The Journal of the Society for Art and Science, Vol. 18, No. 1, pp. 40 – 50 (2019)

Visualization of Flake Knapping Sequence with Analyzing Assembled Chipped Stone Tools

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Abstract
For studying stone tools, repeating assembly and separation of stone tools is an inevitable process. The instructions of this process, however, are ambiguous when traditional 2D illustrations are used. The 3D exploded view is an effective way for instructing the assembly, and it has been widely used in many fields, while it has seldom been used in archaeology. We apply this powerful presentation technique to stone tool models, and study methods of generating exploded graphs and assembly sequences with point clouds of stone tools by computer graphics algorithms. Moreover, lithic knapping methods and relic excavation reports are analyzed to evaluate the difference of flake knapping sequences between the contents of report and automatic generation by using an algorithm. In addition to presentation of principles for restoring stone tools, we design the functions and algorithms of our system based on archaeological rules. The experiment results of stone tool assembly show effectiveness and practicability of the proposed method. The user evaluation indicates that 3D visualization technology can assist in efficient research of flake knapping sequence instruction for chipped stone tools.

Keywords: Stone tools, Flake knapping sequence, Visualization instruction, Exploded diagram.

1 Introduction

In archaeology, stone tools indicate a variety of cutting tools or weapons made by human beings during the Stone Age by striking or polishing rocks. They are very important historical evidences in the research of human activities. Reassembling the raw rock from stone tools is a necessary process for finishing and analyzing excavated relics, as these relics are scattered and distributed in sites similar to the one shown in Figure 1 [1]. With analyzing assembled stone tools, archaeologists can study the technical characteristics of a time period by analyzing the shapes of several matching flake surfaces. Moreover, the relationship between neighboring sites can be determined by the distribution of assembled stone tools. Therefore, repeating assembly and separation stone tools is an inevitable process in the study. However, traditional archaeological illustrations have largely affected the efficiency of assembly operations. This is because it is extremely difficult to identify 3D objects by using 2D scale drawings or pictures. In addition, the process of 2D scale drawings is time consuming.

On the other hand, 3D exploded view diagrams have been widely used in many industries since the introduction of assembly instruction visualization in 2003 [2], including furniture products, CAD models and medical volume data. In the field of cultural heritage, many assembly models are created to restore relics. The technologies and tools of computer

Figure 1: A photo of an excavation site showing scattered stone tools.

graphics can effectively assist archaeologists for analyzing archaeological findings through reconstruction and visualization [3]. In spite of the numerous reassembling methods and pairwise matching algorithms proposed for fractured objects [4, 5, 6], no application of assembly instruction has been developed for archaeological research.

Many methods have been proposed for feature extraction and analysis of lithic [7, 8], while our work focuses on the refitting of stone tools using digital technology that few researches have been proposed.

In this paper, a method to interactively generate a flake knapping sequence is proposed for visualizing assembly instruction of 3D stone tool models, in order to improve the user experiences. This work is extended from a preliminary work presented by our conference paper [9]. In this paper, our contributions include the following:

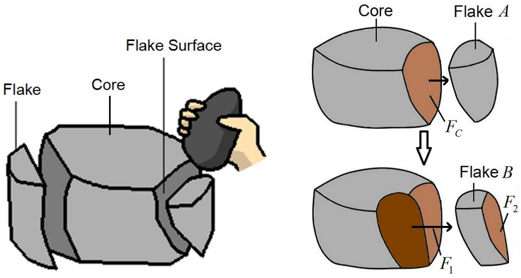
(1) In addition to the design principles for automated generation of assembly instructions [10], we propose the principles for instructing the refitting of stone tools based on archaeological rules, whose details are described in Section 2.1.
(2) A comparative analysis is made between an automatically generated sequence and a flake knapping sequence in the archaeological report.
(3) An interactive system is developed to assist archaeologists through step-by-step instructions and exploded views.

The three contributions are related as follows: item (1) is the elemental technology of our method and item (2) is for evaluation of the consistency between the result of item (1) and the content of the report. Furthermore, when the result of item (2) is different from the user expectation, the intended information can be presented in the editing procedure using item (3).

