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Virtual Recovery of Excavated Relics

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Bringing computer graphics and virtual reality technologies to traditional archaeology raises surprising possibilities. First, it permits exploring, assembling, and visualizing relics without disturbing their physical location or damaging specimens. Second, it brings a "what if" scenario to the task of reassembling fragments, which would otherwise involve applying permanent adhesives, rendering mistakes irrevocable. Virtual recovery affords an opportunity to previsualize alternatives and to repeat processes, reducing the possibility for such errors and adding new flexibility. Third, virtual artifacts can be shared across a network and/or delivered in the context of multimedia presentations. Although clearly no substitute for the painstaking process of uncovering and working with originals, recovering "virtual relics" facilitates a different type of examination—one that complements traditional recovery and presentation techniques.

Benefits of VR and CGI to archaeology

Virtual reality (VR) and computer graphics interface (CGI) technologies offer an alternative to current excavation and recovery processes, as well as educational and museum display techniques. Buried in ancient tombs for thousands of years, archaeological relics inevitably suffer decay and increased fragility. The risk of damage multiplies during the excavation process. Some relics are priceless, for their artistic import or what they reveal about ancient cultures and civilizations. Further, virtual technologies potentially can reduce the time and expense associated with the extraction process.

At present the pre-expedition study required before undertaking a project and the manpower required to unearth and reassemble findings are extreme. Bringing VR and CGI tools onto the site to examine unearthed objects lets the archaeologist "virtually prospect" for valuable information, reducing identification time and the ever-present danger of damaging objects during extraction. Physical problems imposed by large or heavy objects can be reassessed: What's the best way to remove or handle this? Do we have to extract it from the site at all? Or would it be more valuable to leave it in the original excavation and employ only a virtual display?

Having extracted the relics, the archaeological team can use smart CGI tools to accelerate the reassembly process. The traditional process usually requires suspending fragments in a 3D frame and then bonding them together with an adhesive. How these pieces fit together isn't obvious. CGI technology helps in identifying the most likely rebuild candidate and exploring alternatives without damaging the source, reducing time and risk.

In this project—funded through 2000 by the Asahi Glass Foundation, Japan—our team of archaeologists, computer scientists, and museum staff artists uses CGI, VR, and multimedia to investigate the feasibility of recovering specific unearthed relics at the Museum of the Terra Cotta Warriors and Horses, Lin Tong, Xi'an, China. The discovery occurred around 1970 when a farmer noticed a large amount of terra cotta fragments while digging a well. Now an established world heritage site, the museum is an ongoing excavation. A team of 80 has labored more than 20 years to unearth approximately 3,000 sculptures from among an estimated 8,000 total. We believe bringing computer technologies to bear will ultimately enhance workflow and productivity. In the course of the project, we hope to develop and refine tools and techniques that become as commonplace as traditional tools.

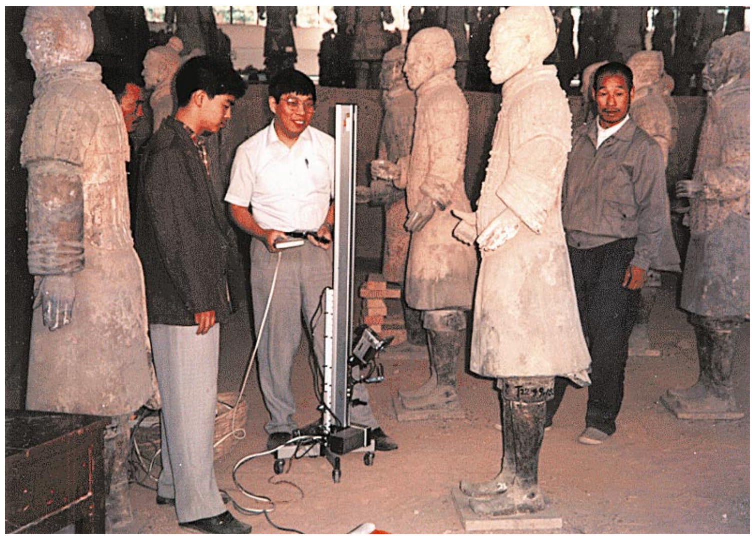
Specifically, the project undertakes to accomplish the following goals.

