Virtual Recovery of Excavated Archaeological Finds

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Abstract

This work aims at a virtual recovery of excavated archaeological finds in cyberspace for ancient relic preservation, archaeology research, and multimedia material generation. Many excavated pottery artifacts have already suffered from a certain degree of damage when they are discovered. Archaeologists have to spend much time in restoring broken pieces before an unearthed object can be displayed to audiences. This work introduces a new application of computer vision, graphics and virtual reality in archaeology. First, we develop an imaging device to digitize damaged pieces in the form of 3D shape and surface texture. Then we build an interface for connecting broken fragments in virtual space so that the original model can be visually recovered. The idea of virtual recovery provides a new opportunity and flexibility for archaeologists to examine complex relics. Moreover, the virtually recovered objects can be directly displayed in a multimedia format, e.g., a virtual museum accessed via internet or with a CD-ROM.

1. Introduction

For thousands of years sleeping in ancient tombs and ruins, archaeological finds have suffered from a certain degree of damage when they are excavated. Many of them are arts and artifacts with high archaeological and culture value. Recovery of these elaborated objects to a certain degree is of significance for understanding different culture and early civilization. It is also an important step towards the display and exhibition of relics using the latest developed multimedia technology. In excavation and recovery processes, a wealth of knowledge and experiences are required. A tremendous manpower has to be employed as well. An archaeologist needs to search damaged pieces, imagine the original shape, and connect fragments to return the appearance of damaged finds in past times. The ancient remains can be clay, terra cotta, china, metal, wood, textile, etc. To restore a broken china, for example, an archaeologist needs to inspect the shape and boundary of each piece, predict the original appearance, and test consistency of combining each pair of pieces. Being supported by some special frame, those pieces are usually placed in a 3D space for augmenting spatial imagination in the reconstruction. Finally, those fixed pieces are glued together, which is almost irreversible and requires full confidence in correctness. Many discovered fragments such as those from a statue might be very heavy and assembly of them is a hard work. One can imagine how difficult it would be to play such a 3D jigsaw puzzle with some incomplete and lost pieces. The difficulties archaeologists normally face in the recovery process are:

1. ambiguity in determining fragments combinations,
2. weight of fragments in a free assembling test by trial and error,
3. irreversibility after fragments are adhered in the recovery.

At the same time, an unearthed relic may have lost its original pigment painted on its surface. It would be of great interests for archaeologists to reproduce the faded or dropped ancient color.

This project aims at assisting recovery of unearthed objects and solving above problems by using image processing, graphics, and virtual reality technologies. The progresses in these areas provide powerful tools to archaeology research. We consider three objectives in the computer-aid excavation as follows:

1. Digitizing excavated finds: imaging and registering discovered pieces and their relations in excavation sites for database construction. A laser range finder is developed to measure 3D shape and surface color of excavated objects.
2. Virtual Recovery: recovering damaged finds in a graphics generated virtual space for guiding adherence of real pieces. An interface is developed for flexible manipulation of graphics objects; 3D aspect views of a figure or 3D models of different pieces are combined to produce a complete model.

Faded colors of objects are also recovered by rendering the remaining color samples to the object surfaces where the ancient pigments have dropped.
3. Virtual Exhibition: producing multimedia sources from the recovered objects for display either in a virtual museum accessed on internet or on a video kiosk at an excavation site. The excavated artifacts hence can be reserved for exhibition in their unearthed states.

The advantages of such new concepts lie in the following.

1. The measured 3D shapes of unearthed relics are in a fadeless digital format. The excavated finds can remain as fragments, which is good for preservation and archaeology study even in the next generation.
2. Virtual recovery is a non-adhesive and repeatable process which can prevent fragments from miss-connecting. It is also carried out in a weightless space. Without moving real heavy fragments, an archaeologist will be able to manipulate fragments on a computer, i.e., planning reconstruction by using mouse and other position sensors.
3. Virtual exhibits can be produced directly in forms of image and 3D graphics model. The recovery of real damaged relics may be omitted. This may even change the conventional exhibition style.

In this paper, we will focus on the topics of 3D measurement of excavated objects, construction of virtual space, and several functions of a designed interface for virtual recovery. We are doing experiments at a world famous excavation site ---- The Museum of Terra-Cotta Warriors and Horses in Xian, China.

2 3D Measurement of Relics

2.1 A Portable Laser Range Finder

Sensing 3D shape and surface texture of excavated relics is the first step towards our goal. Shape and texture are combined to yield a 3D graphics model. How precisely an object is measured directly determines how practical the following processes are. The device we use is a laser range finder. A plane of laser light is projected to 3D space and the ray plane intersects an object being measured. A 3D red curve then appears on the object surface. The curve is taken into a camera which is at a constant distance from the laser projector. The image locations of the curve points are extracted and the depths of the points are then computed. By moving the laser and camera linearly, the ray plane will scan the entire object surface and a depth map of the object can be obtained.