2 Related Work

2.1 Lithic technology and traditional illustration

When a stone tool is created, rock edges are struck repeatedly with a pebble, and flake pieces are obtained in various sizes as shown in Figure 2(a). Each of the flakes is peeled to adjust the stone tool shapes. A flake surface is an adjacent surface between two flakes, and the core is the remaining portion of the rock. Thus, assembly operation of a stone tool is restoration with the core and the flakes peeled from the same rock scattered over an excavation site. The flake knapping sequence represents the order in which flakes are peeled from the outside to the inside in stone tool creation [11]. In addition, when one flake surface may be divided into several pieces [12], part of the flake knapping sequence can be decided by considering reconstruction relationships. For example, as shown in the Figure 2(b), both Flakes A and B are adjacent to Core, but Flake A should be peeled before flake B. This is because the flake surface F_C is obtained by combining flake surfaces F_1 and F_2.



(a) (b)

Figure 2: Making a stone tool.

2D illustrations and photos are employed to depict the shapes and grain characteristics on lithic materials in the traditional archaeological literature [13]. Figure 3 shows traditional illustrations in an archaeological report [1]. A restored stone tool is exhibited in several 2D side views. Figure 3(a) depicts the details of the assembled stone tools, and in Figure 3(b), the pieces are labeled with identifying numbers. Archaeologists decide the flake knapping sequence by observing the real stone tools, and record it as 55→58→61a→· · · . Although these pictures can be more accurately generated by a software [14], assisting hand-drawings, the shape of each stone tool and their position relationship are difficult to determine with such simple outlines. While the flake knapping information is explained more intuitive by 3D techniques, such as, 3D data display with flake ID, diagram viewers for assembly and separation direction and posture of flakes, a demonstration of flake knapping sequence.

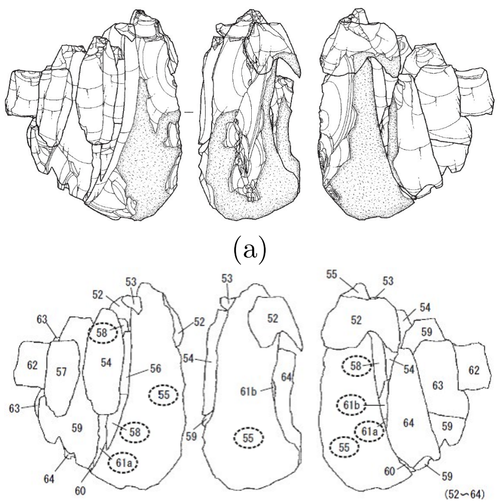

(a)
(b)

Figure 3: Traditional illustration of stone tools in a relic excavation report [1]. (a) The outline of the shape and grain characteristics of stone tools. (b) The identification of each stone tool by numbers.

2.2 3D illustrative visualization

The 3D exploded view diagram is a view that can separate an assembly using a specified order, orientation, and distance. The view can expose and analyze the inner structure of the assembly, and exhibit the position relationship between parts. Action diagrams can be generated to clearly depict parts and operations required in each assembly step using the exploded view [2].

Tatzgern et al. [15] and Li et al. [16] presented the systems that automatically generate exploded diagrams of complex 3D CAD models. Lau et al. [17] developed a framework for generating parts to be fabricated and connectors from 3D furniture models. Igarashi el al. [18] introduced an interactive system to assist design and construction of 3D beadwork with a step-by-step guide. Karpenko et al. [19] presented a technique for visualizing complicated mathematical surfaces. Bruckner and Gröller [20] applied exploded views to volumetric data, then Balabanian et al. [21] introduced an interactive illustrative visualization for medical volume data. Furthermore, 3D illustrative visualizations have been developed for more functionality. Mitra et al. [22] illustrated the motions of individual parts and the interactions between parts, and an automated approach was presented to illustrate how mechanical assemblies work. Assembly and disassembly illustration is applied to the design of a burr puzzle from a given 3D geometric model [23]. A computational solution is presented to support the making of interlocking furniture assemblies [24].

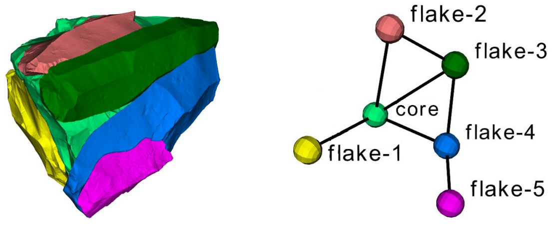
All of these methods using 3D visualization technology obtained superb instruction results as compared with manual works. However, it is simple to obtain the relationship and the exploded direction between adjacent parts for CAD designed models by input. While we have to study the method to calculate these basic informations for the point cloud models of stone tool.