- *Digitize excavated finds*. Using digital imagery and a laser range finder, the team makes images, registers the location of artifacts in relation to their position in the excavation, and builds a database consisting of both information sets. This yields permanent 3D imagery of both artifact and site, viewable from any angle or any vantage point, while leaving original objects at their point of discovery, undisturbed and in no danger of damage.
- *Test and employ virtual recovery techniques*. This involves developing tools and methods to represent and reassemble virtual relic fragments in virtual space, as a guide for professionals. A software interface must display virtual fragments in different views and enable their manipulation for reconstruction into a single object. This process involves identifying common points on different pieces, letting software "snap" them together. Recovery also involves acquir-

ing color samples from the fragment (or earth surrounding it) for texture mapping. Virtual recovery is weightless, nonadhesive, and repeatable—less likely to produce a misconnection or damage—and possible from a remote location.

- *Present the results in a virtual exhibition*. The last step involves assembling the recovered relics in a multimedia presentation, for distribution over a network or for display in a stand-alone, on-site kiosk. This preserves representation of the real object in its original unearthed state; prevents removal, which might destroy the most fragile items; and yields a high-resolution 3D image formatted for multimedia exhibition. While the virtual merely substitutes imagery for the original, imaging could become the preferred method of exhibiting. A fragile sculpture is usually encased, on a platform, beyond the viewer's tactile evaluation. In this circumstance high-resolution VR affords a more detailed, leisurely examination.

1 **The areas of a pit excavation are typically small and confining, with the artifacts crowded close together. To use a scanner in such conditions requires a scanner with a small footprint, easily located.**



2 **The laser range finder uses a single digital video camera to scan the unearthed statues and fragments.**

We've completed preliminary experiments on a small portion of the find—a troop of sculptures from the Qin Dynasty (about 2,200 years ago). Destroyed in ancient times, the site had remained buried and undisturbed until the 1970s. Consequently, the fragments have suffered two thousand years of decay and damage, complicating their reassembly.

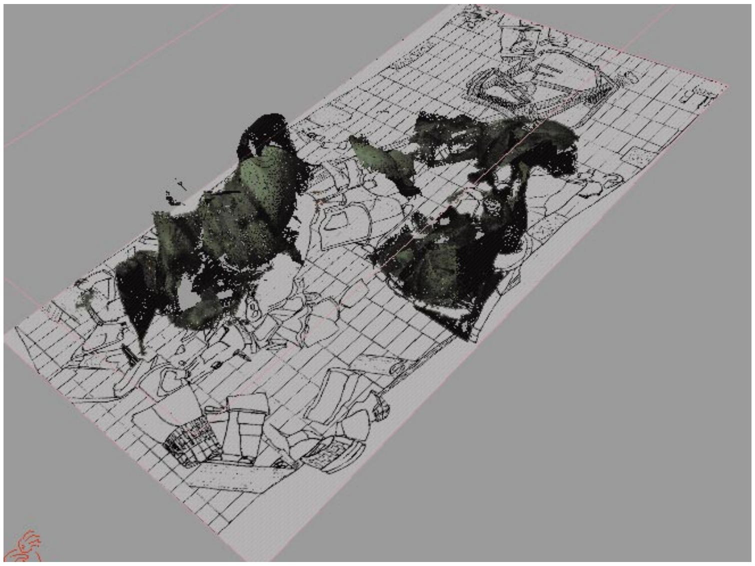
Measuring relics with a portable laser range finder

The first step in representing the 3D object employs a laser range finder to accurately sense the object's shape and surface texture. Although several types of scanners exist, none possessed the portability necessary to quickly make many measurements at different locations and depths within the confined space of this particular excavation (Figure 1). Further, fragments vary dramatically in size, and many cannot be moved from their excavated position. Lastly, the scanning device had to gather 2D texture data and 3D geometric data. So, we wanted a lightweight, stable, very adaptive, and portable range finder capable of locating points in space as well as photographing textures.

