Building a Digital Model of Michelangelo's Florentine Pietà

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Abstract— **We describe a project to create a three-dimensional digital model of Michelangelo's Florentine Pietà. The model is being used in a comprehensive art-historical study of this sculpture that includes a consideration of historical records and artistic significance as well as scientific data.**

A combined multi-view and photometric system is used to capture hundreds of small meshes on the surface, each with a detailed normals and reflectance map aligned to the mesh. The overlapping meshes are registered and merged into a single triangle mesh. A set of reflectance and normals maps covering the statue are computed from the best data available from multiple color measurements.

In this paper, we present the methodology we used to acquire the data and construct a computer model of the large statue with enough detail and accuracy to make it useful in scientific studies. We also describe some preliminary studies being made by an art historian using the model.

CR Categories I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling – Geometric algorithms, languages and systems; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism – Color, shading, shadowing, and texture; I.3.8 [Computer graphics]: Applications.

Keywords: scanning, registration, mesh integration, normals maps, reflectance, cultural heritage.

I. Introduction

Three-dimensional scanning technology is being used in a wide range of applications as scanning devices become less expensive and easier to use. Various organizations are producing models of cultural artifacts and works of art.

Members of the National Research Council of Canada, developers of high-accuracy scanning equipment, have applied their technology to scanning paintings, sculptures, and archaeological sites. Recent work emphasizes the importance of portable, reliable equipment that can be easily deployed at the scanning site [1]. Jiang Yu Zheng *et al.* have scanned archaeological relics in cooperation with the Museum of Terra Cotta Warriors and Horses, China [2]. Among their goals were creating a database of information about the excavation site and testing and employing virtual restoration techniques. Recently Marc Levoy and a team from Stanford University have undertaken a project to scan many of the sculptures of Michelangelo [3], including the 5 m tall David in the Museo dell'Accademia. They have used several types of scanners, including a high-resolution laser triangulation system mounted on a custom-made mechanical gantry, and a time-of-flight long-range sensor. The large quantity of data collected is expected to have a major impact in future development of shape reconstruction algorithms. Numerous other projects have been conducted or are currently underway. The motivations and equipment used for these different projects varies.

Fig. 1. (left) A photograph of Michelangelo's Florentine Pietà. (right) A synthetic picture from our three-dimensional computer model.

In this paper we describe a recent project to acquire and build a three-dimensional model of Michelangelo's Florentine Pietà. A photograph of Michelangelo's Florentine Pietà and an image of our model are shown in Figure 1. The work described here is unique in that it was conceived and specified by an art historian, not a technologist. Our goal was not simply to produce a model of the statue but also to provide the art historian with material and tools to enable him to answer his own research questions. The project gave us the opportunity to explore the value of 3D scanning and visualization in a non-technical discipline, art history. A second goal of the project was to develop scanning technology accessible to other cultural heritage projects both in terms of cost and usability. Such technology could potentially be used in widespread commercial applications, such as e-commerce, in which equipment cost must be minimal.

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We present the system of hardware and software we assembled to create this model at relatively low expense. We also discuss methods we developed to make a large and complex model usable by a non-technical user. We describe our design considerations and the practical limitations we encountered in scanning and using the model. We also present examples of results we produced to assist Dr. Wasserman in his study.

II. Overview

Dr. Jack Wasserman, professor emeritus of art history at Temple University, had been studying Michelangelo's Florentine Pietà for several years, intending primarily to fully document all aspects of this important work and its history for future researchers; and secondarily to investigate his own theories on Michelangelo's composition. He had used high-quality traditional photography, x-ray and ultra-violet light studies, as well as researching the complex history and symbolism of the statue and its analysis by past art historians.

Although is not clear that a 3D model would be useful in studying every sculpture, Dr. Wasserman felt that this new technology was especially well-suited to the study of the Pietà [4].

Accounts from Michelangelo's contemporaries tell us that the artist intended the Florentine Pietà as his own tomb monument. Beginning late in his life, in the 1550s, he executed a massive work, four larger-than-life figures carved from a single block of marble. The Christ figure in the center rests across the lap of the Virgin Mary, supported on the left by Mary Magdalene. Behind and above, supporting the Christ, is a figure believed to represent Nicodemus and to bear the face of Michelangelo himself. At some point, Michelangelo decided for unknown reasons to break off parts of the statue. He then abandoned it, and shortly before his death permitted one of his students, Tiberio Calcagni, to repair the statue. Calcagni reattached several pieces to the statue and partially finished the figure of the Magdalene [Giorgio Vasari, *Life of Michelangelo*, 1568]. Thus, what we see today is, in a sense, a composite of Michelangelo's work and his student's: his original design, damaged, repaired, and overlain by later work.