3 Our System

Our system is designed to comply with archaeological rules. The input of our method is a set of matched point clouds C created by scanning stone tools with almost the same density, as shown in Figure 4(a) [25]. In addition, we assume that users already know which part is the core.

3.1 3D exploded diagram generation

Relationships. The adjacent relationships of the parts to be assembled are scored by the number of adjacent points with the Hausdorff distance smaller than d_ε. For each pair C_i and C_j of stone tools from C, it is assumed that the number of points in C_i is smaller than C_j. C_i and C_j are regarded as adjacent models according to the number of adjacent points A_{ij}, which is greater than $\alpha(\alpha < 1)$ times the number of points in C_i. The adjacent point p_i from C_i is computed by equation(1). To improve the robustness of the error metric, the mean distance of k nearest points p_j from C_j is calculated for point p_i from C_i.



(a) (b)

Figure 4: Original input models and the generated adjacent relationships. Spheres in (b) correspond to the stone tools with the same colors in (a).

By calculating and connecting the center points of each stone piece using the axis-aligned bounding box (AABB), the 3D adjacent relationship graph is obtained as shown in Figure 4(b).

$$d(p_i, C_j) = \frac{1}{k}\sum_{j=1}^{k} \|p_i - p_j\|^2 \qquad (1)$$

Directions. The flake surfaces of stone tools approach to a plane. Consequently, the exploded direction of each part is determined as an approximated normal vector of the adjacent points using the principal component analysis (PCA) on the center point. For example, in Figure 5, the red points represent the adjacent points A_{ij}, and the coordinate system is computed using equation(2), where p_i is each point from A_{ij} and $\bar{p}$ is the average point of all the adjacent points. The eigenvectors v_1, v_2 and v_3 of the covariance matrix M_c represent the coordinate axes z, y and x, respectively, corresponding to the eigenvalues of λ_1, λ_2 and λ_3 ($\lambda_1 \leq \lambda_2 \leq \lambda_3$). Thus, the exploded direction lies along the coordinate axes z. The exploded distance about each part is set by the user.

$$\begin{aligned} &M_c = \frac{1}{k}\sum_{i=1}^{k}(p_i - \bar{p})(p_i - \bar{p})^{\mathrm{T}}, \\ &M_c \cdot v_l = \lambda_l \cdot v_l, \\ &p_i \in A_{ij}, l \in \{1, 2, 3\} \end{aligned} \qquad (2)$$

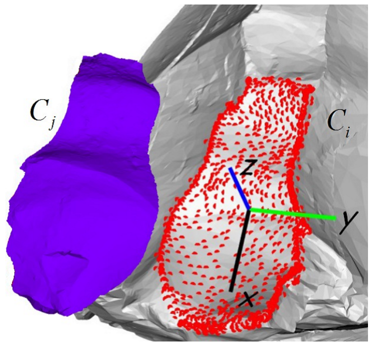
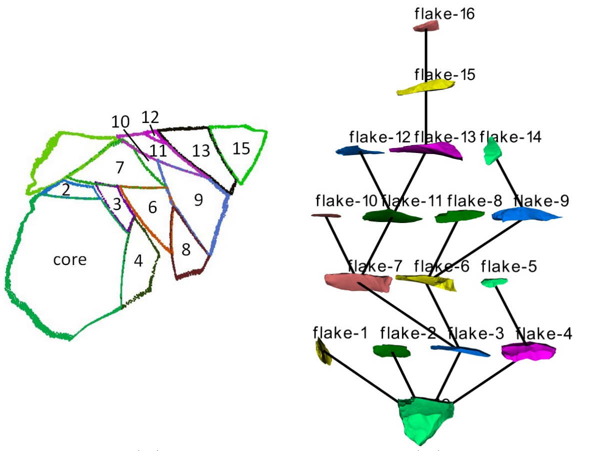


Figure 5: Calculation the coordinate system of a flake surface from adjacent points.