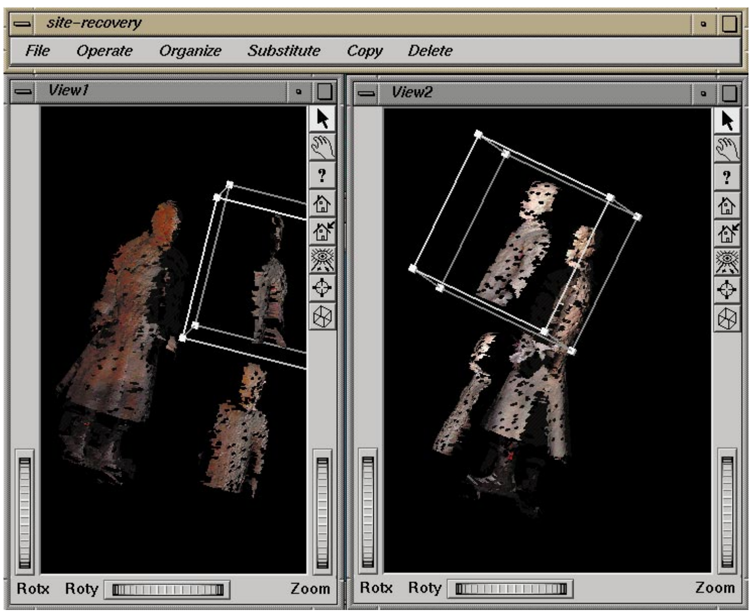
The final scanner design (Figure 2) uses a 1.5-meter linear vertical track, mounted perpendicular on a thin base composed of two slats, each about 0.5m in length, set perpendicular to each other. (The apparatus resembles a 3D axis). A single digital video camera, which moves downward at a fixed velocity, sits mounted on top of the vertical track. The laser, mounted on the track below that, moves vertically with the camera. An electric motor at the base drives their changing position along the vertical track.

The range finder captures both 3D and texture information. Moving the laser-camera combination linearly lets the ray plane scan the object surface, producing a depth map. The digital video camera records an image sequence, subsequently read into the computer frame by frame. The image positions of the laser points give the depths, which provide the image velocities. By setting a time delay and counting the frames, the program determines where those points go according to the computed velocities. The system then takes colors at the predicted positions in the (delayed) new frame and associates them with the laser points. The system thus obtains a color map associated with the depth map. The color is mapped to the depth when the system generates a 3D model from both maps.

A prototype, the laser range finder's design will likely evolve during the project toward greater efficiency



3 **The museum staff prepared detailed maps and drawings of the site. The measured models (dark surfaces) are positioned by the software interface.**



4 **Written in Inventor, the software used to reassemble fragmented relics uses two viewports to provide 3D perspective. It can snap fragments together using one-point and three-point matching techniques.**

and ease of use. For example, the next version will be longer—at least 1.8 meters—to accommodate scanning an entire statue with a single pass. Nonetheless, we'll continue to dispense with the conventional two-camera design, in favor of a single camera moving in tandem with the laser. This reduces size and weight, but requires the extra step of adjusting color in postprocessing.

Museum archaeologists supplied accurate "ground truth maps" showing detailed top and profile views of the excavation and the position of unearthed objects (Figure 3). We used the maps to position the laser range finder and record a series of 3D images. Each 3D image captured a volume of 1200 × 500 × 500 mm, with a resolution of 1400 × 640 × 240 points. The greatest image accuracy is 0.03 × 1 × 1-5 mm—sufficient with respect to the size of the statues and fragments. When we prepared this article, one week-long dedicated scanning effort at the site had produced about 20 scans. Each scan took about one minute (excluding setup time). Additionally, we scanned more than 20 sculptures (each sculpture requiring 5 to 13 3D views), resulting in approximately 4 hours of digital tape and a database exceeding 700 Mbytes.

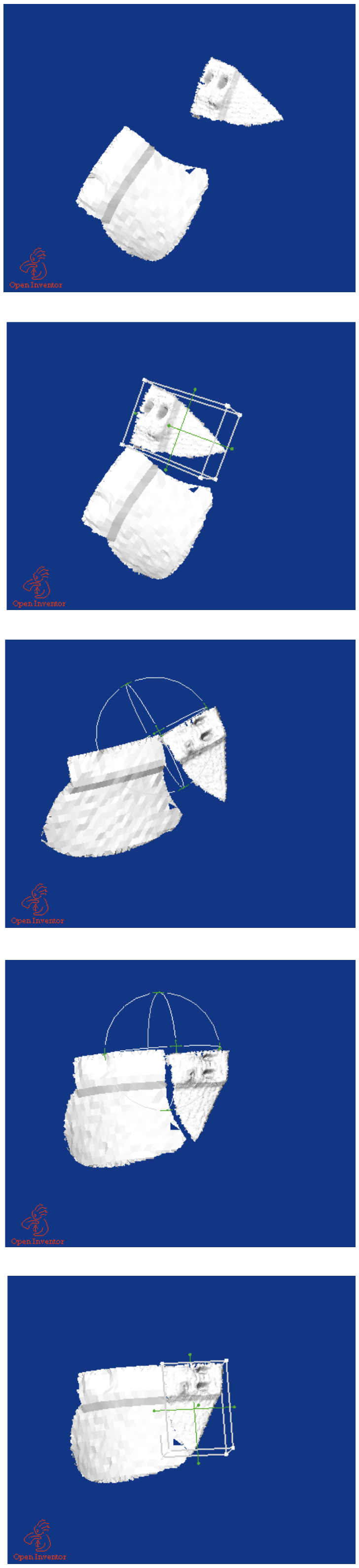
Virtual recovery of unearthed relics

Virtual recovery of unearthed relics involves processing and combining scans from the laser range finder into a mesh model, applying a texture map, and assembling these virtual fragments into an accurate representation of the original object. This postprocessing takes place on a Silicon Graphics O2-5000 and O2-10000, with a digital video board and expanded memory. For some tasks, the team uses a Silicon Graphics Octane with a magnetic position sensor.