Various laser range finders have already been developed [6~8]. However, in an excavation site, a portable laser range finder is preferable according to the following considerations.

1. The unearthed pieces may not be allowed to move from their excavated positions temporally or permanently. The excavation site may only have a limited space for sensing.
2. The sizes of unearthed objects may have a big variation from several centimeters to two meters.
3. Surface texture is important information in addition to the shape information in the recovery and exhibition.
4. The 3D sensing changes from position to position in an excavation site. It is crucial if a designed device has a weight tolerable for frequent moves during the measurements; each measure takes few minute.

According to the above requirements, a laser range finder is constructed (Fig. 1). Image sequences are recorded in a video tape. The tape is later read into a computer frame by frame for processing. Because the device is not connected to any computer and off-line image processing is carried out, the structure of the device is very simple. In order to obtain texture data, many laser range finders use two cameras; one with a filter that catches the red laser line and the other catches the surface texture. This requires an accurate system setting and may result in a big device. In our case, however, only one camera is used. This makes the whole device light enough for the frequent move and convenient setting.

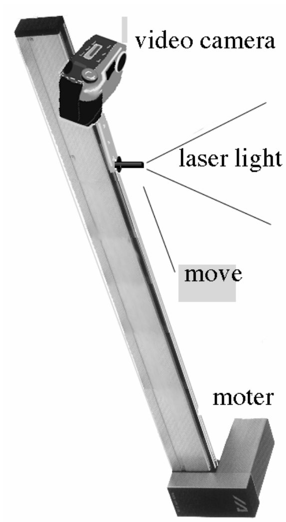


Fig. 1 A portable laser range finder (with length of 1.5m) developed for sensing unearthed finds at excavation sites.

In more detail, the relation of the camera and the laser projector is shown in Fig. 2. Let us denote the moving direction of the camera and laser as Y. The laser ray is set perpendicular to the direction of move, which is denoted as Z direction. The direction orthogonal to both

Y and Z directions is then the X direction.

We then define the base line between the camera and the laser as H and the angle between the camera axis and the moving direction as θ. If a laser plotted point P(X, Y, Z) on the surface is viewed in the image frame at p(x, y), we can obtain the 3D position of the point as

$$X = \frac{Hx}{f\cos\theta + y\sin\theta} \quad (1)$$

$$Z = H\tan(\theta-\alpha) = H\frac{f\tan\theta - y}{f + y\tan\theta} \quad (2)$$

where f is the focal length of camera and is obtained from the field of view of the camera along with its image size.

$$f = \frac{SIZE_y}{2} ctg \frac{FOV_y}{2} \quad (3)$$

The Y coordinate is determined from the moving speed of the laser-camera set, which is set by selecting the motor speed.

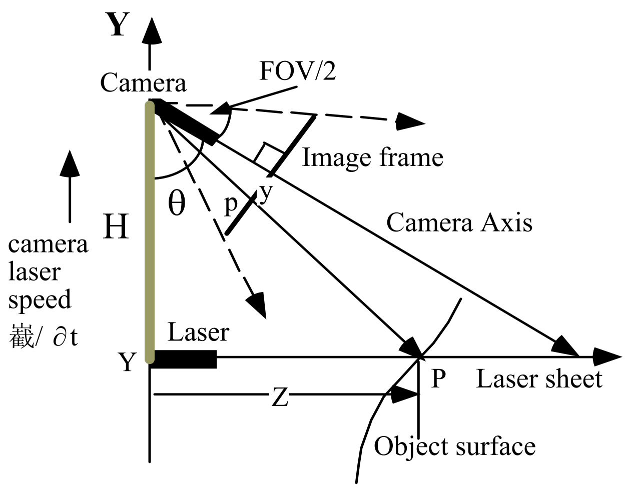


Fig. 2 Geometry of the laser scanning viewed along the X direction.

For each image taken into the computer, we search red points vertically. We can find laser plotted points at the peak of intensity bounded by two edge points in the image. The located y coordinates of the laser points are then filled into equations 1-3 to yield 3D locations at the height the image is taken.

As the laser-camera set moves along the Y direction at a constant speed, the ray plane scans the whole object surface facing the device. Surface points at different heights are measured and a depth map which consists of the y values of the laser positions in consecutive images is generated. The lowest speed of the laser-camera set determines the highest accuracy in Y values and it can be as fine as 1mm. The highest resolutions in the Z and X directions are approximately 1mm. In many cases, we do not need such a good accuracy because we are only able to display the result with a limited data amount.

