100 scanner. The former topic is treated first, below.

Defining 'Resolution' in 3D Scanning

Resolution is unquestionably the primary metric for all 3D scanning. Nonetheless this metric eludes quantification. Everyone who works with laser data is familiar with the vagaries of defining *"resolution"*. Below we offer some definitions on which to build our concept of *"Adjusted Resolution Index"*, or ARI, which will then be used as the foundation for a proposed technique.

1. Definitions:

- *Distance to Point* (DP): the linear distance from the lens to the point being measured, in millimeters.
- *Point Interval Value* (PIV): the averaged minimal regular spacing of 3D points for a set of measurements, in millimeters, forming the effective resolution limit for edge-length resolution, below.
- *Point accuracy* (PA): the intrinsic ability of a scanner to resolve a point in space, independent of the distance between points. Point accuracy is subject to inverse-square law falloff, as below:
- *Point falloff* (PFO): erosion of point accuracy as DP increases, according to the inverse square law, lens quality, and other effects.
- *Maximal grid resolution* (MGR): the UV framing grid used to define a given scan's viewpoint.

For instance, consider the following scan:

- PIV=1 mm
- PA=.5 mm
- MGR=10mm

While the grid resolution for this long range scan is set to 10mm, this spacing value will only be consistent for a plane extending in front of the scanner. (In the case of the GS-100, this would instead be a cylinder swept in XYZ space at a fixed distance from the pivoting GS-100 scan head.) Therefore, for non-conforming objects, the PIV will effectively change for each sample, creating much higher or lower values, some which may unintentionally dip below the scanner's intrinsic accuracy limits (PA).

2. Computational Terminology (Intrinsic to Correlation)

Minimal edge length resolution (MELR): the average linear distance between adjacent points in a point set

- Since adjacent vertices will be tesselated into triangular polys, ***edge length actually represents a real limit to resolution.***

ICP resolution (ICPR): the effective resolution to which ICP can generate meaningful solutions

* In most ICP approaches, edge length (delta from vertex location A to vertex location B) represents a real limit to the resolution of a merged point cloud.
    - The GSI Studio approach allows registration of meshes at points other than vertices, enabling sub-edge-length registration.

Confidence and Intrinsic Surface Characteristics

Since all laser data is dependent on the surface characteristics of real-world objects, there can be no objective consideration of scan *"resolution"* without factoring in the intrinsic qualities of the scanned surface(s).

1. Composite Surfaces

The above is complicated by composite materials, where specularity, color or lacunarity change across a "limb", as shown below. Computational sensitivity is especially required in optical triangulation systems, since color limbs across flat planes (i.e., black writing on a white sheet of paper) can in fact be interpreted as a Z displacement. (See notes below on Levoy's Space/Time Analysis for expansion)

Reprocessing algorithms are needed to compensate for these artifacts.

Desired homogenous, isotropic surfaces

The scanned surfaces in KV7 were nearly ideal in terms of isotropism and surface characteristics. Specifically, the walls of KV7 exhibit:

- Light surface color, excellent laser return (allowing minimal laser levels and therefore minimal noise/distortion).
- Extremely homogenous surface color.
- Low specularity.
- Nearly total control of ambient light. In the same way that light-colored walls allowed the Minolta 900 to scan at lower laser power and therefore with less noise, the fact of KV7's underground location allowed nearly total control of lighting.

Adjusted registration index (ARI)

As noted above, *"resolution"* is a term without a fixed identity for laser scan data. Therefore, we would like to suggest a new metric, called *"adjusted registration index"* or ARI, for appropriately quantifying the actual registration of scan data,. Whereas "confidence" is generally expressed as a per-vertex value, here we suggest assigning ARI for a set of points.

