4th International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage
VAST (2003)
D. Arnold, A. Chalmers, F. Niccolucci (Editors)

Digital Reunification of the Parthenon and its Sculptures

Jessi Stumpfel, Christopher Tchou, Nathan Yun, Philippe Martinez*, Timothy Hawkins,
Andrew Jones, Brian Emerson, Paul Debevec

University of Southern California, Institute for Creative Technologies
*UMR 8546 du CNRS, AOROC, École Normale Supérieure.

Abstract

The location, condition, and number of the Parthenon sculptures present a considerable challenge to archeologists and researchers studying this monument. Although the Parthenon proudly stands on the Athenian Acropolis after nearly 2,500 years, many of its sculptures have been damaged or lost. Since the end of the 18th century, its surviving sculptural decorations have been scattered to museums around the world. We propose a strategy for digitally capturing a large number of sculptures while minimizing impact on site and working under time and resource constraints. Our system employs a custom structured light scanner and adapted techniques for organizing, aligning and merging the data. In particular this paper details our effort to digitally record the Parthenon sculpture collection in the Basel Skulpturhalle museum, which exhibits plaster casts of most of the known existing pediments, metopes, and frieze. We demonstrate our results by virtually placing the scanned sculptures on the Parthenon.

Keywords:
3D scanning, archaeology, reconstruction, sculptures, structured light, Parthenon

1. Introduction

The Parthenon, set on the Athenian Acropolis, remains one of the most powerful visual symbols left by Antiquity to the modern world. To many, it is linked to the very roots of classical aesthetics, democracy and western culture. On the eve of the 21st century, this symbol is but a shadow of its long lost splendor. The Acropolis, while still a marvel to behold, is a ruin that has been depleted of most of its riches through the passing of time. Over the centuries, it has been in turn remodeled, neglected, destroyed, passionately dismantled and forcefully restored, each of these stages changing our appreciation of its original nature.

Trying to understand this monument is rendered more difficult by the fact that its remains now lie scattered around the world. Despite the publication of more than a hundred volumes and the construction of a few fair but miniature replicas, it is still hard to comprehend the visual impact of the Parthenon in its unblemished state.

The main goal of this project has been to create digital models of all of the sculptures of the Parthenon. These virtual sculptures could then be used to create a renewed experience placed as a complete set on digital representations of the Parthenon.

Figure 1: *This model of south metope 29 depicts a centaur abducting a Lapith woman. It was assembled from 14 individual scans, and rendered with global illumination using the Arnold renderer.*

Apart from being reunited with the ruin to which they belong, these digital models could also be used as a starting point for new validated trials in realistic reconstruction of damaged or lost parts in virtual space, thus bringing us one step closer to the unattainable dream of seeing the Parthenon as it once stood.

While trying to take advantage of recent developments in computer graphics technologies, we also decided to make the project as efficient as possible in terms of expense, labor, and time, hoping that the lessons learned along the way would prove useful for the archaeological community.

In the face of these conditions, traveling the world in search of the preserved original Parthenon sculptures proved unrealistic. To be able to work quickly and at low cost, we were fortunate to gain access to the Basel Skulpturhalle in Switzerland. This museum features a collection of high quality plaster casts of nearly every known existing piece of Parthenon sculpture. This collection is a key resource in the study of the sculptures; only there can they be seen together as a set. This paper aims to describe the conditions of our digital survey of the Basel Parthenon collections and the results we have been able to achieve to date.

1.1 Previous Work

Other researchers have acquired 3D models of sculptural works in the past few years using a variety of methods. In 1995, Electricité de France was one of the first to envision how 3D laser scanning could be applied to cultural artifacts and monuments. They gathered data on a prehistoric painted cave as well as the decoration of the Tholos at Delphi [Bommelaer 1996]. The Visual Computing Group at CNR Pisa has applied structured light scanning to statues and developed an efficent suite of tools to process scan data into complete models [Callieri 2003]. Using structured light in conjunction with photometric information, Holly Rushmeier et al. at IBM Watson scanned several statues under field conditions to sub-millimeter resolution [Rushmeier 1998]. The Digital Michelangelo project at Stanford University has captured the largest such dataset to date, using a modified Cyberware laser stripe scanner to scan a number of statues [Levoy 2000]. Other recent scanning projects include the Digital Buddha Project at the University of Tokyo [Miyazaki 2000] and the Canadian National Research Council’s museum artifacts project [Baribeau 1996]. Approaches employing structure-from-motion computer vision techniques [Pollefeys 1999], have allowed 3D scan data to be captured, with limited but nonetheless impressive resolution, by simply moving a hand-held video camera around an object .