2.2 Acquiring Surface Texture of Objects

Another function of the designed laser device is the capability of registering surface texture of objects. This is based on the spatial temporal analysis in computer vision. For each point whose 3D position is determined from the laser projection, we need to record its surface color for display. If we take the image value at the extracted laser position, it is the red laser color and the true surface color there can not be obtained (Fig. 3).

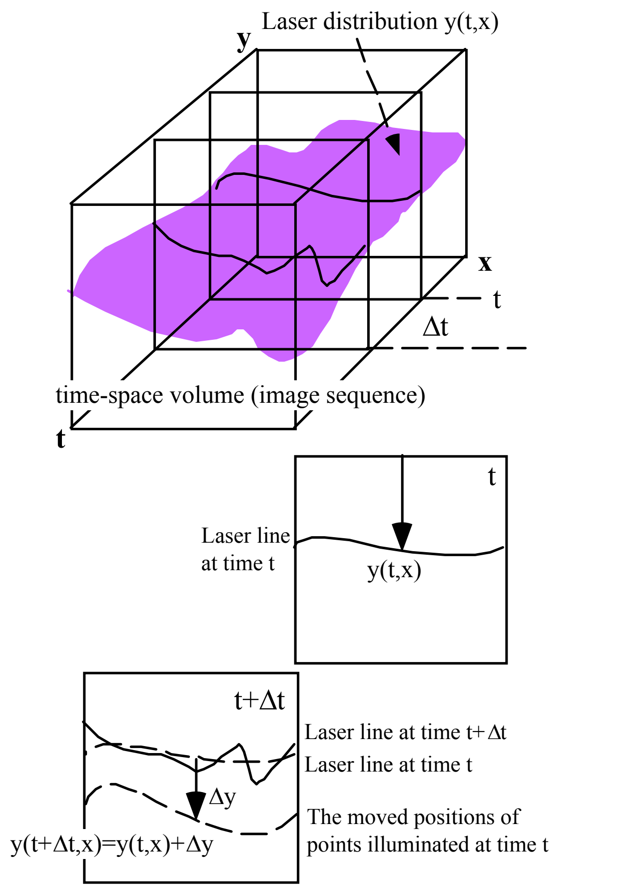


Fig. 3 Capturing surface color of laser scanned points.

To solve this problem, we compute the image velocities of the extracted points, since the 3D positions of the points have been available from their y coordinates along with the known camera speed. The image velocity of a laser plotted point is

$$\frac{\partial y}{\partial t} = \frac{f}{H}\frac{\partial Y}{\partial t}\left(\cos\theta + \frac{y}{f}\sin\theta\right)\left(\sin\theta - \frac{y}{f}\cos\theta\right) \quad (4)$$

which is constant under the constant linear motion of the camera. When the laser-camera set moves upward, surface points move downward in the image sequence.

We choose a time delay Δt, e.g., a few frames, after which the currently focused points will move out of the red laser belt in the image. The image positions of these focused points after Δt frames are predicted. Their true color are sampled in the later frame at the position

$$y_p(t+\Delta t) = y(t)+\Delta y(y(t))= y(t)+\Delta t\frac{\partial y}{\partial t} \quad (5)$$

This relation is depicted by a spatial temporal volume in Fig. 3.

2.3 Digitizing An Excavation Site

As an example, Figure 4 shows a typical excavation site in the Museum of Warriors and Horses in Xian, China, and Figure 5 is a part of a sculpture which is one of the thousands buried in the Qin Dynasty almost two thousand years ago.

For each image taken from the video sequence, the y coordinates of laser points are extracted. The coordinates are registered in gray level in an horizontal array. All the pixel arrays from images taken at different heights are listed vertically. We hence obtain a map containing depth information (here we call it depth map as shown in Fig. 5). The brighter the point, the closer the point is.For each point in the depth map, its image position after Δt frame is further computed. The color there is then picked up from the delayed frame and is written to another image, called texture map, at the same position as in the depth map. From these two maps, a 3D model is constructed. It contains many graphics patches along with local surface colors. The model is displayed in a 3D graphics space for observation by using *Inventor* software (Fig. 6).

The measurement of unearthed objects was carried out in the excavation site of the museum. For flat pieces, one measure is almost enough. For a statue, however, several measures from different directions have to be taken for a complete model. On the other hand, a single measure may include several different fragments. We need to separate them into different models by segmenting the depth map and referring the corresponding texture map (both of them are 2D images).

In an excavation pit, we take many 3D images to record most of the interest parts. A ground truth map is provided by archaeologists. It is composed of a top view and several side views drawn in a graph, some part of them are predicted according to excavation experiences. Based on the ground truth, we set the laser range finder at various positions. We even hang it on ladders whenever necessary for shooting 3D views from the top. Each 3D view covers a space of 1200×500×500mm in height, width, and depth respectively and has resolutions of 1400×640×240 in the corresponding directions. The highest accuracy in the three directions can reach 0.03mm, 1mm, and 1~5mm depending on the object distance. The accuracy is sufficient compared with the sizes of discovered statues.