The unique aspects of the history of this statue make it a promising candidate for using 3D scanning technology. It is of paramount interest to the art historian to view the statue in the environment Michelangelo intended, to examine it without the pieces Michelangelo removed, and to analyze the detailed toolmarks in the unfinished portion of the work. Furthermore, the statue's complex geometry limits what can be done with traditional techniques: A camera cannot capture certain views of the statue because the statue itself or the walls of the room where it stands interfere with proper camera placement.

III. Scanning System and Methodology

Three-dimensional scanning technology is evolving rapidly. A number of techniques are used in current sensors to sample surfaces, *e.g.* laser triangulation, laser time-of-flight, passive stereo vision, and structured light projection. Typical considerations in choosing the most appropriate scanning technology include target accuracy, surface reflectance characteristics, and cost.

A. Design Considerations

Scanning a large statue in a museum poses a number of constraints in designing the scanning system and process. In our case, the small size of the room in which the statue is displayed limited scanner size and standoff distance. We did not have permission to work or leave any equipment visible around the statue when the museum was open to the public. Therefore we needed a system that could be easily set up and removed at the beginning and end of each evening scanning session. The irreplaceable nature of the piece restricted contact to a minimum, and required particular attention to safe operation of the equipment. The complex shape of the group of figures required the ability to freely position the sensor to access recessed parts of the marble surface.

We had a limited budget for buying non-computer equipment, and a limited amount of time for design and customization. These constraints led us to consider a small, portable structured-light system rather than a more expensive laser triangulation scanner. By this choice, we sacrificed geometric resolution which we would have to recover with a supplementary system.

Our main technical requirements were dictated by the nature, resolution, and accuracy of the data needed to address Dr. Wasserman's needs. The goal was to obtain data to allow realistic rendering of the synthetic model. The statue is 2.25 meters tall, and we wanted to capture its shape and surface details, such as cracks and toolmarks, on the scale of 1-2 mm. Besides geometry, we were interested in capturing the reflectance properties of the surface. We therefore needed to achieve sub-millimeter accuracy in measurements.

Capturing such a large object at such fine resolution entails a number of difficulties, especially under the less-than-ideal conditions outside the laboratory. Issues of repeatability and precision make scanners based on moving parts expensive to build and difficult to transport and operate. Subsurface scattering of laser light in marble limits the accuracy that can be achieved by laser triangulation systems. We decided to use a system that could capture a small portion of surface from a single position, acquire a large number of overlapping scans, and rely on software registration to integrate the results.

The amount of data needed to represent the surface at such fine level of detail presents additional problems. A triangle mesh of hundreds of millions or billions of triangles cannot be stored, processed, and visualized on current personal computers, or even mid-range workstations. Since we aimed to make the results accessible to a wide audience, we decided to represent shape as a triangle mesh with resolution of a few millimeters, and to store additional fine geometric details in the form of a normals map. Reflectance values could also be efficiently stored as RGB image maps. Having thus chosen the final representation of our model, we avoided a great deal of intermediate computation by designing a system that captures data directly in that format.

B. Scanning

A schematic of our 3D capture methodology is shown in Figure 2. Our scanner is based on a multi-baseline stereo sys-

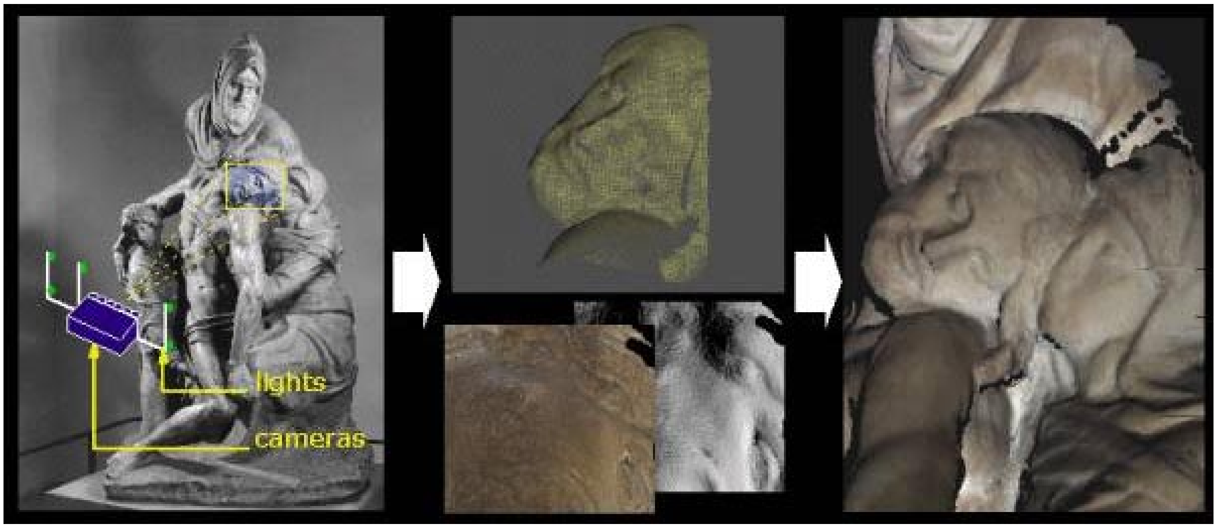

Fig. 2. 3D capture methodology: (a) Multiple digital photos are taken. (b) Surface shape, color and details are computed for each scan. (c) Scans are aligned and merged into a single model.

