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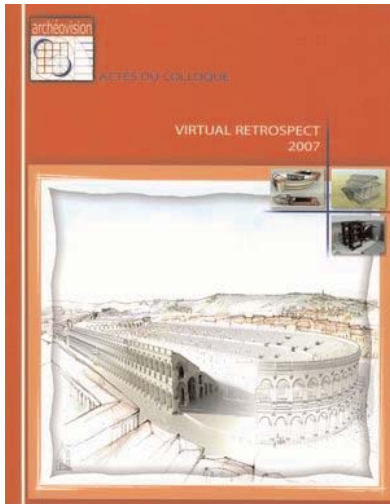
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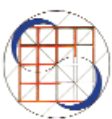
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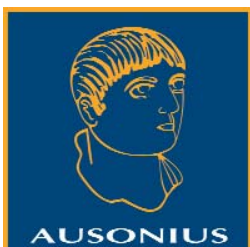
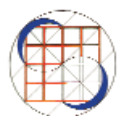
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A System for Re-Assembly of Fragment Objects and Computer Aided Restoration of Cultural Relics

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Abstract: In this paper, a system for re-assembling broken objects is discussed. It includes feature contours extraction, matching and re-assembling of 3D complementary objects, etc. These results are applicable to the restoration of culture relics through computer techniques. A computer assisted restoration system of culture relics is developed, which has been applied to the restoration of Terra Cotta Warriors and Horses of Qin dynasty.

Keywords: Assembly, Relics, Fragment, Matching, Terra Cotta Warriors and Horses

INTRODUCTION

Computer assisted matching and restoration is a difficult problem related to image processing and analysis, computer graphics, computer vision and pattern recognition. But the solution of the problem is meaningful for archaeology, paleontology, culture relic preservation and medical applications. The problem of assembling broken objects can be reduced as "jigsaw puzzle" problems (2D/3D). In 1964, Freeman and Garder¹ firstly proposed a solution of automatic assembling 2D shapes using computer. Later, many research made their contributions to 2D jigsaw puzzle problems². But for 3D case, it is more complicated and difficult. Therefore, the papers on re-assembling of 3D arbitrary broken objects are limited. Most of papers are restrict to ideal cases³, like only considering curved object without thickness. Gokturk Ucoluk and Ismail Hakki Toroslu discussed joining thin-walled fragments through discrete methods⁴.

1. Freeman & Garder 1964.
2. Radack & Badler 1982; Wolfson *et al.* 1988; Freeman 1978; Ayache & Faugeras 1986.
3. Helena Cristina 1998; Menard & Sablatnig 2001; Kishon *et al.* 1991, Del Bimbo & Pala 1997; Wang Yong-Mei 1998; Lai & Chin 1995 Ding Xian-Feng *et al.* 1998; Yang & Ma 1999; Anderson & Bezdek 1984.
4. Ucoluk & Toroslu 1999.

China is a country with long history and has very rich culture relics like Terra Cotta Warriors and Horses. There is a huge of relic fragments (fig. 1). It is very difficult and slow to restore them manually. Therefore to explore computer technique to assist restoration of culture relics is meaningful and necessary.

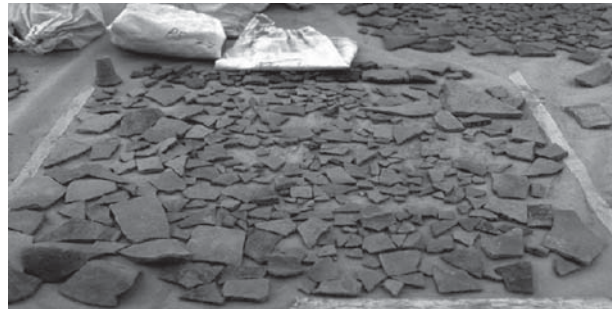


Fig.1. Relic Fragments.