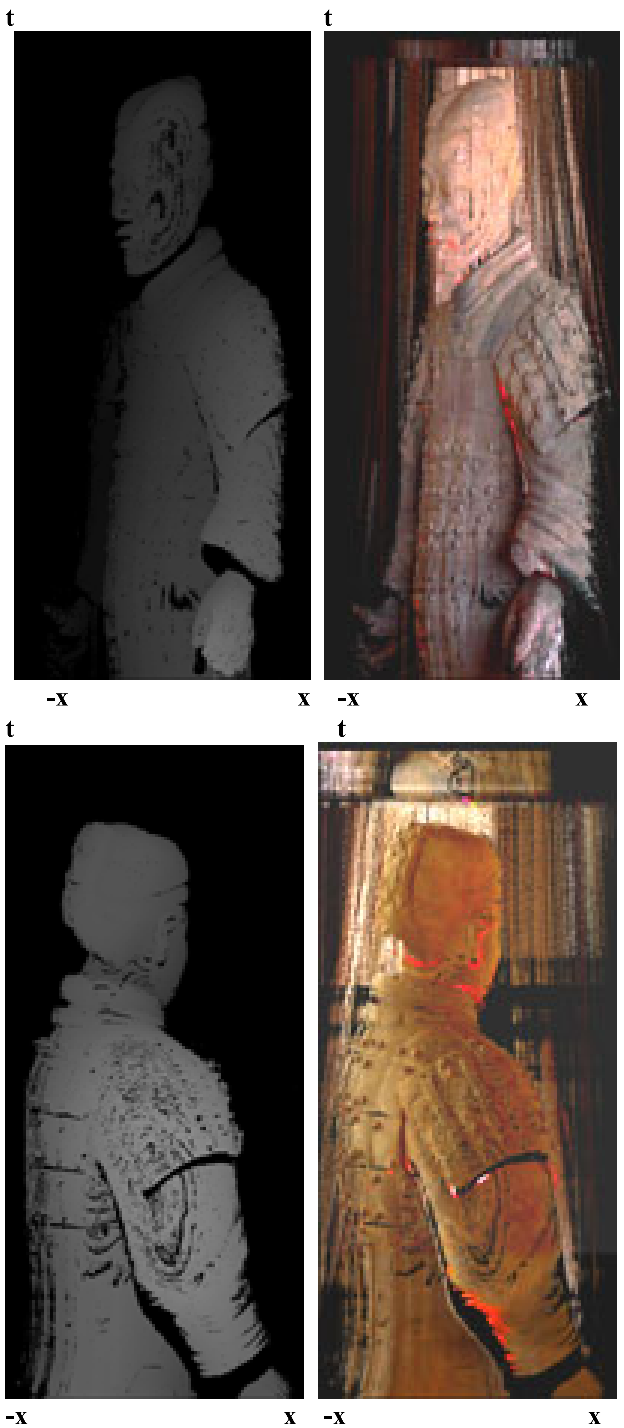
In the excavation site, the device is moved from place to place. It is hard to set and control ambient light. Compared with other existing laser range finders sensing at fixed positions under adjustable illumination, the extraction of laser lines with the portable device is more difficult and complicated. We have to set the dynamic range of the camera near the laser level and adjust the resulted dark surface intensities in the texture map later by other image processing approaches.

If we put the measured data of excavated pieces on internet, archaeological experts and amateurs at remote sites will be able to join the recovery operation of the relics.

(a) An excavation pit.

(b) Statues are restored from fragments.

Fig. 4 A typical excavation site at the Museum of Terra-Cotta Warriors and Horses of the Qin Dynasty in Xian, China.



(b) Depth map (c) Texture map

Fig. 5 Depth map and texture map of a sculpture.


Fig. 6 Reconstructed 3D model mapped with texture.

3. Virtual Space Construction

3.1 3D Data Compression

A measured 3D piece usually contains a large amount of data. It is indispensable for both virtual recovery and multimedia exhibition to reduce the data amount but keep the shape and texture as complete as possible. Dense graphics patches should be arranged at high curvature areas and vice verse. Similarly, we need to keep dense patches at the places where textures have many changes and to give coarse patches at places with homogeneous color. In order to make the recovery of broken pieces easy and accurate, fine patches should also be arranged at boundary of each pieces.

We are not attempt to generate patches faithfully along the maximum and minimum curvature directions since it will result out a patch distribution in a non-grid form. The computation of surface curvature is simply done in the X and Y directions.