tem, supplemented by a photometric system. The scanner, visible in Figure 3(a)-(b), is a customized version of the Virtuoso ShapeCamera. A photographic flash projects a pattern of vertical stripes on the subject. At the same time, six b/w digital cameras photograph the illuminated area from different angles. An sample stripe image is shown in Figure 3(c). An additional digital color camera provides a texture image. A multiview stereo algorithm [5], part of the software suite provided with the Virtuoso system, computes a triangle mesh approximating the scanned area. In our scanning conditions each scan typically covered a 20 cm by 20 cm area and comprised on average about 10,000 measured points. The typical intersample distance for these scans is about 2 mm. In tests conducted on reference objects, we have measured an accuracy in depth of 0.1 mm for a single scan.

We augmented the Virtuoso scanner with a photometric system (Figure 3(a)-(b)) consisting of five light sources and the built-in color camera, plus some control electronics. For each camera pose, we take five additional color pictures, each with one of the five light sources, while all other lights are turned off. We also used low-power laser sources to project red dots onto the statue (shown mounted on light stands in Figure 3(b)). The laser projectors that we used each generates an 11×11 grid of rays. From a distance of about 1 meter, they produce an irregular pattern of red dots on the statue, with an average spacing of 2 to 4 cm. For each pose, we took a picture of the dots (with all other light sources turned off) to help in the alignment of overlapping meshes. An example is shown in Figure 3(d). The color pictures have a resolution of 1280×960 pixels, with 24-bit RGB per pixel. Typically we have a 0.5 mm intersample distance in the color images. We can therefore compute reflectance and surface normals from these pictures at a resolution about 4 times greater than the underlying geometry.

Our initial design included a magnetic tracker to record an approximate estimate of the camera position and orientation with respect to a global frame of reference. We hoped to use this pose estimate to provide a starting point for our software registration process. We used a Polhemus system, fitted with the long-range source to provide an EM field large enough to cover our work volume. We attached a sensor at the tip of a 40 cm plastic rod, rigidly secured to the camera body. Unfortunately, we quickly discovered that metallic material present in the room, including our own equipment, distorted the field to the point of making measurements useless. We also had initially planned to use additional hardware and software to remotely control the scanner and facilitate data transfer operations. However, to keep setup and teardown time to a minimum, we simplified our system considerably.

Our streamlined procedure consisted of the following steps: The large photographic tripod was positioned and the scanner secured to it. Then, the five laser projectors were placed on three light stands to cover the area to be scanned in one session with a grid of laser dots. Data capture started by placing the scanner at one extreme of the area to be covered and shooting one set of pictures; and moving the scanner across the target area to take successive overlapping picture sets, covering the region with a regular pattern of scanned tiles. We kept track of the approximate area covered by each picture set on paper diagrams of the statue. We estimated that we had enough overlap by comparing previews on the scanner display, and we moved the scanner conservatively, about 10 cm between shots, to ensure that we had enough data. The stripe pictures were processed during the day, before the next evening's scanning session, to make sure that we had acquired enough data and not left any holes. One person operated the scanner, while another acted as supervisor to make sure that the proper standoff distance was respected and safety rules followed. Dr. Wasserman was present during the entire process to provide input on his priorities.

We did a preliminary scan of the statue (without the photometric system) in February 1998, spending five 6-hour evenings and four full days in the museum. We repeated the scan in June 1998 and completed it in July 1999. The total time spent doing the final scanning was about 90 hours over 14 days, including the equipment setup/teardown each day. It took about 800

(a) (b) (c) (d)

Fig. 3. (a) The scanner used in the project. The five-light photometric system was added to a Virtuoso ShapeCamera. (b) The scanner in use in the museum. The stands visible in the picture are used to hold the laser projectors. (c) Detail of one of the six stripe images simultaneously taken by the scanner. (d) Detail of the laser dots projected on the statue, as captured by the color camera mounted on the scanner.

scans to cover the whole statue. The raw data consists of 4800 640x480 pixel, 8 bit grey-scale stripe pictures, plus 4800 co-registered 1280x960 pixel, 24 bit RGB color images. Stored in lossless compressed format, the raw data occupies 3 GB of storage.

