The Digital Michelangelo project: 3D scanning of large statues

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***Abstract*—We describe a hardware and software system for digitizing the shape and color of large fragile objects under non-laboratory conditions. Our system employs laser triangulation rangefinders, laser time-of-flight rangefinders, digital still cameras, and a suite of software for acquiring, aligning, merging, and viewing scanned data. As a demonstration of the system, 10 statues by Michelangelo were digitized , including the well-known figure of David, two building interiors, and all 1,163 extant fragments of the Forma Urbis Romae, a giant marble map of ancient Rome. The largest single dataset is of the David - 2 billion polygons and 7,000 color images. In this paper, we discuss the challenges faced in building the system, the solutions employed, and the lessons learned. We focus in particular on the unusual design of the laser triangulation scanner and on the algorithms and software developed for handling very large scanned models.**

***Index Terms*—laser, triangulation rangefinders, 3d modelling, data acquisition**

I. Introduction

In this paper, we try to understand digitizing the sculptures and architecture of Michelangelo. Recent improvements in laser rangefinder technology, together with algorithms developed at Stanford for combining multiple range and color images, allow us to reliably and accurately digitize the external shape and reflectance of many physical objects.
Then we process the data collected to create 3D digital models of these works.

II. Related Work

A. Technological underpinings

From a technological standpoint, the Digital Michelangelo Project contains two components: a collection of 3D scanners and a suite of software for processing range and color data.
We use a principal scanner which is a laser triangulation rangefinder and motorized gantry which is customized for scanning large statues. The rangefinder has a standoff distance of 1.2 meters, a Z-resolution of 0.1mm, and an X-Y sample spacing of 0.25mm which is sufficient to capture Michelangelo's chisel marks.

B. Laser triangulation rangefinder

Our perception of the world is 3-dimensional. Equipped with two eyes (a.k.a. "stereoscopic vision"), we are able to perceive depth, in addition to width and height. We intuitively learn to extrapolate a 3-dimensional world using the two different 2-D images passed from our eyes to our brains.

While 3D vision is second-nature to humans, using cameras to generate an image with depth information is more challenging. Several methods have been devised to extract depth information from camera images. One of the most popular techniques is Laser Triangulation.

Laser Triangulation is a machine vision technique used to capture 3-dimensional measurements by pairing a laser illumination source with a camera. The laser beam and the camera are both aimed at the inspection target (as shown in Figure 1), however by adopting a known angular offset () between the laser source and the camera sensor, it is possible to measure depth differences using trigonometry.

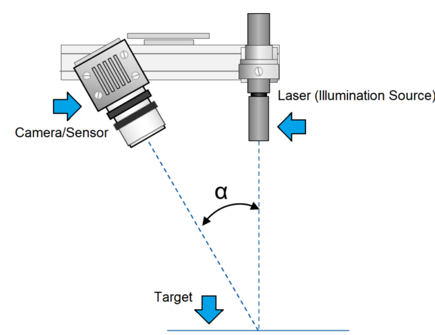


Fig. 1. Laser Triangulation Set-upUsing the fixed angular offset of the camera and laser positions, it is possible to derive the linear distance between the inspection surface and the camera's sensor.

C. More details on the scanner

The scanner head also contains a calibrated white light source and high-resolution color camera with a pixel size of 0.125mm on the statue surface. The scanner head is mounted on a 4-axis motorized gantry (Figure 2) with a working volume 3 meters wide by 7.5 meters high - tall enough to scan Michelangelo's David on its pedestal. For those hard-to-reach places, we have also used a commercial jointed digitizing arm and small triangulation laser scanner manufactured by Faro Technologies and 3D Scanners.