Along the X and Y directions, radii of curvature are computed from functions Z(X) and Z(Y), and two maps of radius distribution are resulted. We approximate a surface with triangle patches. Three dimensional curves that compose the surface along the X and Y directions thus are substituted with a series of line segments of patches, which can be further detailed as approximating arcs with chords. A chord should be as long as possible for saving the total number of chords that replace the curve, as long as the curve details can be preserved to some extent. The length of a chord is controlled by the radius of curvature; an arc with a small radius of curvature should be replaced by a short chord and vice verse. Selecting an angle as a common tolerance for the whole depth map, we obtain, at each curve point, a tolerable chord for curve approximation by multiplying the defined angle with the radius of curvature there. The maximum chord allowed to fit there is then determined.

In order to arrange patches to the surface, an algorithm is designed to recursively divide patches into small ones, until a local patch is small enough to satisfy the above criteria in both X and Y directions. Figure 7 gives a set of broken pieces of a pottery container and Figure 8 shows the dense and coarse models of the bottom piece in Fig. 7.

3.2 Combining Different Views

We separate objects into two types: volumetric objects such as a sculpture (Fig. 5) or an unbroken container, and flat objects such as a plate or a piece of volumetric object. Fragments in Fig. 7 are considered as the flat type objects.

For a volumetric object, its surfaces are measured from different directions by the range finder and a set of 3D depth maps are obtained. A remaining task is to combine surfaces into a complete model. This topic has been studied in computer vision area, which requires extensive computation in fusing aspect views.

Because, for the reason of space, we are not able to take enough 3D views to ensure every two views overlap sufficiently, the existing automatic algorithms fusing common surface areas are not applicable. We employ an approach that is similar to what will be described in the next section, i.e., manually connecting different pieces by using an interface for a complete shape. The only exception here is that the relations of aspect views are available.

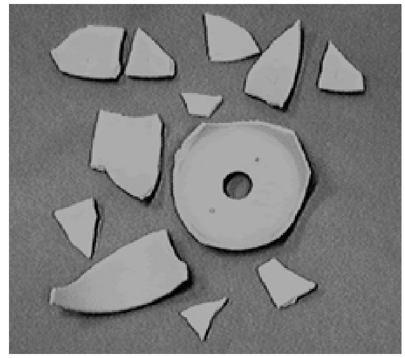


Fig. 7 A set of broken pieces of a pottery container for virtual recovery.

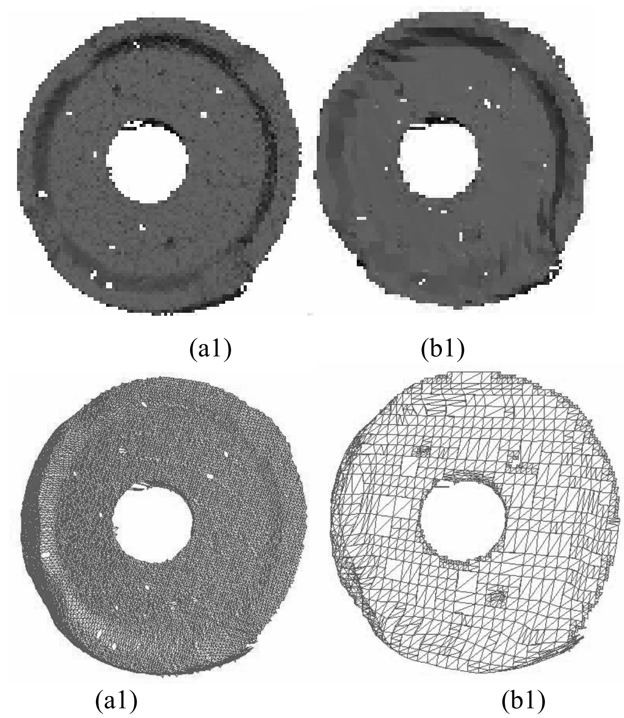


Fig. 8 Data reduction of graphics patches from the original measured data to the model used in the virtual recovery. (a) Original measured data with dense data grid. (b) The reduced data set.

The system performing such a task as well as the virtual recovery task in the next section is composed of a workstation with a graphics environment. A 3D position sensor catching three degrees of translation and three degree rotations is employed. We use the mouse to select an object and the position sensor to manipulate it.

4 Virtual Recovery of Unearthed Relics

4.1 Combining Broken Pieces into a Model

The virtual recovery of unearthed ancient articles is to connect those broken pieces in a graphics generated virtual space. After 3D data of broken pieces are loaded into the virtual space, they are labeled on the screen for selection by mouse (Fig. 9).