1. Per-point values:

- *Confidence scalar* (Conf)r: 0 to 1 (0=scan angle parallel to given surface (perpendicular to normal), 1=scan angle perpendicular to given surface, parallel with normal)
- *Gain threshold* (Gain): 0 to 1 (0=device-dependent limit at which intrinsic light return/ambient lighting blind the CCD to incoming sensor laser light, 1=perfect return of laser to CCD)
- *Specularity scalar* (Spec): 0 to 1 (0=nominal gain threshold, 1=perfect light return of laser to CCD)

1. Computing global ARI from a group of points, 1…n:

$$\frac{\sum_{i=1}^{n} PIV_i PIV_n \left(\frac{PA}{2}\right)}{Spec_{average}\left(Conf_{average}\right) + Gain_{average}^{\,2}} - \left(\sum_{i=1}^{n} DP_i DP_n\right)^2$$

ARI values can be used to filter point data for low-confidence points, as discussed below.

Subdivision Scanning: capturing polyresolution samples

During scanner viewpoint framing, all current scan control software (Mensi, Minolta, Cyra, Quantapoint, Eyetronics) assumes:

- A uniform bounding box selection (parametric UxV) within an XYZ world.

Here we suggest scanner control that does not make this assumption, but instead uses active parsing of incoming points (using ARI, above) to enable automated, “subdivided” scan viewpoint framing.

Our approach includes three main ideas intended to increase scan speed, accuracy, and enable higher-confidence registration.

1. AGI-based ICP for long range scanning

Classical target registration (i.e., Mensi’s entity registration) allows correlation of two viewpoints sharing three or more points in common. Mensi, for instance, has used spheres for entity registration since the S-series and is now pushing towards the use of reflective targets.

ICP registration, of the other hand, does not rely on specific entities for registration but instead uses a user-defined percentage of the total point set.

Below we briefly summarize the key strengths and weaknesses of targeting vs. ICP.

2. Benefits of targeting techniques

* Targets are independent of object scan resolution, enabling quick, low-res scans of large area while maintaining high-resolution areas needed to correlate multiple views.

3. Drawbacks of targeting

* Since all registration information is drawn from a small number of points, registration quality is totally dependent on the scan quality of these regions.

4. Benefits of ICP

* ICP registration is a robust technique for achieving

5. Drawbacks of ICP

* Quality of the final registration is subject to suitability of incoming data

Auto-generation of targets using ARI

Here we propose using ARI (above) to parse incoming points and make automated polyresolution scans using this data:

1. Frame scans as before (isotropic bounding box, top left XYZ, bottom right XYZ)
2. Scan all points, resulting in point list L
3. Compute ARI for L
4. Filter point list, resulting in new point list NL
    a. NL=10% L, selecting 10% of L approaching value 1.0
5. Automatically segment L into sub-viewpoints based on NL
    a. Create new framing list FL by centering on individual points from NL
    b. Consider overlapping bounding boxes in FL and conflate as possible, creating a minimum set of new bounding regions (NS)
6. Scan NS set at user-specified point interval.

This approach differs from that of entity/target registration in the following ways:

1. ICP is able to make use of more points, and points at greater distance from each other than (usually) practical when using target registration.

2. ICP obviates the need for target placement and removal.

3. By using less localized spatial areas, ICP is less subject to poor laser reflectance/pickup in areas of the scan data.

Resolving penalties

We propose that polyresolution points should appear in marquee for the user at the end of a given scan. The user could then delete polyresolution point groups as needed.

'Reverse Decimation': using depth cues to refine resolution and find edges

Since the measurement of edge length between vertices in many cases defines minimum actual resolution, increasing the distance between points necessarily reduces the ability to perform high-confidence viewpoint registration. This is especially true when multiple viewpoints must be combined in succession: in these cases, error is multiplied through the chain.

In general, we believe that there are many good reasons to sample large scenes at relatively low resolution. In the case of our scanning at the Ramesseum, our broad goal was to establish architectural plan, section, and elevations of a site many hundreds of meters in dimension.

For a very detailed plan view, acceptable resolution is roughly equivalent to the width of the lines present on a 24'x36' architect's drawing. In real terms this resolution is approximately PIV of 10 millimeters.

Even through we were able to acquire points rapidly (~1000 points/sec using the Mensi GS-100), it was still not practical to scan the entire site at PIV of 10 millimeters--although some data was collected at this resolution. The technique below proposes a refining technique that could provide, for instance, 10mm detail within a general 100mm scan. Thus, this is a poly-resolution approach that aims to concentrate detail only where it is especially needed.