3.2 Flake knapping sequence analysis and editing

Starting from the core of the assembly specified by a user, the undirected relationship graph can be converted to a directed graph. In the previous work [9], a hierarchical tree is constructed as shown in the Figure 6(b), according to the shortest path of each part of the directed graph. The exploded order can be determined by the breadth-first-search (BFS) algorithm of the hierarchical tree from root. Then, the assembly sequence of stone tools is exhibited through a visualized step-by-step instruction.

In the previous work, the problem of the order of the parts that belong to the same node is



(a) (b)

Figure 6: (a) A cross section of the assembly of stone tools. (b) A constructed hierarchical tree from the relationship graph of the assembly of stone tools.

solved by an interactive control. By introducing the detection of flake surface reconstruction described in the Section 2.1, this problem can be solved very well in most cases. For example, let us consider the order of $flake - 6$ and $flake - 7$ that shown in the Figure 6. Obviously, $flake - 7$ should be peeled before $flake - 6$ because $flake - 2$, $flake - 3$ and $flake - 6$ are reconstructed to match with $flake - 7$. In order to display the relationship of flake surface reconstruction, a relationship graph is employed instead of the hierarchical tree as shown in Figure 7, and node R is inserted before each reconstruction flake for highlighting such relationships.

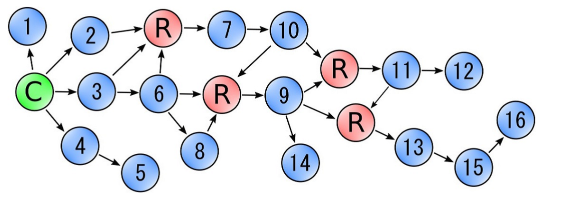


Figure 7: A relationship graph including the reconstruction relationships. The red nodes show reconstruction relationships and the arrows indicate assembly directions.

In addition, the flake knapping order of some stone tools is difficult to determine since the stone tools are not adjacent to each other. Figure 8 shows an example in the relic excavation report [1], where a part of the recorded sequence is ⟨485⟩⟨487⟩→489→488→486→490→⟨492⟩⟨491⟩···, and symbol ⟨◯⟩ is employed to express undetermined context. In other words, we cannot decide the order of peeling. For this situation, in archaeology, the order is estimated and decided by experts who are familiar with stone tool manufacturing techniques. Consequently, our system provide a function that enables free editing of flake knapping sequence.

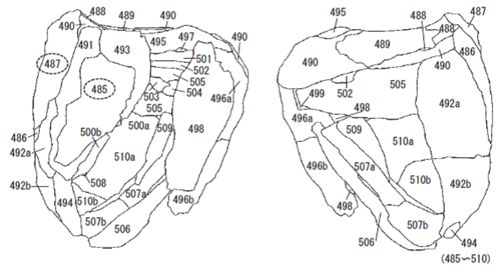


Figure 8: An example from the relic excavation report [1].

4 Experiment

We have implemented the proposed method on a PC with Intel Core i7-4790 CPU and 8.00GB memory, the C++ programming language is used with Visual Studio 2013 and Windows 7.

4.1 Results

The assembly of group 1 consists of 18 stone tools and the assembly of group 2 consists of 12 stone tools. The original models are shown in Figure 10. For groups 1 and 2, the average number of points in an object is about four thousands and ten thousands. The threshold d_ε and α for the relationship calculation are set as $\{1.0, 0.02\}$ and $\{0.5, 0.01\}$, respectively. The computation time lengths of diagram generation are about 12.3 seconds and 3.1 seconds. Figures 11 and 12 display the 3D exploded diagrams for the two assemblies. The space positions of the models and adjacent relationships between the restored stone tools