Two kinds of input devices available for piece manipulation are a mouse and a 3D magnetic position sensor. Because many excavation sites have not been equipped with position sensors, we have to use a mouse that only provides 2D motion vectors in the 3D manipulation. Nevertheless, it needs less computational power and is feasible for a fine operation. Two windows showing different views of focused fragments are displayed for perceiving relative locations of fragments.

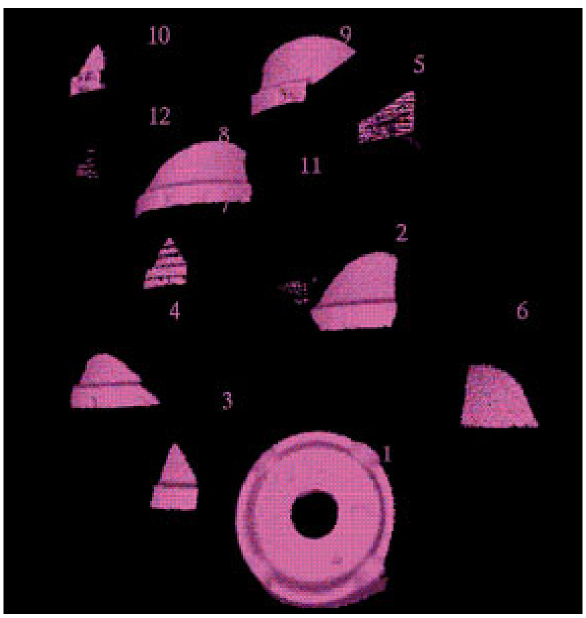


Fig. 9 3D models of broken pieces numbered in the virtual space.

When we click a piece in the virtual space, a transform box appears in both windows. By pushing the mouse at an edge of the box and moving it, we can control the object rotation around the axis parallel to the edge. By clicking the mouse in a surface of the box and moving it, we can control the object translating parallel to the clicked box surface (Fig. 10). The recovered model of the pieces given in Fig. 9 is shown in Fig. 11. Figure 12 is another example of manipulating excavated pieces by using mouse.

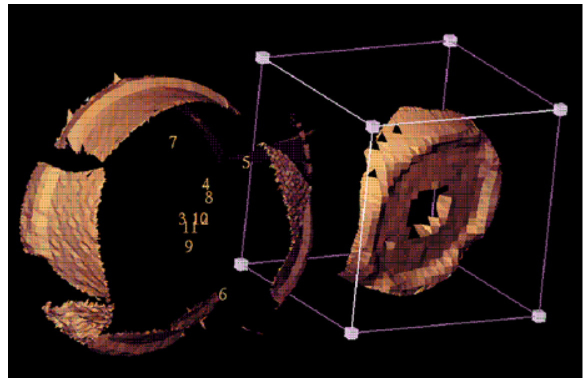


Fig. 10 An interface implementing damaged pieces restoration in the virtual space. Selected piece is assigned with a transform box which can carry the piece to move and rotate when itself is manipulated with the mouse.

Moreover, we can select a point on the object using the mouse and generate a center ball at that point. We can rotate the object around it by clicking and moving the center ball. By using this function, we can first move a piece to contact with another one and then rotate the piece around the contacting point to achieve a complete fit. More automatically, if we select a pair of corresponding points which will become a common position after assembly of two pieces, the system can move the pieces until the points are overlapped and fixed. The remaining move of the fragment is a pure rotation around the fixed point. This is called *one-point matching*.

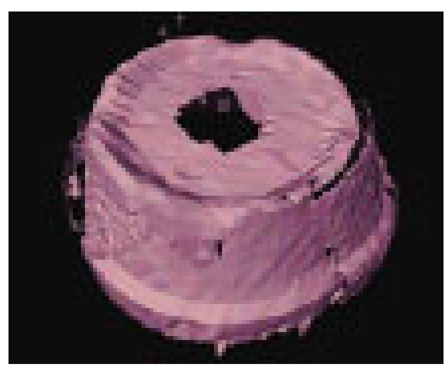


Fig. 11 Recovered pottery container in the virtual space.

An advanced function prepared is the connection by selecting three corresponding points, which is called *three-point matching*. The operator selects three corresponding points on both pieces. These points should not be on the same line. The transformation between the two pieces is then computed from them, and two pieces are connected automatically.

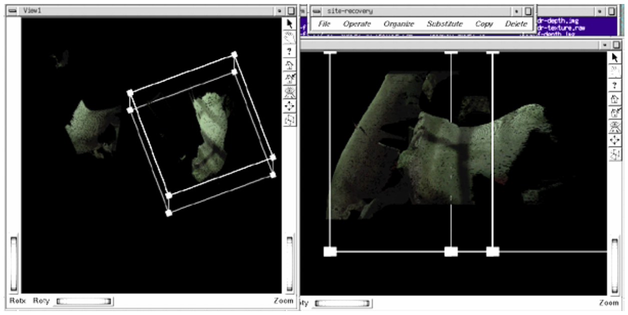


Fig. 12 Two pieces of a broken horse (about 2m long) are being connected. We can see their positions from two windows and manipulate one of them in either window.