In retrospect, we believe that the choice of scanning technology was the right one, although with additional planning and design we could have built a more efficient system. The main bottlenecks in the process were the relatively long cycle time of the scanner, the small area covered by each scan, and the offline processing of data. The time required to complete the acquisition and local storage of one set of images was about 2 minutes, and about the same time was required to process one set of striped images to obtain a triangle mesh. Tracking the camera pose would have saved us the long and tedious pairwise manual alignment of the scans that provided a starting point for our registration algorithms.

The main advantage of our scanning system, besides meeting the requirements of our original design, is that it potentially provides a starting point for future development of a very low cost system built out of commodity components. If it is augmented with reliable tracking, fast capture, and high-resolution cameras, it could lead to a system for real-time scanning of large objects.

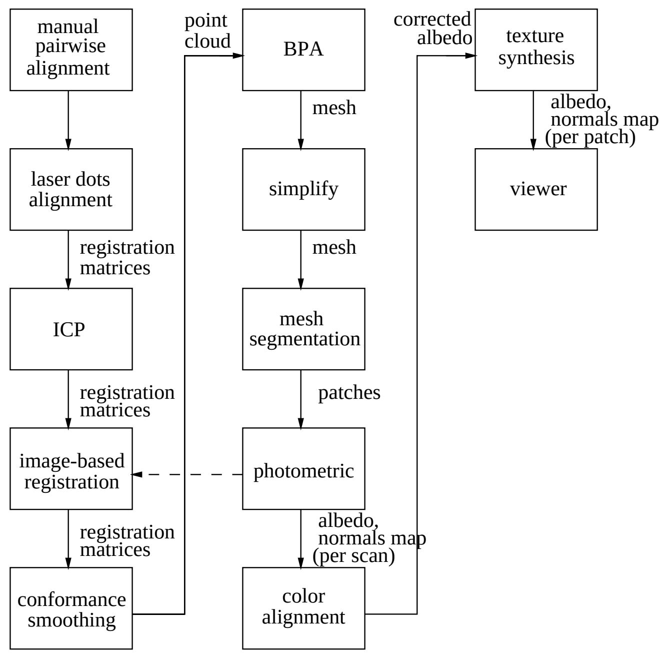

Fig. 4. The reconstruction pipeline.

IV. Reconstruction Pipeline

The acquired raw data comprises roughly 800 scans, each consisting of six b/w stripe images and six color images. We use the Virtuoso Developer software to compute triangle meshes for each single scan from the six stripe images. From this point on, we apply a number of algorithms to the data to build the final model. The individual scans are registered together based on matching geometric and image features. The resulting point cloud is remeshed to obtain a seamless geometric model. Color and detail information is extracted from five of the color images and reorganized in the form of normals and reflectance maps. Figure 4 illustrates the sequence of steps involved.

A. Registration

We start with a pairwise, manual, approximate alignment of the meshes, obtained interactively selecting three or more matching features on overlapping pairs of scans. We use the diagrams recorded during scanning to identify sequences of overlapping scans, and construct a tree of pairwise alignments that spans the whole set of scans. This initial manual alignment is necessary because the tracking hardware we intended to use did not perform satisfactorily in the museum. We progressively refine the alignment using several registration algorithms that make use of geometric and image information at increasing levels of resolution.

For each scan, we find the red dots in the image taken with the laser projectors on, and map these image points back onto the scan geometry. Given the initial manual alignment, we search in the neighborhood of each laser point for matching points in overlapping scans, adding additional consistency constraints to prune false matches. We improve the registration by minimizing the sum of square distances between matching points using Besl and McKay's method [6]. We then run several iterations of an n-scan Iterated Closest Point (ICP) algorithms [7] to further reduce the registration error. Additional details of our geometry-based

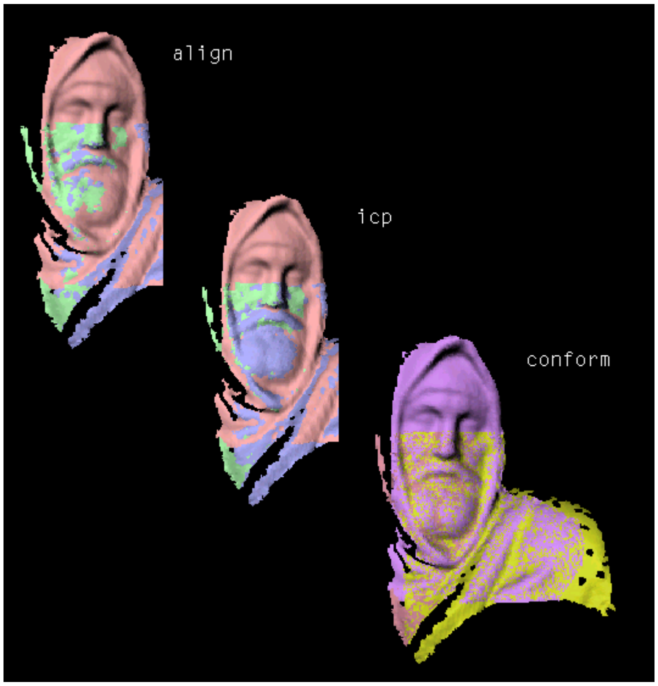

Fig. 5. Subsequent steps of the registration of three test scans. Each scan is shown with a different color. In the "conform" step the scans have been slightly deformed (and so shown with a changed color) to compensate for residual registration and measurement error.

alignment are given in [8].