For the re-assembling these fragments like in Terra Cotta Warriors and Horses, they can not be regarded as surface of thin-wall objects. In the paper, a solution of the problem for fragments with thickness is proposed. The rest of the paper is organized as follows. In section 2, data capturing and processing is introduced; in section 3, the Representation method and extraction algorithm of contours are discussed; in section 4, matching and assembling algorithms are investigated; in the end, some results of virtual restoration of culture relics are demonstrated.

DATA CAPTURING AND PROCESSING

Data Capturing

For the restoration of broken cultural relics, capturing high precision 3D data conveniently is very important. Here FastSCAN is used to obtain 3D geometric data (fig.2).

Data Processing

After capturing scattered data, some geometry processing is employed to obtain smooth and regular mesh. It is called preprocessing. Here we use Delaunay triangulation technique to convert scatter points to a smooth and regular triangle mesh. The algorithm includes three steps: preprocessing, triangulations and mesh optimization (fig. 3).

EXTRACTION OF CONTOURS

Extracting the exact feature contour curve is the key solve shape matching. Our work aims at extracting feature contour from fractured solid objects with thickness in triangular mesh representation. Here we divide the fractured solid objects into external surface and fractured surface, internal and external contours. For external contour extraction, a method based on the multiplicity of edges is employed (fig. 4).

When fractured surfaces are captured, the contour consisting with boundary edges is called external contours; the feature curve consists of internal edges on the fractured surfaces is called internal contour. The normal directions change cross these edges on the internal contours (fig. 5).

When fractured surfaces exit, the internal and external contour must intersect. For the extraction of internal contour, we take advantage of this information on edges as well as faces and their normal distributions. The intersect points are regarded as seed vertices to compute internal contour and a seed searching algorithm of internal contours is designed. Figure 6 is result of extracting internal and external contour of solid object with fractured surfaces.

MATCHING AND ASSEMBLING

Matching 3-D polygonal arcs based on junctions

Matching 3-D polygonal arcs is a problem in computer vision, image analysis and pattern recognition. The goal is to find the maximum 3-D polygonal overlapped sub-arcs between given two 3-D polygonal arcs, i.e. determine the part with same shape they have.

Here a fast algorithm of matching 3-D polygonal arcs is used. The algorithm is built through introducing junction vertices after analyzing the shape of 3-D polygonal arcs. Moreover, through the local coordinate system of junction vertex, a spherical coordinate system is created. So the spherical coordinate set on junction vertex is used to represent polygonal arcs. The representation is invariable under the transformation of translating and rotating. Therefore, the

spherical coordinate set is regarded as feature set of the polygonal arcs. Such feature set keeps geometric attributes as well as topological attributes of polygonal arcs. And the problem of matching 3-D polygonal arcs is reduced to matching 1D numerical string. So the match method is becoming simple and fast. The measurement function is mean-square errors of the corresponding junction vertices. Matching example using the algorithm is shown in figure 7.

Matching under surface constraints

During matching fragments of culture relics, even if their contours are matched, these fragments can not be assembled as only information of contours are not enough. So more constraints are needed. Here based on contour matching, some surface constraints are employed.

Matching under surface constraints is implemented by the following work: (1) during obtaining contours from triangle mesh, these cross tangents are computed; (2) matching polygonal arcs of corresponding vertices; (3) To these curve segments which are successfully matched, the 3D transformation is employed so that these curve segments meet together. Then the cross tangents on them are tested if they are smooth.

3D assembly based contour matching

The problem of 3D assemblage is far difficult than 2D. Matched contours are only necessary condition. It often happens there are several cases of matching contours. Therefore assembling different part generates different results. As in figure 8, assembling the longest matched contour is not real original shape. But in figure 9, although only sub curve is matched, the result of assemblage meets original shapes.

From above examples, we know to obtain effective assemblage, more constraints are needed. Here two conditions are suggested:

- 1) Maximum possible assemblage condition For a fragment, the fragment will assemble it has the longest matched contour among all fragments;
- 2) Geometric constraint condition: As the whole surface after assemblage is smooth, the two matched fragments should be at least G continuity.