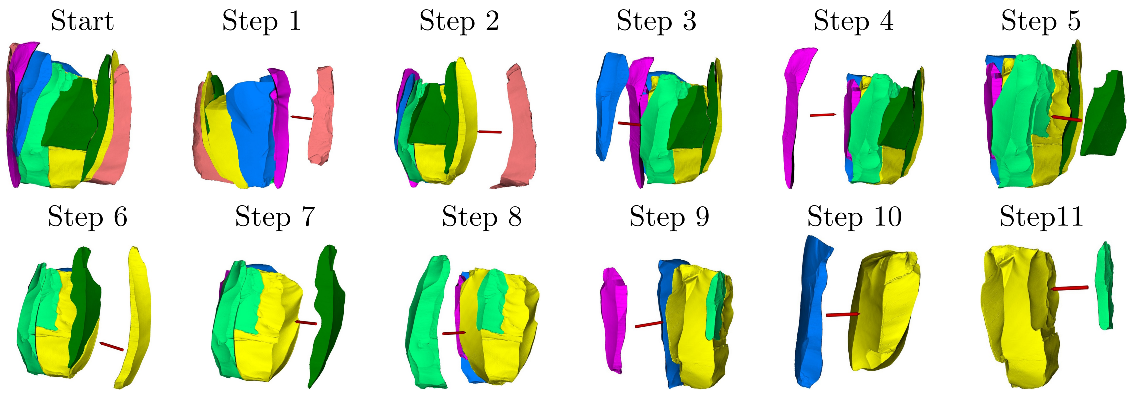


Figure 9: Flake knapping sequence instruction with a step-by-step guide for group 2.

are powerfully visualized in the 3D exploded diagrams.

Figures 13 displays the relationship graphs with reconstruction relationships for groups 1 and 2. Four reconstruction relationships are detected in group 1 and six in the group 2. According to the information of reconstruction surfaces, ambiguous flake knapping sequence can be decided in most cases.

Figure 9 presents each step of the flake knapping process for group 2. Our system could automatically generate the flake knapping sequence, and the sequence can be edited by user. The experiment results demonstrate that our system automated generation of exploded views for the assembly of stone tools, and the assembly or separation operation is exhibited distinctly via the step-by-step instruction.

In addition to conventional materials of archaeology, trace patterning can be more objective with utilizing 3D data obtained by measurement. It can make a contribution to stone certification theory, model theory and the analysis of manufacturing traces. Besides, it is necessary to mutually verify construction of assembling algorithms and deciphering of stone fabrication technologies. Our system assists archaeologists to reproduce the making process of stone tools repeatedly and observes the peeling traces between adjacent flakes.

4.2 User experience

For the user evaluation, all models of groups 1 and 2 are fabricated by a 3D printer. Two experiments are designed to evaluate our system. In the first experiment, we compared the reassembly time of stone tools with three methods: no reference, traditional illustrations, and our system. We invited six users as our subjects who had no experience for this research. They were required to reassemble stone tools within an hour. Each method was tested by the two subjects and each subject was not supposed to reassemble a group of models twice in order not to use the memories. The experiment results are shown in Figure 14. The dashed lines, evaluation results from experts, will be explained later. The solid lines show the average recorded reassembly time lengths, in which group 1 could not be reassembled without reference in an hour. In contrast, our system assembled groups 1 and 2 in 9 and 5 minutes. This result shows that our system greatly reduces the time length for reassembly.

We invited four subjects to carry out the second experiment. Each subject compared the feeling of reassembly referring to traditional

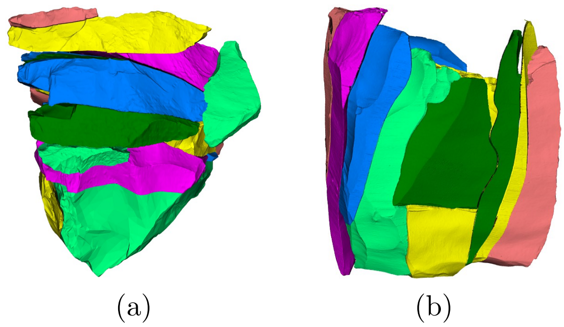
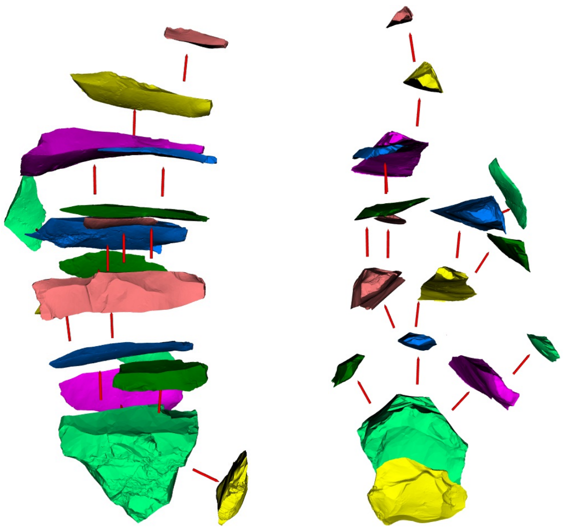
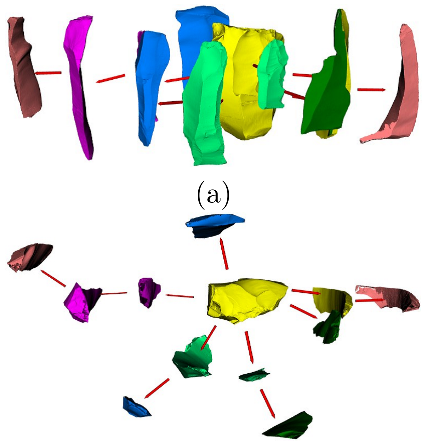