To refine the geometry-based alignment obtained with the ICP algorithm, we apply an image-based registration method that takes into account additional information contained in the high-resolution reflectance maps computed for each scan (see Section IV-C). We use a combination of smoothing, edge detection, and thresholding operations for the selection of candidate points in feature-rich areas of each image. A correlation-based search is conducted in images associated with overlapping scans to find corresponding points. The resulting pairs are subsequently back-projected onto the scans and used to derive a rigid transformation that minimizes distances in a least-squares sense. Additional details of the image-based phase of registration are given in [9].

We also attempt to reduce scanner line-of-sight error by computing more accurate estimates of true surface points from multiple overlapping scans, while filtering out small high frequency components (which are better captured by the photometric system). We call this process *conformance smoothing*. An example of the successive alignment steps on three test scans of Nicodemus' face is illustrated in Figure 5. The finer grain of the color variations after the "conform" step indicates that the shape of the overlapping scans are nearly the same. Experiments showed that the registration error can be improved if the line-of-sight error is accounted for during the alignment. We are experimenting with alternating iterations of registration and conformance smoothing to obtain a better final alignment.

We did not have equipment to measure accurately large distances between points on the statue (e.g. from the top of Nicodemus' head to a point on the base.) We were unable therefore to make a quantitative statement of global accuracy of the alignment. We discuss the validation of our results using 2D projections and photographs as discussed in section V.

B. Meshing

The result of the alignment and conformance processing described above is a large set of estimated surface samples. This point cloud has non-uniform density because the number of overlapping scans varies from one part of the surface to another; and because the density within each scan varies locally depending on the angle at which the scanner saw the surface. However, except for areas that the scanner could not reach, the sampling density is usually larger than strictly necessary to recover the shape of the surface to a reasonable approximation. We designed our system to acquire geometry with an average intersample distance of 2 mm. Note that this spatial resolution is independent of the accuracy in measuring point position. The scanner we used has a precision of 0.1 mm in computing depth for each sample point.

The Ball-Pivoting Algorithm [10] (BPA) computes a triangle mesh interpolating the point cloud, using a region-growing approach. Our implementation of the BPA is designed to handle large data sets in a memory-efficient way, by processing input data in slices.

The Pietà data consists of 800 scans containing a total of 7.2 million points. We process the data in slices of 10 cm, using ball radii of 1.5, 3, and 6 mm. The BPA runs in 30 minutes on a Pentium II PC, using 180 MB of memory, and outputs a 14 million triangle mesh.

We apply a mesh simplification algorithm to generate a hierarchy of models at different resolutions. We found that conventional, in-core, simplification algorithms cannot handle the large mesh generated from our data. We are able to compute simplified models by breaking up the mesh into smaller, manageable pieces, We then apply a traditional, high-quality simplification algorithm [11], leaving the boundary of each piece untouched, and stitch the resulting simplified pieces together. In a successive pass, we break up the mesh along different edges, so that the previous boundaries can be simplified. The process can be repeated as many times as needed. Eventually, the simplified mesh is small enough to be further processed in a single pass by the in-core algorithm. We expect memory-efficient simplification algorithms to become a hot topic of research as capture methods improve and large models become widespread.

C. Details and Color

The mesh produced using the Virtuoso camera has a spatial resolution of approximately 2 mm, which is adequate for studying the proportions of the statue from various viewpoints. However, it is not adequate for studying the small-scale tool marks. To capture data at a higher spatial resolution, we exploit the fact that the Virtuoso includes a color camera that produces images with a resolution on the order of 0.5 mm per pixel. We compute detail at this pixel resolution using a photometric stereo system built around the Virtuoso.

Our photometric system is shown in Figure 3. Given three images of a surface as lit by three different light sources in known positions, a set of simultaneous equations can be solved for the surface normals corresponding to the points visible at each pixel

(a) (b)

Fig. 6. (a) Color images taken with four of the five light sources. (b) Synthetic picture computed using the surface normals obtained with the photometric system.

in the image. Given the normal at each pixel, the relative reflectance, or albedo, at each pixel for the red, green and blue bands can be computed. We used five light sources rather than three because in any given image a point may be in shadow or a specular highlight. Four typical images obtained at single camera position are shown in Figure 6(a), and the resulting normals (lit from the side) are shown in Figure 6(b). Further detail of the physical design of the system is given in [12].