Notwithstanding the advantages CGI brings to the recovery task, the process proves arduous, time consuming, and exacting. In instances where we could employ a 3D magnetic position sensor on site during data gathering, we used it to control object positioning in virtual space. When it wasn't available (or the extra processing power required by the sensor wasn't available), we used a mouse. Unfortunately, a mouse operates along only two vectors, requiring manipulation in at least two independent viewports to establish an accurate 3D position (see Figure 4).

The software used to process the data sets and display virtual fragments—developed in Silicon Graphics' Inventor—has an interface for the two or more viewports. Clicking an object activates a bounding box around it. Clicking the edge and surface of the box enables rotation and position transforms in 3D space, respectively. Clicking on the object under semi-automatic matching modes places a point on the object that functions as a pivot or snap point for positioning and joining fragments. If the operator locates a common point on each of two virtual fragments, software can align a common pivot point (one-point matching). The operator can rotate the fragments until they appear joined (Figure 5).

An advanced function lets the user locate three common non-colinear points (three-point matching), in which case software computes the transform to snap the fragments together. A grouping function provides the virtual glue to hold multiple fragments together once aligned, facilitating an interactive assembly process. Assuming you have identified the pieces and know how



5 Clicking an object encompasses it with a virtual bounding box. A second click locates a common point, which can serve as a point of rotation and a common snap point. The operator uses one or three non-colinear points to visually align and join two objects. These are grouped and the process repeated.

6 The reassembled virtual statue.

they should fit together, combining 10 fragments into a single object using a mouse takes one to two hours. Figure 6 shows the final assembly of fragments in Figure 4.

The most difficult part, however, remains identifying the fragments and relationships, for two reasons. First, a high-resolution texture-mapped object has so far proved no substitute for careful inspection of the original's shape boundary, texture, thickness, and other features by a trained archaeologist. Second, even though one-point and three-point matching quickly align fragments, the operator thereafter must use free-hand mouse moves to fine-tune the positioning.

We continue to experiment with a 3D magnetic position sensor to speed the fitting process. This technique allows simultaneous position and rotation translation, making the alignment process faster and more interactive. But it requires Octane-class hardware, still uses the one- and three-point matching techniques, and, at the end, requires user fine-tuning. The time spent in digitizing and assembling virtual fragments varies dramatically, according to the computer hardware, data set resolution, and operator skill. The magnetic position sensor proved superior in low to medium resolution situations, but may not prove a time saver when we need precision.

Where the task involves recovering a complete sculpture, virtual techniques prove faster than physical recovery by a trained archaeologist. However, when the task involves searching for and identifying fragments, the hands-on, real-world approach proves faster and more accurate. Partly this results from comparatively low screen resolutions and the fact that large data sets cannot be loaded and unloaded or compared in real time.

Display appearance currently offers the only measure of the accuracy of virtually recovered relics. We have no other method to quantitatively evaluate the results, other than to visually check the joining of corresponding points, look at any overlap, and so forth. Different techniques work better for different types of tasks. One-point matching is the most difficult to use; three-point matching is easier, but requires three matched pairs. Future research will include developing an automated connection program to take fragment measurements and automatically assemble an object or groups of fragments. This could also help check the accuracy of current techniques.

Color recovery of excavated finds

The current fashion in museum display presents archaeological finds to the public in their excavated, unearthed state. Virtual technologies can enhance this experience by reconstructing the entire object—complete with restored surface color and texture.

The video camera captures color from small areas of pigment taken from the original object and/or the adjacent earth. Because the camera captures both laser and color data, the color images come out unacceptably dark, requiring global adjustment by the program. Following this uniform global enhancement, the color simulates the true color of the unearthed object, with or without the remaining pigments.