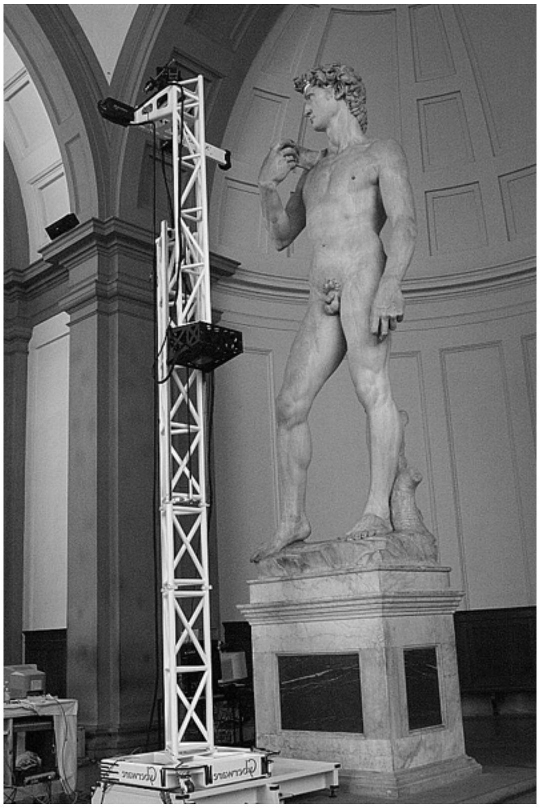


Fig. 2. Laser scanner gantry positioned in front of Michelangelo's David. From the ground to the top of the scanner head is 7.5 meters.

III. Background

A. Range Processing Pipeline

The range processing pipeline consists of aligning the scans taken from different gantry positions, combining these scans together using a volumetric algorithm, and filling holes using silhouette carving and similar techniques. Since gantry movements are not tracked in hardware, alignment is bootstrapped by aligning each scan to its neighbor interactively. This is followed by automatic pairwise alignment of scans using a modified iterated-closest-points (ICP) algorithm and finally by a global relaxation procedure designed to minimize alignment errors across the entire statue.

B. Colour Processing Pipeline

The color processing pipeline consists of compensating for ambient lighting, discarding pixels affected by shadows or specular reflections, and factoring out the dependence of observed color on surface orientation. This requires knowing the bidirectional reflectance distribution function (BRDF) of the surface being scanned. For marble statues, we have successfully employed a simple dichromatic model consisting of a colored diffuse term and a white specular term. The result of our range and color processing pipeline is a single, closed, irregular triangle mesh with a diffuse RGB reflectance at each vertex.

C. Non-photorealistic rendering

Non-photorealistic renderings of our datasets are also possible. For example, by coloring each vertex of a mesh according to its accessibility to a virtual probe sphere rolled around on the mesh, a visualization is produced that seems to show the structure of Michelangelo's chisel marks more clearly than a realistic rendering. Also the application of geometric algorithms and non photorealistic rendering techniques to scanned 3D artworks is a fruitful area for future research.

IV. Object Modeling by registration of multiple range images

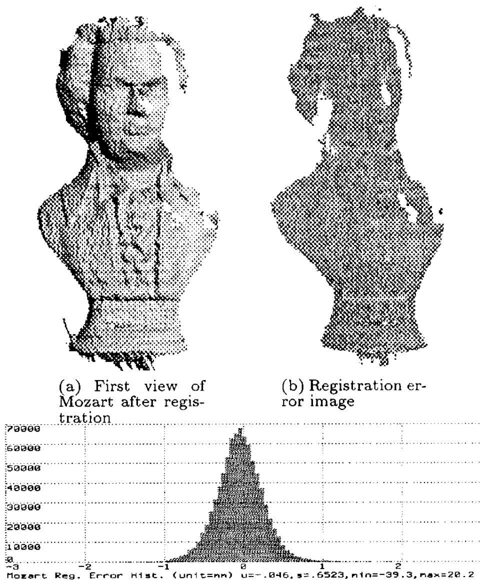
Here, we study the problem of creating a complete model of a physical object. We use range images which directly provide access to three dimensional information. We adopt a new approach, which works on range data directly and registers successive views with enough overlapping area to get an accurate transformation between views. This is performed by minimizing a functional which does not require point to point matches.
If one needs a complete model of an object, then the following steps are necessary:-
1. Data acquisition
2. Registration between views
3. Integration of views

By view, we mean the 3D surface information of the object from a specific point of view. While the integration process is dependent on the representation scheme used, the precondition for performing integration consist of knowing the transformation between the data from different views. The goal of registration is to find such a transformation, which is also known as the correspondence problem.