In addition, a grouping function has been completed so that a group of fixed pieces can be moved together in the virtual space. This allows us to select remarkable pieces to perform the partial assembly, which provides more opportunities in selecting different ways of assembly.

In our experience, providing 3D shape and texture on the screen is not sufficient for determining the combination of fragments. We have observed that an archaeologist inspects the shape of fragment boundary carefully, checks the thickness and texture in searching piece candidates. This process is still required on real objects to have an approximate understanding on the relation of pieces.

4.2 Advanced Interfaces and Functions

Although we can move an object to a given position and rotate it to a desired orientation, it takes much time to fit all the broken pieces. To solve this problem, we use a 3D magnetic position sensor to input free movements of our hand in the object manipulation. The position sensor can provide translation and rotation simultaneously so that moving a piece to a position and in a particular orientation is straightforward. A trial and error in selecting pieces is easy to be done with the position sensor since such an operation only checks the piece combination briefly. A window shows the scene in front of the operator. The position sensor is calibrated to coincide the window coordinates system. A mouse is used to click objects, and the object motion follows the hand motion delivered by the position sensor. Figure 13 gives an example of using the 3D position sensor in fragment manipulation. The resulted shape is shown in Fig. 14.

Since the computer screen is two dimensional, judging depths of two pieces to be connected in the virtual space is very difficult. The operator has to move his view point frequently (rotate the whole set of objects in the virtual space) to check the difference in the locations of two focused pieces. Adding stereo display or adding head motion input to the computer so as to move objects in correspondence with the head motion may improve the flexibility of the system. However, it may also raise the cost very much.

An extra function being prepared is a collision detection of different objects. When we move a piece close to another, there has no restriction on the intersection of two pieces in the graphics world. This causes a difficulty in achieving a perfect connection. A collision-detecting function is required in the manipulation. The detailed way of finding collision is to examine if the triangular patches on the boundaries of both objects intersect. Because of the computational time, this function is fired only when we call it on the menu after a coarse move has been performed.

We are now improving the efficiency of virtual recovery. The idea is to let computer do as much trivial operation as possible to facilitate archaeologist's decision making. One of the approaches considerable is preparing an auxiliary model if the shape of an artifact is not complicate. When we move a piece close to the auxiliary model, the piece will be attracted to the model surface automatically and the fine adjustment is only performed along the model surface.

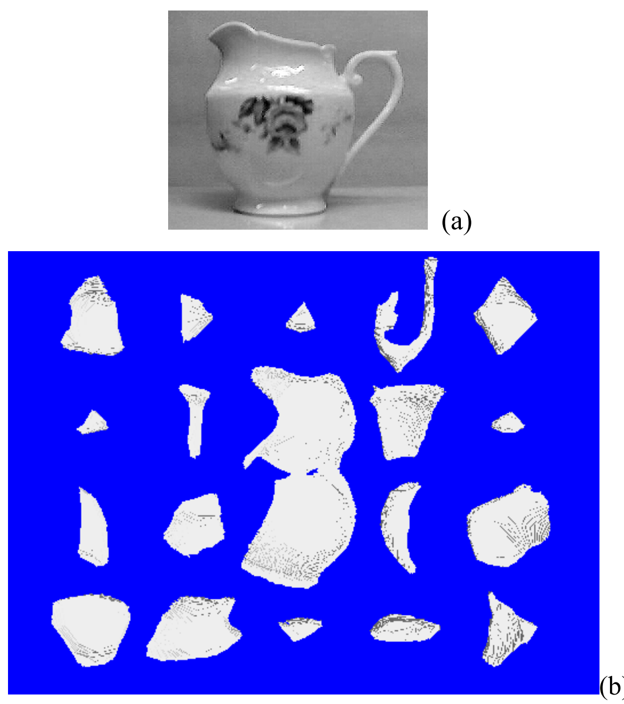


Fig. 13 A 20 pieces pot for testing virtual restoration using a 3D magnetic position sensor. (a) Original shape,

(b) Broken pieces.

4.3 Color Recovery of Excavated Finds

Recently, there is a trend in archaeology excavation to display unearthed objects in their excavated states. In order to show both the initial state and the recovered shape, multimedia technology becomes important and helpful. In the Museum of the Terra-Cotta Warriors and Horses, a part of excavated site will be remained in their original state: horses and warriors were collapsed, original pigments on the surface have dropped, and etc.