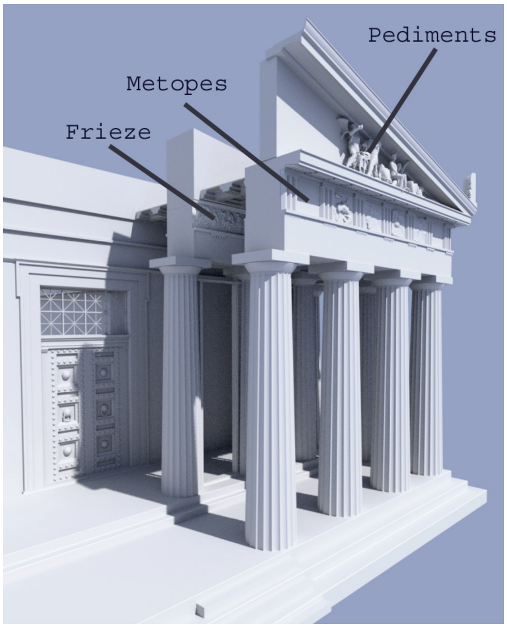


Figure 2: *Cut-away model of the Parthenon, illustrating the original placement of the scanned sculptures.*

1.2 The Parthenon and its Sculptures

The Parthenon was erected during the 5th Century B.C., replacing an earlier project that was ransacked by Persian invaders before completion. Dedicated to the goddess Athena, it was her most magnificent monumental offering. The numerous decorations on the Parthenon, thought to depict various Greek myths, historical events, and stories, provided the temple with complex sculptural narratives, making it impossible for modern beholders to understand the temple solely through its architecture and spatial deployment.

Three major groups of Parthenon sculptural decorations still survive today: the pediment sculptures, the metopes, and the frieze (Figure 2). Once towering above both facades of the temple, the pediment sculptures are larger-than-life free standing figures. Each pediment develops a single iconographic theme, while being constrained to the typical triangular shape. The central characters would have stood up to 5 meters high. Today, most of the preserved pediment sculptures exist only as fragments. It is generally agreed, thanks to Pausanias' ancient account, that the east pediment depicted the miraculous birth of Athena from the head of Zeus, and the west represents the fight between Athena and Poseidon over the possession of Attica [Tournikiotis 1994, p. 103, 110].

The Doric frieze, set on the entablature above the outer colonnade, is composed of metopes separated by triglyphs: simple carved panels bearing three vertical ridges [Jenkins 1994, p. 9]. The metopes measured 1.2 meters high, and averaged 1.25 meters in width. While the best preserved metopes, originally set along the south face, depict a battle between the Greek Lapith tribe and the semi-divine but barbarous centaurs (Figure 1), the northern metopes show episodes of the Trojan War. In a similar parallel mode, the east metopes described the battle between the Gods and the Giants, while its human counterpart in the west portrays the war of the Athenians against the Amazons. The whole program thus revolves around the eternal victory of the order brought by the Greek gods and the Greeks, and of course mainly the Athenians, over the barbarous and chaotic beings and nations that threaten the Greek world and cosmos [Jenkins 1994, p. 9].

The Ionic frieze, considered by some to be the most unique and refined of the Parthenon sculptures, was carved into the entablature of the inner façade colonnade and on the upper outside part of the cella walls. Carved in low relief, the frieze sculptures stand about one meter tall, and once ran continuously for over 160 meters around the four sides of the Parthenon. Though its iconography remains open to subtle debates, the frieze is believed to depict the Panathenaic Procession, a yearly festival revolving around the renewal of the ritual necessaries of the cult of Athena. Under the gaze of the assembled Gods, various portions of the frieze show an almost never ending parade of soldiers, offering-bearers, and sacrificial animals. Interestingly the procession moves in two parallel but somewhat unequal lines, beginning from the south-west, to finally meet in the middle of the eastern façade. They thus seem to represent the festive crowd moving along the sides of the Parthenon to deliver to their Goddess her new garments and servants for the year. These sculptures thus have to be placed in their ancient spatial setting if one wants to understand their relationship to the monument. For example, the frieze was set high up under the main portico running around the temple. Once the scaffolding used to carve the frieze directly into the blocks of the Parthenon was removed, the sculptures would have only been visible from below, partially occluded by the outer colonnade and almost invisible in the shadow [Jenkins 1994, p. 19].

1.3 Historical Background

Over the centuries, the Parthenon has changed greatly. Athens, facing difficult financial times, depleted the sanctuary of most of its valuable riches and metal adornments. During the 3rd century B.C., the temple was destroyed by fire and then minimally restored by an impoverished state. The new roof covered only the central space, exposing the ionic frieze to the sun.