According to above condition, the assemblage has three parts. (1) 3D curve matching and recording all possible matching pair of sub curves; (2) assemblage according above rule; (3) determine and select an effective result.

The whole procedural is one generates a binary tree (fig.10). Each node is a fragment. The root is the reconstructing result.



(a) Scanning data



(b) Scattered points

Fig. 2. Scanning relics.

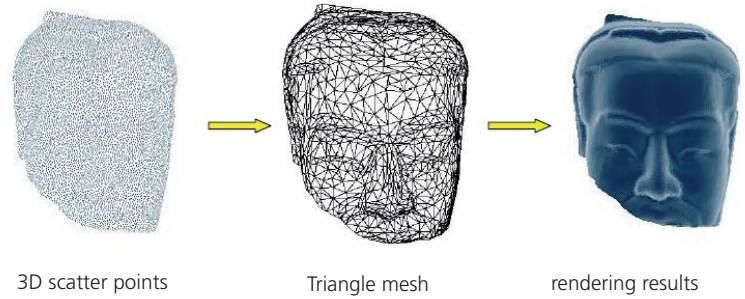


Fig. 3. Data processing.



Fig. 4. The results of contour extraction.

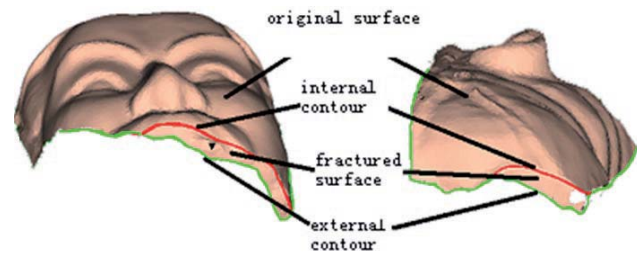


Fig. 5. Internal and external contour on fractured solid object.

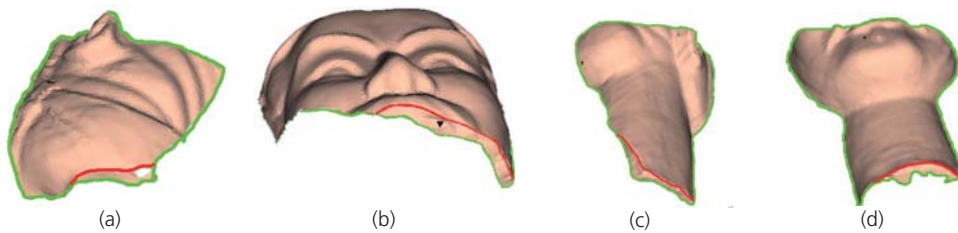


Fig. 6. Extracting internal and external contour of solid object with fractured surfaces

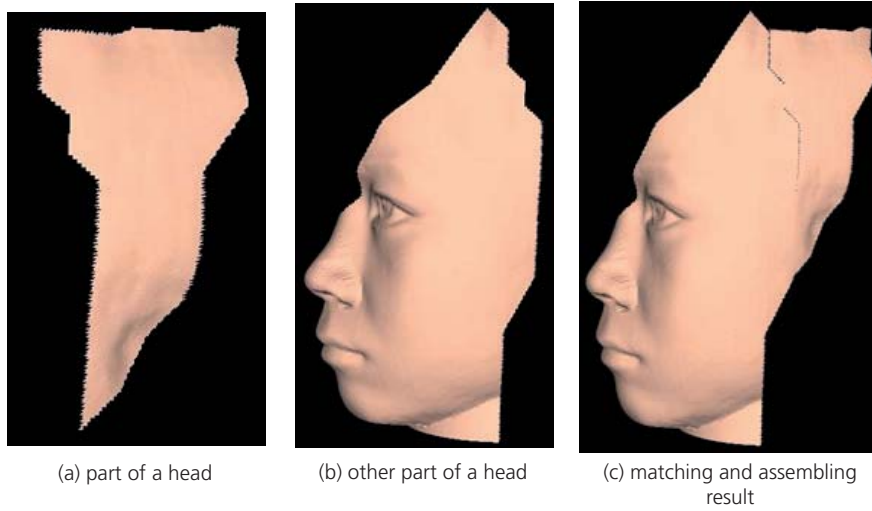


Fig. 7. Matching results.