User-defined framing input consists of:

1. BB=Bounding box in XYZ space
2. Ux, Vx=General angular resolution (U, V) for basis scan
2. PIVtarget=PIV for edges/detail areas
3. RT=Threshold in linear units for triggering automated scan refinement

Evaluation:

```
1. Point-by-point evaluation of Z-depth during scan
    a. Uprev, Vprev = previously clocked data point (ignoring depth)
    b. Ucurrent, Vcurrent = current data point (ignoring depth)
    b. Where delta UVprev UV current > BB:
        1. reset laser to UVprev
        2. frame from UVprev to UVcurrent at PIVtarget
        3. scan framed region, then continue (loop to 1. above)
```

This technique allows the user to frame general, low-res viewpoints while maintaining high accuracy at geometric boundaries.

Working with the 3D Archive

Software development

Technically, the most crucial aspect of our 2003 field work was the deployment of a new suite of laser scanning and control tools. Our two part goal was:

1. To develop stronger and faster tools for alignment and merging of an extremely large number of meshes
2. To perform these operations in the field as a way of checking the validity of our laser scanning work.

Both topics will be briefly considered below.

1. Align & merge process

Via Geometry Systems Inc., Marc Levoy's pioneering ICP (iterative closest point) registration tools were added into an entirely new application framework. The system allows the user to quickly align two meshes and then use Stanford's ICP code to seek the optimal fine alignment of the meshes.

This software successfully allowed us to be able to work with models containing many hundreds of millions of polygons. However, this process remains dependent on careful processing and still requires a great deal of operator time to examine the data as it is registered. The following figure shows the kind of slight registration error that, for now, can only be detected by human eyes.

Figure 15. Improper 3D Registration.
Note the doubled features in the center of the image, a clear indication that the ICP results were not correct.

2. On-Site Align and Merge

As mentioned above, the second important goal for our software field work was the ability to perform sophisticated align/merge operations in the field on portable equipment. In order to be able to handle the demands of large models, we brought small, portable PCs built around Intel Pentium 4 2.8 GHz chips. These machines, then, were used to test align/merge data as it was being recording elsewhere in the tomb.

We found that, under ideal circumstances, it was possible for one person to be able to test align meshes as quickly as they could be shot by a team of three people. This was crucial to the success of our overall mission, since it allowed us to monitor the quality of the data we were shooting almost in real time and see if any regions of the KV7 walls were being inadvertently missed in the scanning process.

Figure 16. A portable workstation in the burial chamber.

Software development with GSI

For a note on the hardware we used in January 2003, see Appendix A.

INSIGHT is currently working with commercial hardware and software vendors to help develop faster, easier workflows for our extremely challenging production situations. In January 2003, we used a new laser scanning control system in Egypt that was created with the cooperation of Minolta Corp., who is providing the laser scanner and its control architecture, and Geometry Systems Inc. (GSI), who is writing custom code to control the scanner according to our detailed specifications.

1. *Software Today*
   a. Software authored by laser scan manufacturers
      RealWorks & Pointworks+Survey (Mensi), CGP Suite (Cyra), Polygon Editing Tool (Minolta)…

   b. Third-party development
      Paraform, GeoMARIc Studio, FreeForm, Maya, et cetera

The vibrant third-party applications community attests to an unmet demand from laser scan users. Scanner manufacturers being (rightly) focused on hardware development, it is thus unsurprising that third-party software developers have been able to create dramatically more efficient software by concentrating on the missing elements of the user's experience.

2. *Software, the Near Future*

Increasingly, we hope that the companies who create scanners will embrace the evolution of third-party tools by supplying software development kits and other relevant support tools. Not only would this help solve the currently unacceptable state of tool development, it would save engineering time for scanner manufacturers.