Figure 3: *This section of the Ionic frieze is east block VII from the Louvre in Paris. It is rendered here with subsurface scattering.*

When it was turned into a church in the 6th century A.D., the temple went through architectural modification. As a cathedral, the Parthenon was now meant to receive a congregation and thus needed light. High windows were carved through the walls. Most of them cut without hesitation through the ionic frieze. At the same time, the east pediment was dismantled, and most of the north, west and east metopes were defaced or reworked to suit Christian imagery.

Falling under Ottoman rule, the temple/cathedral was then turned into a mosque, where it suffered more from neglect than radical changes. Athens was now a small city set in the backwaters of the Turkish Empire. But the Acropolis remained a tactical place, and a Turkish garrison used it as its stronghold. In 1687 the Parthenon, being used as a storehouse for gunpowder, came under bombardment by the Venetian fleet; an incoming cannonball ignited the gunpowder and large sections of the north and south frieze, as well as significant portions of the building, were destroyed in a catastrophic explosion [Korres 1990]. While a small mosque was built at the center of the destroyed structure, the Parthenon was now just another ruin in what was left of ancient Athens. It then became the prey of aesthetes and collectors from Northern Europe.

Over time nearly all of the sculptural decorations were removed from the Parthenon. Through the zeal of Lord Elgin’s agents, over half of the existing sculptures are now held in the British Museum in London, but a number of other museums hold pieces as well. These include the Louvre in Paris, the National Museum in Copenhagen, the Kunsthistorisches Museum in Vienna, and the Vatican Museum in Rome. The rest of the original sculptures have remained in close proximity, now housed at the Acropolis Museum in Athens to escape the modern effects of air pollution.

Ernst Berger, once the director of the Basel Skulpturhalle in Switzerland, spent over 20 years assembling a uniquely complete collection of casts representing the Parthenon sculptures in their best known preserved state. This made our task possible by consolidating these sculptures in a single space.

2. Data acquisition

Due to limited time and funding, our scanning was restricted to just five days in Basel. We adopted a methodology of systematically scanning the sculptures in order to capture as much data as possible. For example, in the case of the frieze, the blocks are arranged lengthwise in the museum, allowing us to take the scans at regularly spaced intervals. We scanned the frieze at 100 cm intervals from four angles: from the top as in Figure 4, as well as from below, from the left, and from the right. We also took straight on scans at 50 cm intervals. The south metopes were each scanned from 14 predefined angles. The east, west, and north metopes in their current state have lost most of their high relief features. These were scanned from 8-14 angles each. In Basel, the Pediments fragments have been placed in Styrofoam reconstructions of what is known and conjectured of the missing pieces. Because of the limited time and the complexity in separating each piece from its neighbors, these were scanned as a set from positions in front of the display.

Using our scanning system and methodology, we were able to scan the 160 linear meters of frieze, 52 metopes, a caryatid column from the Erectheion, and partially scan both pediments, totaling nearly 2,200 individual scans. This is equivalent to scanning nearly one sculpture per person per hour over the entire trip.

2.1 Scanner Design

To scan the sculptures, we required a scanning system that was portable, fast, flexible, and provided good detail at a resolution of approximately 1 mm. To meet our scanning goals, we designed and constructed a custom structured light scanner, similar to the systems used in [Callieri 2003] and [Rushmeier 1998]. Built from off-the-shelf components, the scanner consists of a camera and projector connected to a portable computer and attached to a reconfigurable mounting system as seen in Figure 5.

Figure 4: *Scanning a panel of the east frieze from above. The scanner was designed to be flexible and easy to operate with a minimum of personnel.*

Figure 5: *The re-configurable structured light scanning gantry consisted of a digital camera, a projector and a tri-pod mounting system.*

As we had a team of four people in Basel, it was important that the scanner be easy to operate with a minimum of personnel. While only one person is required to operate the scanner, it proved faster to have one person position the camera-projector gantry and another operate the computer. We also documented capture positions and methods through video and measurements, allowing us to later reconstruct the sequence of scanning events from the trip.

The basic operation of the scanner involves displaying a sequence of patterns from the projector and using the video camera, recording the image of each pattern as it falls onto the surface of the subject. The patterns uniquely identify each pixel in the projector; this allows the identification of corresponding camera and projector pixels that 'view' the same point on the surface of the subject. Then, given a calibration describing the position, orientation and distortion of the camera and projector, these correspondences can be used to triangulate the 3D position of the surface points.