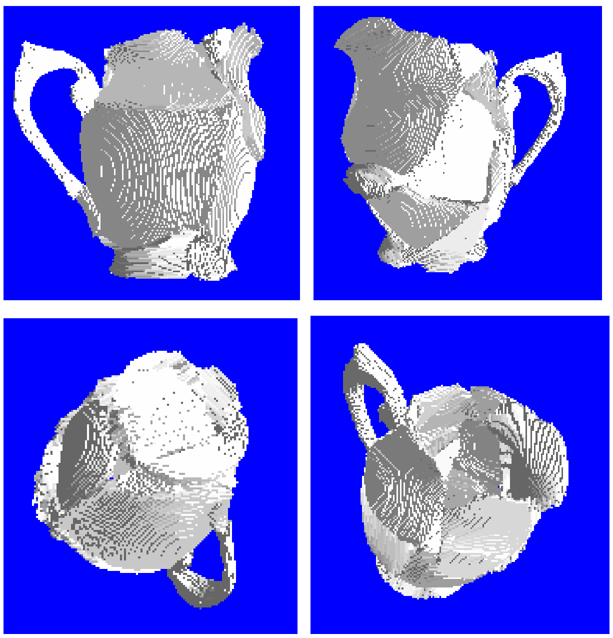


Fig. 14 Recovered shape from the fragments shown in Fig. 13.

In order to show the ancient state of unearthed objects, we need not only to connect broken pieces but also to recover the surface color, which is easy to be done using multimedia technology. We first open the texture map by *Photoshop*, and sample the remaining pigments at some small areas. Based on the knowledge from archaeologists, we determine different regions in the texture map corresponding to different materials on the object body. For each region, we change saturation, hue, and brightness there to make the color there close to the sampled color (this never means the region will have a homogeneous color). After the texture map is colored, a 3D model is established in the same way as we described previously. Figure 15 shows an original measured texture map and its recovered color distribution. The model is then generated and shown in Fig. 16. This process omits the construction of a new sculpture and painting on it for displaying the ancient colors.

5. Real Application

We select the Terra-Cotta Warriors and Horses of Qin Shi Huang Archaeology Line in Xi'an, China as a testing site. Totally about 8000 warrior and horse sculptures are estimated to be buried there. Each whole figure has about 100kg and a horse is even heavy. The museum side has spent almost 20 years in the excavation and recovery of those damaged relics. In our experiments, more than twenty sculptures and broken pieces at an excavation pit are measured.

Original texture map   Recovered color map

Fig. 15 Color the texture map of a 3D measure.

Before starting the virtual connection of broken pieces, we should have a brief understanding on the relation of different pieces, and the position each piece may locate. Inspecting details for connection using real fragments is more effective than inspecting measured models on the computer screen with a limited resolution. However, the real connecting process is easier to be carried out in the virtual space than on the real sculpture.

As to the accuracy of virtual recovery, the final goal is the consistency of different pieces visually observed on the display. The locations determined from the transformation of measured data are accurate as long as the selected corresponding points are precise. The locations determined from the manual manipulation of the pieces sometimes have big errors. Fortunately, what we want achieve is the consistency visually recognized on the screen. If we use the mouse system and perform a fine localization of pieces, we can still obtain a satisfactory result by means of enlarging the view and improving the position of objects repeatedly in both display windows. The magnetic position sensor, however, is hard to perform this task because of the limitation in its spatial resolution and its constant response to the hand motion.

The operation time to recover an object depends on how much we understand the relation of different pieces, how accurate the final position we want to achieve, and what type of computer we use. In the experiment, coarse localization of the pieces takes less time than modifying fine locations of pieces. Planning assembly on the screen does not take much time because we only confirm the consistency of connecting pieces and move them close to each other approximately, but have no requirements on the perfect alignment. Producing a 3D model for multimedia exhibition, however, takes much time.

The graphics machines used to do image processing and virtual display of the excavated finds is SGI O2 with a video board. A video control device Sony-VBox is used to connect a digital video camera Sony PC-7 to the graphics workstation by RS232. The laser range finder is developed ourselves and the 3D positions sensor is POLHEMOS-isotrack.

Fig. 16 Recovered surface color by referencing the remaining paints in the small areas of the sculpture.

6. Conclusion

This paper introduced a new concept of recovering ancient damaged relics, and an application of imaging, graphics and machine interface to archaeological excavation and exhibition. A portable laser range finder is developed for sensing artifacts at excavation sites. Virtual recovery of ancient relics in a computer generated virtual space has been first experimented and tested here. The significant advantages of the virtual recovery lie in preservation of unearthed objects and providing repeatable operation in restoring damaged relics. It may become an effective way of planning assembly and generating original shapes of relics in a multimedia format.

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