To compensate for possible errors in the photometric normals calculations, we use data from the 2 mm resolution mesh to compute the direction and relative distance to each point visible in each image, and to estimate the relative light source intensity in the neighborhood of each pixel from each of the five lights. To compensate for scan-to-scan color variations, we performed a color registration analogous to the geometric registration of scans. We found corresponding points in all overlapping color albedo maps, and then found a least-squares solution for scaling factors for each of the color channels in each of the images to obtain the best color match on corresponding points. Additional details of adjustments made using the underlying mesh and the color registration can be found in [13].

D. *Texture Synthesis*

We partition the triangle mesh into height-field patches with a simple region-growing heuristic. For each patch, an orthogonal projection in the direction that maximizes the projected patch area defines a mapping between geometry and corresponding textures.

The texture synthesis process computes surface normals and reflectance maps as weighted combinations of corresponding values in all the overlapping images. Weights are assigned to take into account the degree of confidence in each pixel value, based on distance to the camera and viewing angle. Because weight maps correspond to scans and not to patches, transitions across patch boundaries are not visible. Also, since the weights for each scan decrease with distance to the scan border, scan-to-scan boundaries are not visible.

In our implementation, computations are streamlined by presampling the patch geometry and by loading values from all maps simultaneously. Occlusions are handled elegantly by comparing depth values in precomputed depth buffers. Image and geometric information is loaded on demand to allow for processing of large data sets that do not fit in memory. Additional details regarding our image-based registration and texture synthesis algorithms can be found in [9].

V. Validating and Using the Model

A large digital model is not useful to the art historian. We needed to derive an assortment of presentations of the data suited to Dr. Wasserman's needs, which in some cases required new techniques. Before developing other results from our model we needed to validate its accuracy to Dr. Wasserman's satisfaction. His test was that images derived from our model must correlate well with the high-quality photographs he had commissioned from a professional photographer.

A. *Validation methodology*

To perform the validation we selected features in digitized versions of Dr. Wasserman's photographs and found the corresponding 3D coordinates of those points on our model. We then used Tsai's calibration methodology [14] to compute camera parameters to generate a synthetic image from the same viewpoint. We were not able to estimate the lighting conditions in the commissioned photographs. To address the effect of lighting we also matched camera viewpoints for images we took with a digital camera for which we know the flash location. Initially we computed images with geometry alone and we found that including the surface albedo was essential to perceiving the proportions in the synthetic image.

B. *Overview of Results*

Our primary goals for the Pietà project were defined by Dr. Wasserman's research questions, and our presentation of the results was shaped to fit his needs. We developed a plan to fulfill his requirements by delivering a variety of results:

- Precisely-defined views
- Impossible views
- Embedding the statue in virtual environments
- Precise measurements
- Modifications to the statue
- Interactive viewer

In order to answer certain questions about Michelangelo's composition, Dr. Wasserman wanted to see the statue from physically or practically impossible points-of-view. These included views from directly above the statue to reveal details of the composition not normally visible (Figure 7(c)); and from various angles at a height below the base of the statue to illustrate it as it would have appeared in the context Michelangelo originally intended. We also re-created some of the settings in which the Pietà stood over its history, using 3D models and animations to illustrate the visual impact of the statue in these various environments. (Figures 7(e), 7(f)). To reconstruct the tomb and garden settings shown in these figures, Dr. Wasserman provided drawings and images of similar environments and some initial crude dimensions. Accurately modeling the environments required a number of variations of each environment which Dr. Wasserman evaluated against his understanding of the historical record.

In the virtual world, we can manipulate the statue in ways not possible in reality. Measuring the distance between points on the real statue can be difficult: The statue itself can interfere with a precise measurement. This problem does not exist in the digital world, where we can obtain the precise location of any point on our model.

C. Editing the Model

The ability to modify our model of the statue provided Dr. Wasserman with opportunities to study it in ways otherwise impossible. Using the 3D model, we re-constructed the statue with Christ's missing left leg, approximating its appearance before Michelangelo broke it. We removed the pieces that Calcagni reattached, illustrating the statue as it may have appeared without his efforts. This second modification is shown in Figure 7(g). In the figure, some of the surfaces that would be occluded by the limbs removed are now visible. Internal areas revealed where the marble was broken are colored a flat gray. We also separated the four figures that make up the statue so that they can be examined in isolation.

Identifying the pieces that Michelangelo removed is itself a problem. Four major pieces were removed from the statue (three arms, and a portion of a leg never replaced). The three pieces that were reattached were each composed of a set of smaller fragments, so it is not obvious what exactly was removed. Based on his own close study of the physical work and the X-rays he had commissioned, Dr. Wasserman sketched on electronic images of the statue the various lines where he believed the breaks were made.