In our system, we chose the Pulnix TM-1040 black and white digital video camera; its uncompressed frame capture at a resolution of 984 x 1010 gave us sufficient detail to cover the frieze to the required accuracy, while its capture rate of up to 30 frames per second made the scanning process quick. The camera's variable exposure was critical in synchronizing each camera frame to the 120 Hz rotation of the color wheel in the projector, ensuring a constant light intensity despite the quickly switching colors emitted by the projector.

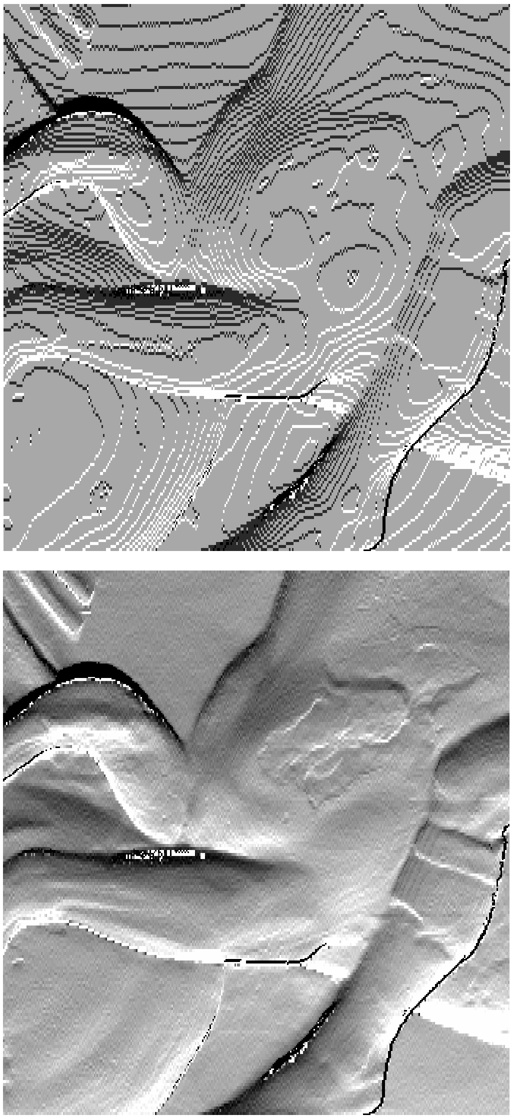
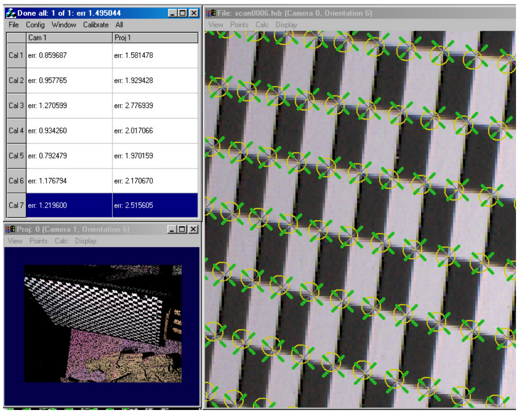


Figure 6: *By analyzing the intensity of the camera pixels it is possible to determine correspondences to sub-pixel resolution (below), extracting much more detail out of the scans.*



	Cam 1	Proj 1
Cal 1	err: 0.859687	err: 1.581478
Cal 2	err: 0.957765	err: 1.929428
Cal 3	err: 1.270599	err: 2.776939
Cal 4	err: 0.934260	err: 2.017066
Cal 5	err: 0.792479	err: 1.970159
Cal 6	err: 1.176794	err: 2.170670
Cal 7	err: 1.219600	err: 2.515605

Figure 7: *A calibration program was created to assist in solving for the internal and external parameters of our scanning system.*

For scanning purposes, a color camera is not ideal; the increased data rate of a true color '3-chip' camera would slow down the scanning process, and the artifacts introduced by Bayer-pattern cameras would decrease accuracy. Even with the black-and-white camera, we found that we were able to record full-color reflectance information by separately projecting red, green, and blue light from the projector, and then combining the three resulting grayscale images into an RGB image.

For the projector, we chose to use the Proxima Ultralight x350 DLP projector. Aside from being one of the smallest and lightest projectors available at the time, its digital input, fast pixel transition speed, and nearly unpolarized light output made it suitable for quickly achieving high quality scans.

The mounting system was designed for maximum flexibility and ease of use. The camera and projector were attached to FOBA ball-joint mounts to allow them to rotate to nearly any angle and be locked down securely. These two mounts were fixed to a steel rod attached to a third ball-joint mount. This scanning head could be attached to a tripod capable of extending to over 3 meters in height, or attached directly to the tripod's wheel base for low-angle scanning.