To summarize, from our viewpoint (sic):

* Increasingly, scanner equipment companies ought to concentrate on maintaining robust SDKs
   o These SDKs / DLLs / APIs should be freely available (Mensi has graciously provided code for the .SOI format in this way)
   o Companies also should spur development by publishing the architecture used for their scan data formats

3. *Current Development*
   o We are currently considering ways to implement the computational strategies outlined in this brief paper, alongside our effort to align and merge the models from our 2003 field work.

4. Continuing Work

The following schedule outlines our continuing work:

Processing and Final Output Schedule

Dates	*Activity*	*Location*	*Specific Work*
January 20-February 15, 2003	Rough Modeling	Oakland, CA	Registration of 3D data
February 16-March 21, 2003	Fine Modeling	Oakland, CA	Texturing of 3D models
Monday, March 24, 2003	Draft Presentation to EdF	Paris / Oakland	via Internet, DVD
March 24-April 4, 2003	EdF Review Period	Paris / Oakland	-
Monday, April 7, 2003	EdF Comments to INSIGHT	Paris / Oakland	-
April 8, 2003-July 25, 2003	Second Round 3D modeling	Oakland, CA	Detailed modeling
Monday, July 28, 2003	2nd Presentation to EdF	Paris / Oakland	via Internet, DVD
July 29-September 26, 2003	Bilateral review	Paris / Oakland	
September 27-November 14, 2003	3D model completion	Oakland, CA	Addressing final needs
Monday, November 17, 2003	Presentation of final models, "2003 Field Work Final Report"	Paris / Oakland	

Figure 17. Proposed Schedule.

Our scanning projects in Thebes will culminate in the following forms:

A. Browsable web output (2D images)
   o The scan data gathered in KV7 will be browsable via a Java interactive interface
      ▪ This work requires
         - Integration of the digital photography with laser scan data

Since the walls of KV7 are essentially flat, it is possible to give a good sense for the final 3D models via 2D still images.

The pipeline for final rendering of our 3D models will be a radiosity-based renderer, in order to make full use of sophisticated lighting.

B. Interactive web output (3D models)

1. We will also publish select parts of the tomb as true 3D models
2. In this cases, we will use "Octree" voxel viewer format, since this is an openly supported, free viewer format.

B. Graphics Research

- "Epigraphic Curve Extraction" code to develop publication-quality line drawings from 3D laser scan data
  - This work still requires research and coding

C. GIS Publication (ECAI)

1. Finally, we will connect our detailed 3D scans to simple GIS waypoints, so that our database can be readily included in ECAI's comprehensive world heritage GIS database.

5 Appendices

A. Hardware Notes

During January 2003 we gathered more than 600 million measurements from the tomb and temple of Ramesses II. Naturally, it takes an incredible amount of CPU power to be able to gather and work with this huge archive. Synthesizing the hundreds of millions of 3D points into viewable models requires a staggering amount of computing power.

In previous seasons, the sheer size of the computing challenge required many months to parse all the data we gathered in the field. With current hardware, we were able to do this work in the field, which allowed us to verify the quality of our work and optimize our techniques. For processing 3D data, we used Intel's 1845E Hyper-threading Desktop Board and Intel 2.8 GHz chips.

The following is a brief description of our on-site setup:

- In our lab, we used a wireless ethernet network to connect our Pentium4 Desktop PCs to the roving laptops, DVD burners, video projectors, digital wallets, and more.
- In the field and back in the lab, we used USB-2 solid state drives to "sneaker net" files.
- Pentium 4 PCs were frequently used to capture DV video via 1394 (FireWire). In the field we used DV cameras: the Canon XL-1, Canon GL-2, and Panasonic 24P D100.
- As we were generating 3D data every day, burning DVD-R discs was a necessary part of our backup regimen.

Figure 18. At work on the data in our field lab.

B. Data migration planning, archive

A full report will be prepared by November 17, 2003 in conjunction with our publication of 2003 data.