Fig. 8. Assemblage of fragment objects through contours matching does not meet original shape.



Fig. 9. Assemblage of fragment objects through contours matching meet original shape.

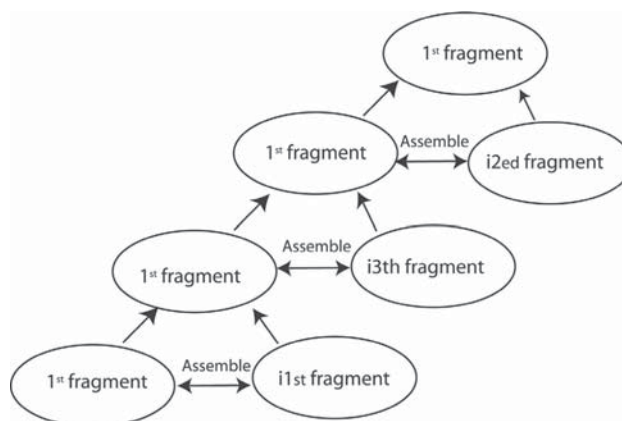


Fig. 10. Diagram of assemblage.

POST PROCESSING

Repair of beams and holes

After assembling two objects according to their contours, there exist some seams and holes as some data have been lost. Therefore, to these seams and holes, the repair is necessary. Here the repair method is investigated: given two triangle mesh models which will be assembling. Firstly these redundancy triangles are removed so that their boundary triangles are overlapped; then these isolated vertices form a suture lines after removing boundary triangles. So the suture lines as skeleton links the two triangle meshes.

1) *Removing redundancy triangles*

A redundancy triangle is these triangles which are overlapped completely by other triangle. Taking the average viewpoint of assembling mesh as viewpoint, these triangles are projected onto 2D plane so that the relationship like overlaying, intersection and overlapping are determined. Redundancy triangles are deleted from outside to internal until they are deleted completely.

2) *Removing these boundary triangles which intersect*

Boundary triangles are these triangles on outside boundary. After deleting these intersected boundary triangles, isolated vertex and new boundary are generated.

3) *Generating suture lines*

Suture lines are obtained by above isolated vertices. Firstly the distance between each two isolated vertices are computed. If it is less than a given threshold, the two vertices are combined into one; secondly, all vertices are linked to form a suture line through nearest vertex extension. The above threshold is perspective to the average length of edges in mesh. Nearest vertex extension Initially all vertices are not linked. Firstly nearest two vertices are searched and linked. Then the nearest unlinked vertex to these linked vertices are searched. If the nearest linked vertex to it is inside, it is deleted. If not, it is linked. After repeating above action until each vertex is linked or deleted.

4) *Generating suture surfaces*

The two meshes are sutured through constructing suture surface between new boundary and suture lines. For each mesh, starting one segment of new boundary, suture surface is constructed one by one segment. Suppose the vertices of suture line as p_0, p_1, \dots, p_n , the vertices of new boundary as q_0, q_1, \dots, q_m . p_{prev} represents the best vertex for suturing last triangle on new boundary, p_{now} represents the best vertex for suturing current triangle on new boundary.

The holes are repaired through approximating surface (fig.11) demonstrates the effect.