The system was capable of capturing a 3D scan of nearly one million points in 15-30 seconds, depending on the exposure settings of the camera. The scanning time could be reduced by using a projector capable of producing more light; however such a projector would at the time have been larger and less flexible.

By analyzing the pixel intensities in the captured structured light patterns and modeling the intensity curve in the transition from one pixel to the next, it was possible to generate correspondences between the camera and projector pixels accurate to a sub-pixel level.

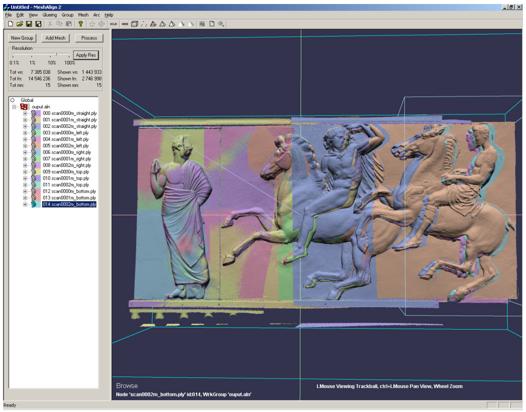
These methods, as described in [Tchou 2002], resulted in a depth resolution of better than 0.2 mm at each point, as visible in Figure 6.

2.2 Calibration

Because we needed to aim and focus our scanner on the sculptures from different angles as we moved around the museum, the mounting system was reconfigured many times. Each time we changed the spatial relationship between the camera and projector or their internal parameters, we needed to calibrate the scanner. Our scan calibration process involved scanning a flat checkerboard grid pattern in several orientations, allowing us to solve for the distortion characteristics and the relative orientation of the camera and projector using a method described by [Zhang 2000]. We developed an application to automatically detect the corners of the checkerboard and optimize the sixteen internal and six external parameters of the calibration while displaying the results visually (Figure 7).

3. Data processing

After scanning was complete, the first step in processing the raw scan data was to automatically generate an HTML index that associated the combined color reflectance images with the raw scan data. This catalog allowed us to quickly identify calibrations and individual scans for processing.



Tot vn: 7 385 038 Shown vn: 1 443 933
Tot fn: 14 546 236 Shown fn: 2 746 998
Tot mn: 15 Shown mn: 15

ouput.aln
000 scan0000m_straight.ply
001 scan0001m_straight.ply
002 scan0002m_straight.ply
003 scan0000m_left.ply
004 scan0001m_left.ply
005 scan0002m_left.ply
006 scan0000m_right.ply
007 scan0001m_right.ply
008 scan0002m_right.ply
009 scan0000m_top.ply
010 scan0001m_top.ply
011 scan0002m_top.ply
012 scan0000m_bottom.ply
013 scan0001m_bottom.ply
014 scan0002m_bottom.ply

Node 'scan0002m_bottom.ply' id:014, WrkGroup 'ouput.aln'

LMouse Viewing Trackball, ctrl+LMouse Pan View, Wheel Zoom

Figure 8: *MeshAlign 2.0, written by CNR Pisa, was used to align the scans. In the case of the frieze here, an automatic initial alignment is used.*

The raw scans captured extraneous surfaces, which we did not want to merge into our completed models. This undesired geometry included adjacent sculptures, display mounting, and out of focus regions. Since our individual scans were on the order of two million triangles, displaying and masking the geometry in 3D was prohibitively time consuming. We found it was faster to mask out geometry in the 2D camera image space before the scans were converted to 3D meshes.