C. Resources for portable scanning

Written by Brett Bowman, INSIGHT Engineering Advisor

Delivering reliable AC power to laser scanners at remote archaeological sites in developing countries can be difficult. Even if an extension cord will reach your intended scan site, the power delivered may be of poor quality, containing spikes, brownouts, or blackouts. Low quality power can damage the scanner, corrupt data, and waste your precious time in the field. Under these conditions using battery power has significant advantages over using wall power. Battery systems provide consistent, high-quality power without the AC leash, are easy to purchase from automotive stores, can be installed with plug-and-play ease, and costs less than $250. Given the high cost of wasted time, the minimal expense and effort required to set up a battery system could be an excellent investment.

Using a battery system does not remove reliance on wall AC completely. Even the largest batteries can only power a typical laser scanner for about 15 hours, so recharging the battery from the wall is required every one or two days of work.

There are three off-the-shelf components that make up a battery system: a battery, an inverter, and a charger, plus the included connecting cables.

The battery. The most cost-efficient battery to use is a Deep Cycle Marine lead-acid battery. A cousin of the standard automotive battery, the "deep cycle" type tolerates complete draining without damage much better than a standard car battery. The key property of the battery is its Amp-hour rating, a measurement of energy capacity where larger is better. Batteries rated at 100 Amp-hours are commonly available, and will power a scanner for about 15 hours of continuous use. This battery's size and weight is slightly larger than that of a standard 12V car battery. For maximum transportability, a smaller Amp-hour battery may be selected, although the working time will be proportionally diminished.

Deep cycle marine batteries are available at Sears, West Marine, and well-stocked hardware or automotive stores. A typical example is the Sears Die Hard Marine Starting and Deep Cycle/RV, Model #27582, price $84.00. Sometimes the battery Amp-hour rating is not listed on the packARIng, but it should be listed in the salesperson's reference materials. (CCA, or cold cranking amps, is a common rating but is not equivalent to Amp-hours.)

The inverter. An inverter is an electronic device that allows wall-powered equipment to be powered from a car's cigarette lighter. The inverter converts the battery's 12 Volt DC output into 120V AC output (or 240V for European inverters). The key property of the inverter is its wattage rating, which needs to match or exceed the wattage rating of the equipment it is powering (for a laser scanner, about 100W is sufficient). Additionally, for ease of connection, the inverter should have alligator clamps that attach directly to the battery terminal posts (rather than to a car's cigarette lighter, which is more common).

Inverters are available at most automotive supply or general electronics supply stores. A 300W capacity inverter costs about $50. Check to be sure alligator clamp connectors to the battery are supplied.

The charger. A standard car battery charger is used to recharge the deep cycle marine battery. Because of the need to charge the 115 Amp-hour battery overnight, a charger with a 12 Amp charge setting is required (allowing it to charge the 115A-h battery in about 10 hours).

A 12V automotive battery charger with a 12 Amp charge rate and an indicator to monitor the battery charge progress are available at any automotive supply store for about $70.

The cables. Cables A and B connect the charger to the wall AC and to the battery, and are supplied with the charger. The inverter purchased should have clamps that attach directly to the battery posts for cable C. Cable D is the scanner's standard power cable, which plugs into a wall-AC type outlet on the inverter.

All of the components are of- the-shelf, so there is no knowledge of electronics or specialty wiring required. The most important part of the system setup is making sure that the B and C cables are correctly attached to the matching battery terminals (red = positive, black = negative). For battery transportation ease, consider also purchasing a portable toolbox with top carrying handle that the battery can fit into.

References

LEVOY, M., CURLESS, B.. 1995. Better Optical Triangulation through Spacetime Analysis. In *ICCV 1995.*

LEVOY, M., PULLI, K., CURLESS, B., RUSINKIEWICZ, S., KOLLER, D., PEREIRA, L., GINZTON, M., ANDERSON, S., DAVIS, J., GINSBERG, J., SHADE, J., AND FULK, D. 2000. The Digital Michelangelo Project. In *Proceedings of SIGGRAPH 2000*, ACM Press / ACM SIGGRAPH, New York, K. Akeley, Ed., Computer Graphics Proceedings, Annual Conference Series, ACM, 131–144.

[*] E-mail: philippe@insightdigital.org
[†] E-mail: kevin@insightdigital.org
[‡] E-mail: brett@insightdigital.org