Directly editing a large model with millions of vertices is not feasible, particularly since our triangle mesh does not have sufficient resolution to model the breakage exactly as Dr. Wasserman wanted. We tried two methods of editing the model. First we tried painting each of the color images associated with the individual scans to precisely mark which parts belonged to the removed sections. This approach had some problems, since hand marking did not give pixelwise identical locations for all of the breaks across the various scans. However, given the painted images, we could automatically segment the statue by simply removing vertices that were painted with the ”broken” color. This simple computation was useful while we were producing early versions of the model (before all the data was acquired, added, and tightly aligned) to give Dr. Wasserman an indication of what results to expect.

For the final model, we did a crude segmentation of the model by defining bounding boxes enclosing the broken segments. Individual patches containing portions of the cracks were then identified for editing. While this approach would be more tedious to repeat many times (the cracks extend over many different patches), it was the most reliable approach for the final model.

The painting was also used to separate the four figures in the model. This task is less sensitive to the problem of ambiguous identification across scans since there are no precise lines on the statue defining the figures. Separating the figures was of interest to Dr. Wasserman because it reveals shapes and relationships, like the relative position of the Magdalene's hands, that cannot be observed from the solid statue. While we were able to achieve the segmentation of the statue we needed for this study, our experience indicates that detailed editing of high resolution models is an area in which additional research is required.

D. Interactive Viewer

To enable Dr. Wasserman to study the statue on his own computer, we designed a viewer that could be run on a personal computer (Figure 7(d)). The combination of a very large dataset and a slow computer required special attention to the trade-offs between speed and quality and between usability and flexibility. Our target audience consisted of unsophisticated computer users, not accustomed to the navigation paradigms common to interactive 3D-graphics; and we found that we needed to radically simplify the controls to provide a very fast learning curve and then adapt them to our user's abilities and interests. Maintaining interactivity was essential, so that the user could easily grasp the function of the navigation controls and compensate for their inevitable limitations.

In designing an intuitive interface we had two objectives: maintaining a frame of reference when zooming in on detail, and providing clear separate controls for altering view, and altering lighting. Our viewer presents the user with a simplified model of the statue around which he can navigate interactively; and the ability to render a full-resolution image of a selected detail. The simplified model, only 1% the complexity of the full model, acts as a kind of map to the more detailed model. The user can select an area of interest, using very simple 3D navigation controls to reach the desired view. We chose a navigation paradigm in which the camera orbits around a user-selected center at a fixed distance, and zooms in and out along a radius. The user can select a new center by picking or by dragging the image parallel to the view plane.

To examine a region in more detail, the user frames a section of the scene and renders the desired image from a database of the full-detail model. This step currently can take a few minutes on a laptop computer. The resulting 2D image is enhanced to allow the lighting to be varied interactively by dragging the mouse across the window. Many details invisible with the light in one position appear when the light is moved; the user is thus able to understand fine-scale structure more clearly. This technique was designed to model a method that we observed Dr. Wasserman using on the statue: He moved a small flashlight slowly back and forth across the statue to highlight small surface irregularities. The virtual light editor produces similar effects.

We found the viewer to be useful for isolating portions of the model and rendering high-resolution closeups of sections of interest. We had hoped that the viewer would also be helpful to Dr. Wasserman in evaluating the appearance of the statue from various views, to develop a theory of exactly how Michelangelo intended the statute to be viewed. The simplified model in the viewer proved to be inadequate for this interactive study. When the model was simplified to the extent that allowed interactive viewing, it still looked like a good representation to the casual observer. However, for Dr. Wasserman's in-depth study of specific proportions, the simplified model was not accurate enough.

The current viewer, while making it possible to view the model, still needs improvement. It is far from satisfactory as a tool for art historians. A great deal of work needs to be done