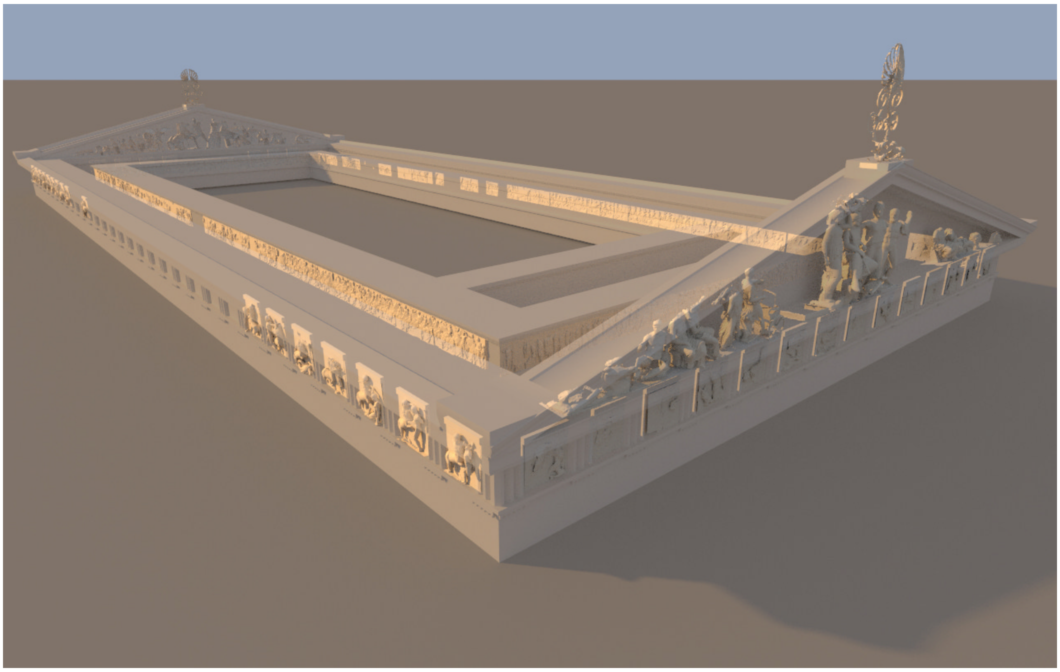


Figure 9: *The entire set of assembled scan from Basel is visualized in location on the architecture of the Parthenon.*

3.1 Aligning and Merging Scans

To fill geometric holes in the scans caused by occluded areas in the structured light images, each sculpture was scanned from multiple angles. These scans were subsequently aligned, merged, and decimated using the MeshAlign v.2 and MeshMerge software tools developed by the Visual Computing Group at CNR-Pisa in the framework of the EU "ViHAP3D" project. MeshAlign provided an interface to estimate an initial alignment and then refine this alignment with an improved iterated closest point (ICP) algorithm. In the case of the frieze, which was scanned systematically at intervals, it was possible to derive the relationships between the first few scans of a section of frieze, and propagate these relationships to the remaining scans. Figure 8 shows the automatically generated initial alignments produced by this process. Scans other than the frieze were initially aligned using MeshAlign's point-based alignment tools.

Figure 10: *Rendering of the scan of the caryatid column from the Erectheion.*

4. Results

We returned from Basel with over 80 gigabytes of raw data. Once the processing pipeline was in place, the high-resolution sculpture models were assembled over the course of several months, largely by a handful of part-time volunteers and one full-time intern. To date, these models have been used to produce several renderings and animations, and a selection of low-resolution models is currently available on our website.

4.1 Models

The scans taken in Basel have been assembled into 152 models, which can be seen rendered in Figure 9. Additionally, we also assembled the caryatid column, shown in Figure 10. Each model is a high resolution mesh containing several million polygons.

Since the relief was low on the frieze, scanning coverage was almost complete, with occasional holes appearing below the feet and above the heads of horses and men. If a manifold mesh is required for purposes such as 3D printing or rendering, these small holes are typically easy to fill [Davis 2002]. While the majority of the metopes had few places of high relief, the south metopes, being relatively intact, had back facing surfaces that we were unable to capture. The resulting holes are complex and difficult to fill automatically. Luckily for our rendering results, these holes are also difficult to see from normal viewing angles. In the case of the pediment sculptures, only the relatively front facing surfaces were scanned.

4.2 Virtual Renderings

Our scanned models of the sculptures were then combined with specifically designed scale models of the Parthenon. They represent the monument at different stages of its complex history and are based on the precise architectural surveys and evocations of Greek architect Manolis Korres, who was for decades the main architect of the Parthenon preservation in Athens. We've also been able to experiment with subsurface scattering (Figure 3) and texture maps, and began to create virtual renderings using global illumination techniques. In Figure 13, you can see the west frieze placed in situ on a model of the modern Parthenon, and an artistic interpretation of the painted frieze.

4.3. Presentation on the Web

The Parthenon Gallery webpage was created in order to share the results of the Parthenon scanning project. The gallery currently contains low-resolution 3D models of a small sampling from the metopes, frieze, caryatid, and pediments. These models are available in the VRML format and can be viewed with a web browser configured with a VRML plug-in, such as the one from Blaxxun, Inc. Also available are presentations and sketches on the Parthenon project along with various 3D images and video renderings created using our dataset of sculptures. The Parthenon Gallery can be found at:

http://www.ict.usc.edu/graphics/parthenongallery

5. Discussion and Future Work

There are several things that we would like to note about the project as well as avenues for the future advancement.

5.1 Scanning Casts versus Originals

There are advantages and disadvantages to scanning the plaster casts in lieu of the original sculptures. In our case, the fact that we had easier access to the cast sculptures was an important advantage. In some cases, we were even able to physically move the sculptures for greater coverage, as almost all of the casts in Basel are mounted on wheeled display casing.