An archaeologist analyzes pigment samples taken from other sources, such as photographs. A museum artist uses Adobe Photoshop in cutting out regions for "painting" (adjusting local regions independently). Actually, the team didn't "paint" any of the regions, instead adjusting their hue, saturation, and color balance. The terra-cotta sculpture undergoes no real, material change. The artist and archaeologist work together to reproduce colors for the virtual sculpture—a task simplified by the fact that paints and glazes of this period were limited to 10 colors. The museum is also involved in research to preserve ancient paints.

Although the painted color originally on the sculptures is lost now, the engraved shapes show the clothing, belts, buckles, ropes, armor, hair, and other fine details. We can distinguish such shapes when added to the texture map by shading them. This shading helps us segment the

The Collaboration

Jeff Abouaf

Jiang Yu Zheng first encountered the Museum of the Terra Cotta Warriors in 1995 while sightseeing in Xi'an. He met Zhong Li Zhang, vice director of the excavation team, whom he told of his research in the areas of imagery, vision, CGI, and VR. He suggested that this technology had something to offer the museum. For example, 3D measurement often proves superior to hand measurement.

The museum team indicated that their most difficult task, by far, was physically recovering the objects. Zheng saw this as an opportunity to apply technology originally developed for industry to the arts. He and Zhang agreed to pursue that research on the museum site. Zheng thereafter obtained funding to develop devices, programs, and test protocols.

The Japan Ministry of Education and Culture funded the project in 1996 and 1997, with the first on-site measurements taking place in the autumn of 1997. The Asahi Glass Foundation of Japan funded the research through 2000. The museum may seek future funding from the China Ministry of Culture, depending on the maturity of the tools and processes as the project approaches the end of the current agreement.

The results to date validate the team's procedures. Their current commitment concerns enhancing the tools and techniques. For example, they're investigating locating a PC on site for real-time laser measurement, developing 3D sensors to enable real-time manipulation in 3D space, enhancing the software's "snapping" capabilities, and building a permanent version of the range finder at the site.

Zheng and Zhang work with the assistance of the two groups of staffers at the museum: an archaeological group expanding the excavation and conducting research, and the artist group responsible for documenting the work by making on-site drawings, paintings, replicas, video, and other media representations. Additionally, Zheng is assisted by volunteer students at the Kyushu Institute of Technology computer lab, who work in virtual recovery, image processing, and data processing. Zheng himself remains involved in every phase employing the technology. He developed all protocols, from measuring to processing data to software design to processing results. He took the on-site measurements, relying on Zhang and his staff for archaeological expertise.

The Web site for the Museum of the Terra Cotta Warriors and Horses at http://cyber.view.mse.kyutech.ac.jp/ includes documentation of Zheng's procedures, more images, and other interesting site information.

region manually. Then we perform color adjustment, texture mapping the additional information onto the model. We then color the resulting model with virtual pigments.

The resulting modified texture map contains substantial variation and subtlety. When mapped onto the mesh, it gives the appearance of the recovered relic. This technique leaves room for artistry, inasmuch as the relics have limited and damaged pigment, and their precise qualities when applied two thousand years ago remains a matter of research and debate.

Data compression problems complicate both the recovery and presentation phases of the project. The large data sets prevent the operators from swapping fragment models in real time, and they're too unwieldy for network transmission. A hi-res model can exceed 10 Mbytes, and a single fragment can exceed 3 Mbytes. We currently achieve compression rates of between 1/3 and 1/2, based on shape curvature computation, texture-map shading information, and simple resolution reduction. A recursive method divides patches to achieve less change in curvature and shading than a set criteria. But these techniques introduce limitations requiring more research: they must maintain a high resolution for accurate point matching and texture mapping, while at the same time yielding a simplified mesh for transmission and display. Developments in compression technology will not only enhance display, but presumably will enable presenting virtual relics in accurate virtual environments.

Directions and conclusions

Although our work continues, we've achieved the general goals of this three-year project: to test feasibility of virtual recovery of damaged relics by

1. digitizing original archaeological finds,
2. recovering them in virtual space using repeatable, nondestructive techniques, and
3. presenting them in multimedia formats for network distribution or kiosk display.

Our current efforts concern improving efficiency, accuracy, flexibility, and cost-effectiveness at each step. In particular, we intend to refine the digitizing device, enhance software to include automatic connection of groups of fragments, upgrade computer hardware to take more advantage of the 3D magnetic position sensor, and improve the compression scheme to maintain the requisite resolution yet be serviceable in the delivery medium. While no one knows whether the museum will implement all or part of this project, it's clear it will not unearth and recover all of the estimated remaining 5,000 sculptures. To this extent they're committed to displaying virtual relics. ■

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