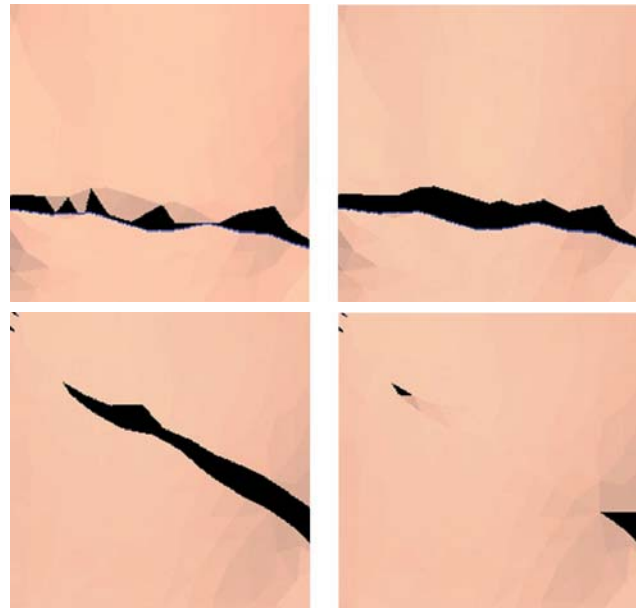


Fig. 11. Repairing.

VIRTUAL RELIC RESTORATION SYSTEM

Based on above methods, a computer-aided heritage recovery system of broken artifacts debris is developed in VC++6.0 and OpenGL. The system structure is shown in figure 12 and system functions are shown in figure 13.

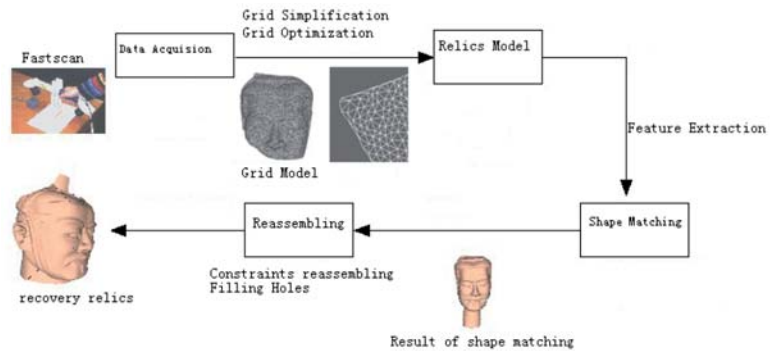
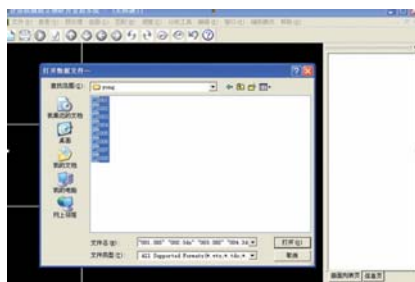
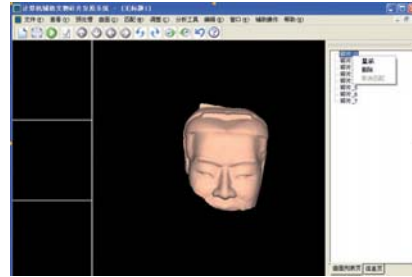


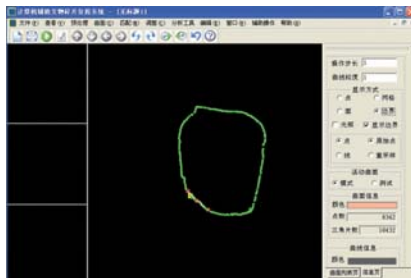
Fig. 12. System diagram of Computer Aided Restoration of Cultural Relics.



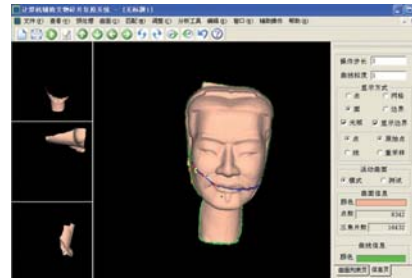
(a) Input data



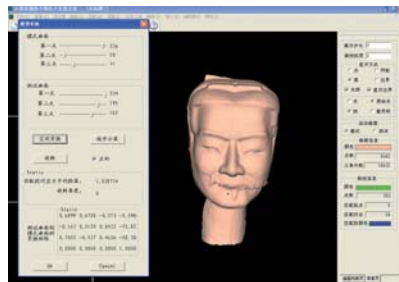
(b) Displaying (rendering)