A disadvantage to having scanned plaster casts is that the captured reflectance information is not representative of the original surface material. As a possible solution, we have experimented with using photographs of the original sculptures as texture maps for the 3D models of the casts. For this we used a dataset of digital images of the Parthenon sculptures in the British Museum to be projected onto scans of the plaster casts. A result from this process can be seen in Figure 12. More complex techniques could be used to capture a model of the bidirectional reflectance distribution function (BRDF) at each point on the original using multiple photographs and/or lighting conditions [Rushmeier 1998], and measurements of subsurface scattering [Jensen 2001]. However this would have required greater access to the original sculptures.

On the Basel scanning trip we also had the opportunity to scan the original Parthenon sculptures in the collection of the Louvre in Paris, which allowed us to qualitatively compare a scan of an original sculpture to a scan of a cast. Figure 14 compares the models of east frieze block VII, scanned both in Basel and the Louvre; we found that the scans were of similar quality up to the resolution of our scanner.

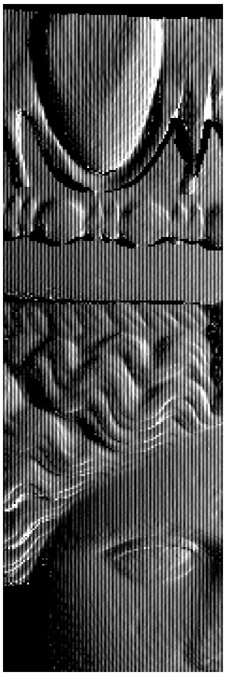


Figure 11: *Scan data showing even and odd line depth discrepancy.*

5.2 Technical Lessons Learned

While processing all of the scans taken in Basel we encountered a few difficulties that may be useful to note.

The exact construction of the imaging devices in the scanner is of particular importance. Our Pulnix camera produced scans with slightly inconsistent depth readings for the even and odd pixel lines, as seen in figure 11. The likely cause is that every other line of the CCD sensor was offset. After testing and calibration, we reduced this artifact by adjusting the sample position of the odd lines by a third of a pixel. Completely removing the effect, however, required a mild low-pass filter on the scan images in the vertical direction.

Figure 12: *This model shows the presentation of the peplos, or robe of Athena. The model is texture mapped with photographs from the British Museum in London and is available for viewing in 3D on our website.*

Producing a large flat checkerboard calibration object to use on site proved challenging; it was obtained and constructed locally with some difficulty. Unfortunately, the checkerboard was smaller in scale than the pediment sculptures. As a result, some of the calibration image sequences for these sculptures failed to observe the object near the edges of the camera's field of view. This complicated reliably fitting an accurate radial distortion function for the camera. To help correct for this, we linearly extrapolated our polynomial distortion function past the last valid data points, and down-weighted the importance of 3D points captured outside the well-calibrated regions.

Logistically, keeping track of over 2,200 scans and calibrations, the sculpture(s) they belonged to, and each scan's state in the processing pipeline was itself a significant challenge. The HTML index, accurate time stamps and a set of spreadsheets that kept track of the processing status for each sculpture proved very helpful for the project.

5.3 A Starting Point for Reconstructions

Several attempts have been made in the past to reconstruct the Parthenon in its original state. Hypotheses as to the original state of the sculptures are usually based on a series of drawings done in 1674 by Jacques Carey [Bowie 1971] along with textual accounts from ancient and modern times. Sometimes, visualizing these additions has been done by filling in missing sections with clay or Styrofoam. The digital archive of the sculptures provides a new tool for investigating possible reconstructions quickly. A future goal is to create tools that can make the 3D models accessible to non-technical archeologists so that reconstruction hypotheses can be put forth.

Figure 13: *Frames from an animation showing the west frieze placed back on the Parthenon. The Parthenon was modelled from architectural drawings by Manolis Korres, and texture mapped by hand.*

6. Conclusion

At the end of this experience, one has to face a difficult reality: the gap existing between the scattered pieces of the Parthenon is in many ways impossible to bridge. Away from Athens, London or Paris, it still seems difficult for anyone to have the same experience as being confronted with the originals. The virtual world, being even more removed from the reality of the Parthenon, cannot replace this experience.

It can, however, open new roads, leading to new frontiers in archaeology and art history. The scans we were able to gather are the faithful images of the sculptures as they stand today, damaged, defaced and incomplete. In itself, our data set is already a unique and useful visual tool for those who want to study the decoration of the Parthenon as a whole. Using these virtual casts, anyone with access to the web should soon be able to approach those works of art from perspectives unavailable in classical museum surroundings. The viewer gains new possibilities for visual and intellectual appreciation of these splendid artifacts.