Figure 10: Original models of groups 1 and 2.



(a) (b)

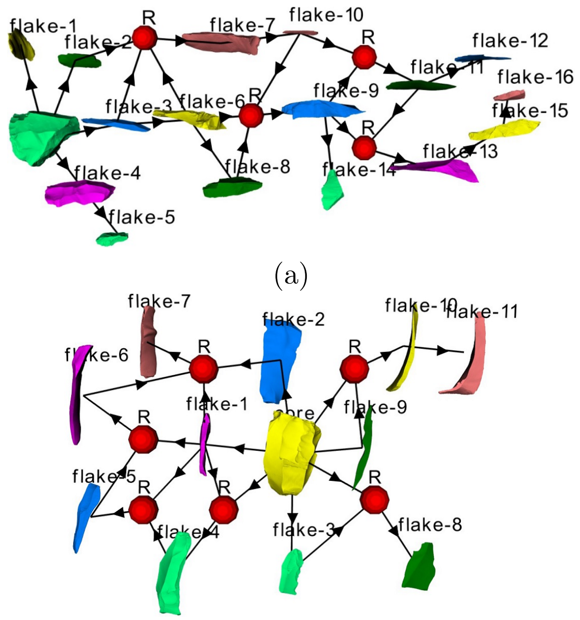
Figure 11: 3D exploded diagram of group 1.



(a)

(b)

Figure 12: 3D exploded diagram of group 2.



(a)

(b)

Figure 13: (a) 3D relationship graph for group 1. (b) 3D relationship graph for group 2.

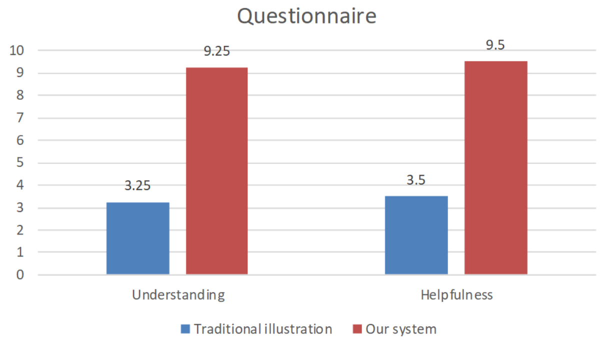


Figure 14: Reassembly time lengths (min).

illustration with our system for one group. Two questions are designed in our questionnaire. Question 1 is: score the comprehension for understanding the guidance and applying it on the assembly. Question 2 is: score the helpfulness between the traditional illustration and our system. The result of the comparison is shown in Figure 15. For the feedback of subjects, they said it is easy to recognize which one should be reassembled in the next step, and 3D exploded diagrams clearly show the position and posture of assembly.

We also invited two experts to let them evaluate our system. One of them made a comparison between assembly with no reference and with our system for groups 1 and 2, which is shown in Figure 16. The dashed lines in Figure 14 show the results. We can see that the assembly time without reference is distinctly shorter than the assembly by the non-experts because of his archaeological experience. On the other hand, the assembly times required by our system are longer than non-experts, since the archaeologist expended a lot of time to evaluate the assembly directions computed by our method. In general, they think our visualization is a new expression way for lithic assemblage and the automatically generated flake knapping