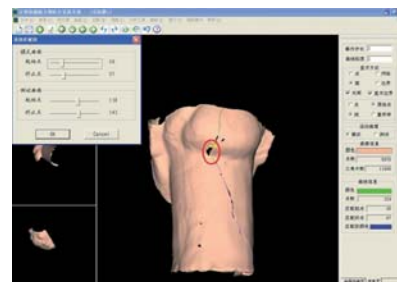
(c) Displaying contours



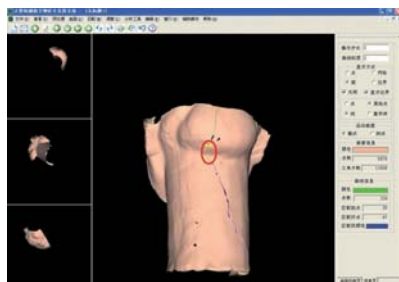
(d) Matching shapes



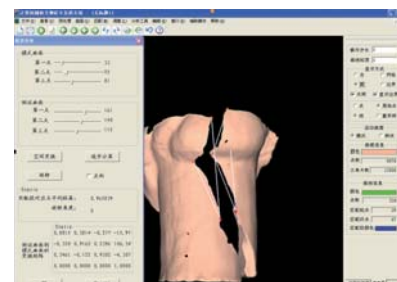
(e) Fine-tuning



(f) Selecting seam is to repair



(g) Repairing seams



(h) Repairing seams

Fig. 13. System functions.

RESULTS AND FUTURE WORK

This paper introduces an approach of re-assembly of fragments. It covers the techniques of extraction of contours on solid objects with fractured surfaces; matching complementary object method based polygonal arcs and matching under surface constraint and 3D assembling. Based on them, a computer aided restoration system of culture relics

is developed which is applicable to cultural relic restoration. Here some examples show the effects of the system which is applied to repairing Terra-Cotta Warriors and Horses (fig. 14).

In the future, more attributes like color, texture are employed into matching and assembling fragments.

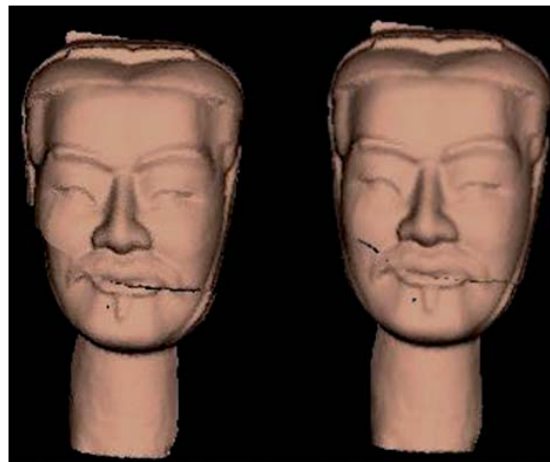
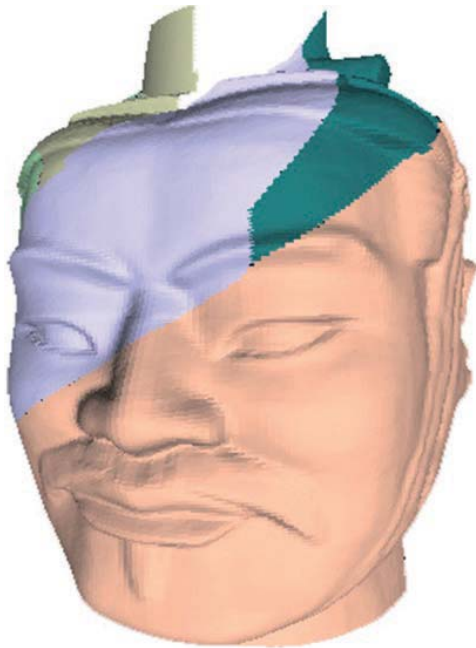


Fig. 14. Re-assembling fragments from Terra-Cotta Warriors and Horses.

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