To be able to view and understand the temple as it once stood, we need to reconstruct its sculptures as fully as has been done with its architecture. 3D graphics reconstructions of ancient sites are not reality and they never will be. It has to be admitted that the output of the best historical and archaeological studies is not reality either. In this respect we believe that fear of possible historic high treason is as dangerous as any consciously disrespectful misrepresentation of cultural objects, as it leaves the field open for other commercial or ethically unsound endeavors.

The digital tools now available can create a virtual reality where enormous blocks of marble weigh nothing, where one can add a limb to a Lapith without any need for anesthetics or concrete. The next stage in our project will encompass the recreation of the missing parts of the sculptures of the Parthenon, from broken marble limbs or noses, through long lost and melted bronze adjunctions, to complete polychromy, returning the blinding white marble temple that inhabits our deceived minds to its somewhat more baroque but lively and exuberant original color scheme.

Figure 14*: On top, the scan of a cast in Basel, and on the bottom, a scan of the original from the Louvre in Paris.*

Acknowledgements

We gratefully thank Tomas Lochman for inviting us to scan in the Basel Skulpturhalle, Roberto Scopigno and Paolo Cignoni of CNR-Pisa for providing their partnership and tools for 3D range data processing, and Marcos Fajardo for his Arnold rendering system. We appreciatively acknowledge the volunteer scan assembly efforts of Genichi Kawada, Zach Turner, and Brian Manson, Marc Brownlow, Andrew Gardner and Donat-Pierre Luigi, the production efforts of Diane Piepol, and the support of Richard Lindheim and Neil Sullivan. This work has been sponsored by the University of Southern California and Toppan.

References

1. E. Berger. Der Parthenon in Basel, Dokumentation zu den Metopen. Philipp von Zabern, Mainz. 1986.
2. E. Berger, M. Gisler-Huwiler. Der Parthenon in Basel, Dokumentation zum Fries. Philipp von Zabern, Mainz. 1995.
3. T. Bowie, Thimme Eds. The Carrey Drawings of the Parthenon Sculptures. Indiana University Press, Bloomington, London. 1971.
4. M. Callieri, P. Cignoni, F. Ganovelli, C. Montani, P. Pingi, R. Scopigno. VCLab's Tools for 3D range data processing. *VAST 2003 and EG Symp. on Graphics and Cultural Heritage*. 2003.
5. P. Cignoni, C. Rocchini, C. Montani, R. Scopigno. External Memory Management and Simplification of Huge Meshes. *IEEE Trans*. *On Visualization and Computer Graphics.* 2003.
6. J. Davis, S. Marschner, M. Garr, M. Levoy. Filling holes in complex surfaces using volumetric diffusion. *First International Symposium on 3D Data Processing, Visualization, Transmission.* 2002.
7. I. Jenkins. The Parthenon Frieze. British Museum Press, London. 1994.
8. H. W. Jensen, S. Marschner, M. Levoy, P. Hanrahan. A Practical Model for Subsurface Light Transport. *Proceedings of SIGGRAPH 2001*, pp. 511-518. 2001.
9. M. Korres. Der Parthenon bis 1687, Reparatur-Kirche– Moschee– Pulvermagazin, Die Explosion des Parthenon. Antiken Museum Berlin. 1990.
10. M. Levoy, et al. The Digital Michelangelo Project: 3D Scanning of Large Statues. *Proceedings of SIGGRAPH 2000,* pp. 15–22. 2000.
11. D. Miyazaki, et al. The Great Buddha Project: Modelling Cultural Heritage through Observation. *Proceedings of the Sixth International Conference on Virtual Systems and MultiMedia,* pp.138-145. 2000.
12. M. Pollefeys, R. Koch, M. Vergauwen, L. Van Gool. Hand-held acquisition of 3D models with a video camera. *Second International Conference on 3-D Digital Imaging and Modeling,* pp. 14-23. 1999.
13. H. Rushmeier, F. Bernardini, J. Mittleman, G. Taubin. Acquiring Input for Rendering at Appropriate Levels of Detail: Digitizing a Pieta. *Rendering Techniques '98*, pp. 81-92. 1998.
14. C. D. X. N. Tchou. Image-Based Models: Geometry and Reflectance Acquisition Systems. MS thesis, University of California at Berkeley. 2002.
15. P. Tournikiotis, Ed. The Parthenon and Its Impact in Modern Times. Melissa Publishing House, Athens. 1994.
16. Z. Zhang. A flexible new technique for camera calibration. *IEEE Transactions on Pattern Analysis and Machine Intelligence,* 22(11):1330-1334, 2000.