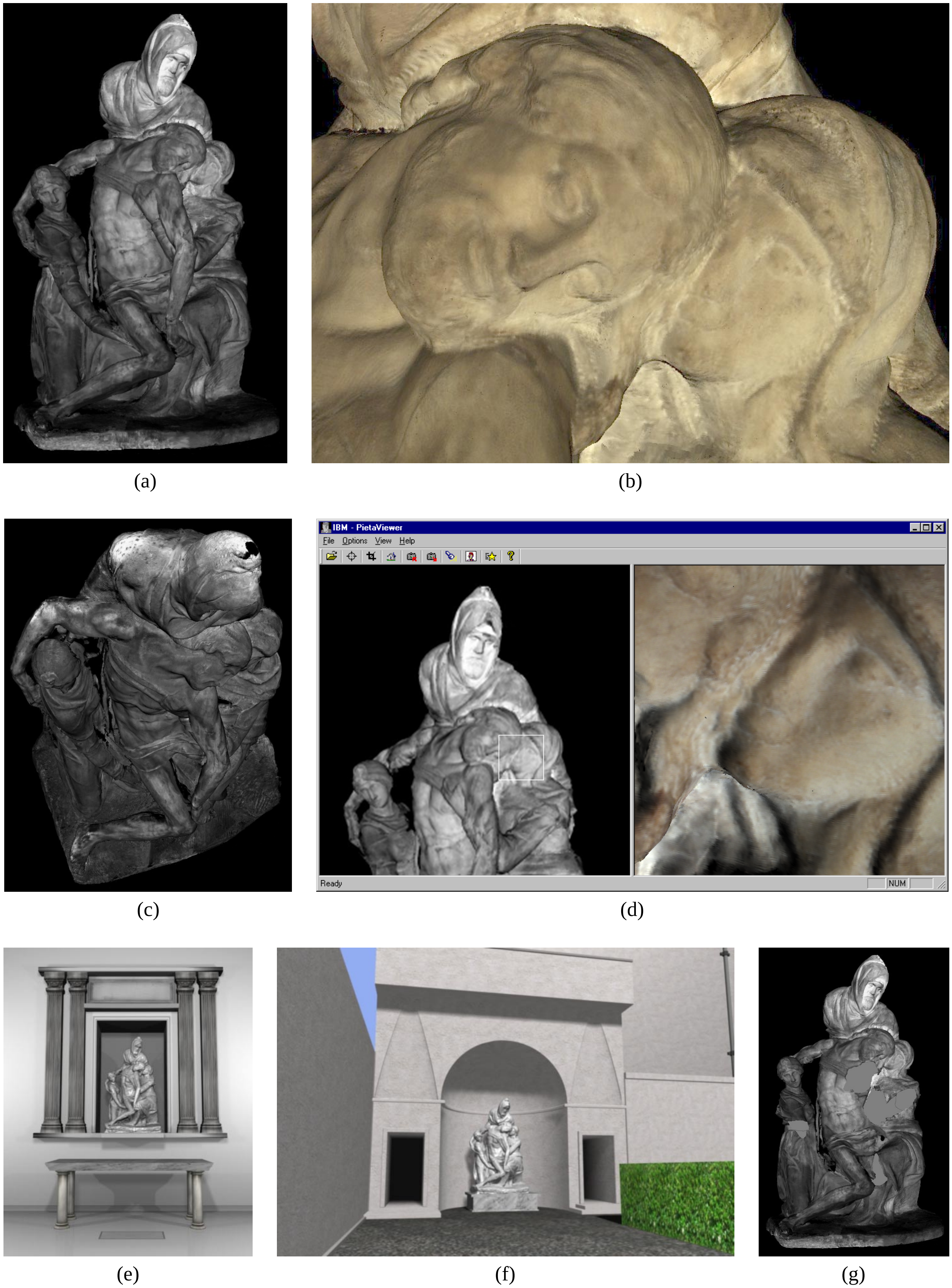

Fig. 7. (a) Black & white rendering of the model. (b) Close-up view of the model. (c) Bird's eye view of the model. (d) Interactive viewer. (e) Synthetic image in a niche above tomb. (f) Synthetic image in a garden. (g) The statue without the pieces removed by Michelangelo.

to find intuitive methods for non-technical users to interact with 3D data, especially when viewing large data-sets that must be simplified to allow interactive display. Part of, but not all of the problem is rendering speed. Incorporating ideas such as point-based rendering [15] or multipass texturing now available on inexpensive graphics cards would improve this aspect of our system.

VI. Conclusions

We believe this project has demonstrated that three-dimensional scanning and graphics can be useful tools for an art historian, and by extension for similar studies in archaeology, architecture, and other disciplines, where detailed examination and manipulation of artifacts is necessary but not feasible in reality. Dr. Wasserman noted three aspects of the virtual model that were of especial use to an art historian:

- Simply having a virtual model of the statue allows the researcher to examine the statue at his leisure, to discover details he had not noticed in the time he could spend with the statue itself, and to verify his recollections and theories.
- The ability to control lighting precisely allows the researcher to see the statue as it might have appeared in environments outside the museum and to highlight small details not easily visible.
- Measuring the statue freely and precisely allows the historian to factor out subjective perception and better understand the artist's use of perspective and composition.

Our technical experience shows that it is possible to build a detailed computer model of a large object from a large collection of small individual scans, which can be acquired with a relatively inexpensive device. Our plans for future work include the study of improved algorithms for the accurate registration of multiple scans, and the development of a hand-held, real-time scanning system. More information about our work can be found at *http://www.research.ibm.com/pieta.*

The final conclusions Dr. Wasserman draws from the digital model will be presented in his book to be published by Princeton University Press, which will include more of our results on a CD-ROM. A kiosk presenting our work and its contributions to Dr. Wasserman's study will be on display at a number of museums in the United States and Europe.

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