The object modeling system attempts to build a complete model for an object through the integration of multiple view range images. We use the information about the range finder setup and find the inter-frame transformation of the range images through range image registration. We avoid the search through the transformation parameter space by assuming an initial approximate transformation for the registration algorithm, since we believe that this information is available from range finder setup. or through high level feature mapping. The registration algorithm is an interactive process minimizing a least square error measure. It minimizes distance measure function derived from the definition of 3D surface registration.

We acquire the range images with a range finder which consists of a projector with a programmable liquid crystal

mask and a CCD camera. The range finder works on the principle of space coding with projected pattern and triangulation.
Below is the registration result for the Mozart model



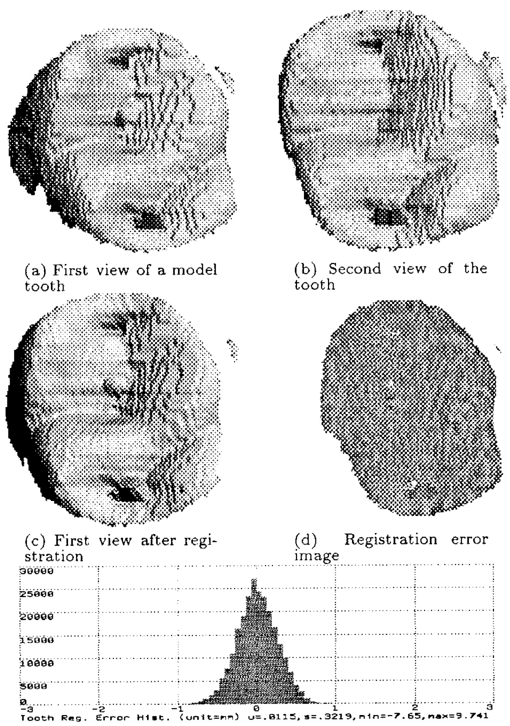
(a) First view of Mozart after registration

(b) Registration error image

(c) Histogram of the error image

Figure 4: Registration results for the Mozart bust

Fig. 3. Registration results for the Mozart bust



(a) First view of a model tooth

(b) Second view of the tooth

(c) First view after registration

(d) Registration error image

Fig. 4. Registration results for the tooth

The drawback of this modeling process is that the representation scheme may not be powerful enough to directly accommodate more complex objects.

V. Logistical challenges in building the model

One significant challenge in the Project was the size of the datasets. The dataset contained 400 individually aimed scans,comprising 2 billion polygons and 7000 colour images.Losslessly compressed,it occupies 60 Gigabytes of data.

The second challenge was to ensure safety for the statues during scanning. Laser triangulation is fundamentally a non-contact digitization method and only light touches the network. Still, the digitization process involves positioning a scanner close to a precious artwork,so accidental collisions between the scanner and the statue is a constant threat. To prevent collisions, a combination of scanner design features - in particular a long standoff distance,as well as safe operating procedures and extensive training of the scanning crew was done.

The third challenge faced was in development of meaningful, equitable, and enforceable intellectual property agreements with the cultural institutions whose artistic patrimony was used for digitizing. Only distributing the models and computer renderings for scientific use was allowed.

The corollary issues of distribution, verification, and enforcement, although difficult in principle, are simplified in the near term by the size of the datasets. In particular, they are too large to download over the Internet. Similarly, distinguishing the computer models from other models of Michelangelo's statues is not currently a problem, since none exist. In the long term, methods of 3D digital watermarking can be applied to large geometric databases.