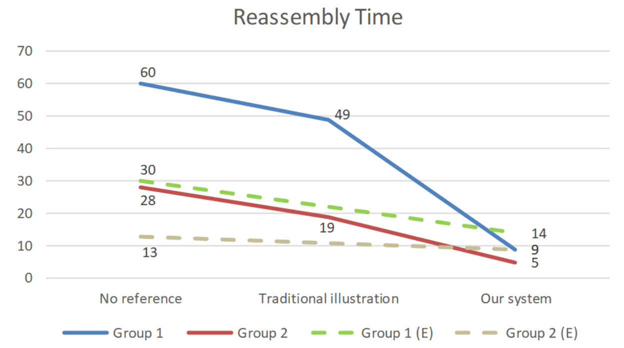


Figure 15: Result of questionnaire.

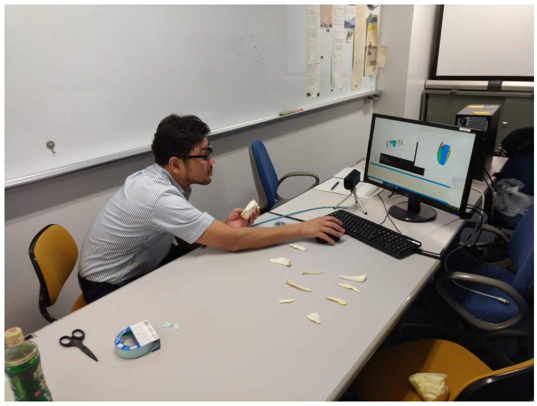


Figure 16: A photo of the experiment by an expert.

sequences are consistent with the principles of archeology, which can be concluded that our system can greatly assist in the research of stone tools, having the following specific advantages:

(1) The drawing of traditional illustration requires a lot of manpower and time. 3D modeling makes it possible to plot all models easily, which greatly reduces the burdens on operators. Additionally, 3D modeling enable easy analysis of the cross-section structure of lithic assemblage.

(2) The understanding of traditional illustrations and symbols requires much expertise, while the feeling of 3D visualization is closer to handling of the actual objects. The exploded diagram is an excellent explanation for showing the place and direction of joining, which saves the time of trial and error.

(3) The visualization of reconstruction relationship 'R' is a great innovation that has not been achieved in archeology.

(4) Sequence editing is an outstanding function for analyzing the technique and intention of production. It also increased the versatility of the proposed system.

4.3 Limitations

The limitations of our system are also pointed out by archaeologists.

(1) The correspondence recognition between a 3D model and an actual object could be further improved by labeling IDs and mapping textures.

(2) The parameters such as thresholds d_ε and α should be tuned via the user interface, instead of manual input, especially the free editing of sequences.

(3) For the instruction viewer shown in Figure 9, free movement of the camera provided by our system is not convenient to demonstrate the assembly directions carefully, thus an obvious view should be computed.

(4) One of the important points for improving the current system is the direction of the stone separation. Different from mechanical assemblies, the separation of lithic assemblage is studied by the striking points and directions to understand the purpose of production and the used technique of ancients. By adding such information, the users can more easily understand the direction of stone separations and can more intuitively assemble stone tools with our system. While we have partially attempted to add the above information in our recent study [9], it was not accurate enough.

For these limitations, items from (1) to (3) could be solved by adding these functions in our system. Since the striking points and directions in item (4) require a complicated inference, these computations will be studied via further discussions with archaeologists.

5 Conclusions and Future Work

In this paper, we proposed a method to visualize the instruction of flake knapping sequence for assembly of stone tools. The visualization system is designed based on the archaeological conventions, and the evaluation results have shown that our system could assist archaeological research. For the further work, we will improve our system according to the evaluation of the experts. We will also study the effectiveness of the proposed algorithm by applying it further to massive data for broad application to the assembly visualization in archaeology.

Acknowledgements

Part of this work was supported by JSPS KAKENHI Grant Number JP18H00734. The basic concept of our method has already been presented in NICOGRAPH 2017 [26] and we extended the concept in this paper. We would like to express our gratitude to Assoc. Prof. Oyokawa, who belongs to Shimane University, for his comments. We are extremely grateful for lots of advice from the paper reviewers.

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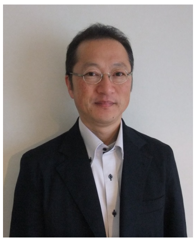

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