VI. Uses of the model

The technology used, can be used for scanning and replicating statues. Among the other clients the model can be used as envision for art historians,museum curators,educators and the public.

For art historians,the methods provide a tool for answering specific geometric questions about the statues. Questions like computing the number of teeth in the chisels employed in carving the Unfinished Slaves, determining the smallest size block from which each of the allegories in the Medici Chapel could have been carved, and determining whether the giant statue of David is well balanced over his ankles, which have developed hairline cracks can be answered.

Apart from this,art historians envision computer models as a repository of information about specific works of art. These models can act as an official record of diagnostics and restorations performed on the statue.

For educators, computer models provide a new tool for studying works of art. In a museum, we see most statues from a limited set of viewpoints. Computer models allow us to look at statues from any viewpoint, change the lighting, and so on.

In the case of Michelangelo's statues, most of which are large, the available views are always from the ground looking up. But it is instructive to look at those statues from other viewpoints.Looking at the statue from unusual directions has allowed the educators to discover about the statue's ingenious design.
For museum curators, while models displayed on a computer screen are not likely to replace the experience of walking around a statue, they can nevertheless enhance the experience. The computer focuses their attention on the statue and allows them to view it in a new way.
By exploring the statue themselves, they turn the viewing of art into an active rather than a passive experience. The art museum becomes a hands-on museum then.

Finally, for the public, interactive viewing of computer models may eventually have the same impact on the plastic arts that high-quality art books have had on the graphic arts, they give the educated public a level of familiarity with great works of art that was previously possible only by traveling.

VII. Side Projects

Although the main objective of the project was to scan statues,we can expand the core ideas to various other projects.

One such side project is the scanning of the architectural settings of Michelangelo's statues.Time-of-flight laser scanner is used.This scanner has a Z-resolution of 5mm and a typical X-Y sample spacing of 4mm at a distance of 10 meters. Using this scanner and an attached color camera,a colored 15-million polygon model of the Tribune del David in the Galleria dell'Accademia and a 50 million polygon model of the Medici Chapel was built.

Unfortunately, these models are irregular triangle meshes, like those produced by our other scanners, and are therefore not useful for most practical architectural applications.

Converting such a dataset into a conventional graphical representation such as a plan or elevation drawing is not easy. Converting it into a segmented, structured, and annotated architectural database is even harder.

Another such side project is,fusion of 3D scanning and other imaging modalities.
A final side project is the scanning of the Forma Urbis Romae, a giant map of ancient Rome carved onto marble slabs in circa 200 A.D. The map now lies in fragments - over 1,000 of them. Piecing this map together is one of the key unsolved problems in classical archeology. Fortunately, the fragments are several centimeters thick, and the broken surfaces give us strong three-dimensional cues for fitting the pieces back together. The primary tool in this project will be automatic search algorithms that operate on geometric signatures computed from our models of these broken surfaces.

VIII. Conclusion

The actual difficulty of the task was surprising. In particular, the statues contained more recesses and partially occluded surfaces than what was anticipated, and positioning the gantry to reach them required more time and effort than imagined. Nearly 50% of the time was spent scanning the first 90% of the statue. 50% on the next 9% and the last 1% of the statue was unscannable. To improve on these numbers, a scanner system would need a more compact scanner head, more positional and angular flexibility, a variable standoff distance,automatic tracking of the gantry position, and a suite of automatic view planning software.
Another hard lesson was about scattering of laser light from the crystal structure of marble. The effect of this scattering is to introduce noise into the range data.This scattering is dependent on surface polish, highly dependent on incident beam angle, and can be reduced but not eliminated by narrowing the laser beam.Furthermore, although the scattering is related to laser speckle, it would occur even with incoherent illumination. In short, there appears to be a fundamental resolution limit for structured light scanning of marble surfaces.

IX. References

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