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A New Method of Refitting Mixture Lithic Materials by Geometric Matching of Flake Surfaces

Xi Yang **Katsutsugu Matsuyama** **Kouichi Konno**

Graduate School of Engineering, Iwate University

{yangxi} (at) lk.cis.iwate-u.ac.jp

Abstract
In Japan, lithic materials are very important evidences of human activity research in the Palaeolithic and Jomon periods, while refitting lithic materials is a complex and hard task. In our previous research, it is possible to refit lithic materials from a single stone core, while it is impossible to refit them from multiple stone cores. This paper proposes a new method for refitting mixture lithic materials by matching flake surfaces. Each of the input point clouds of lithic materials is segmented and simplified to obtain flake surfaces. Then, according to several refitting principles in archeology, the lithic materials are matched starting from a stone core by searching the best matching flake surface. The flake surfaces of matched lithic materials are reconstructed, and the matching process is repeated until all data are matched. The implementation of the new method can obtain good refitting results for experimental examples.

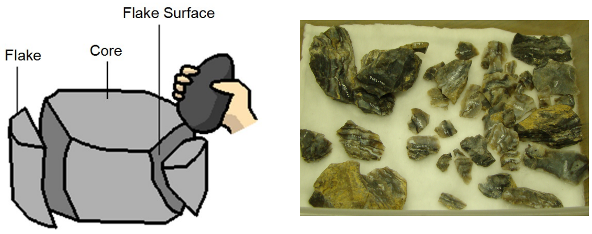
Keywords: Refitting, Lithic material, Matching, Flake surface.

1 Introduction

In archaeology, archaeological materials are very important evidences of human activity research[1]. With the data, archaeologists can study the time's technical characteristics, sociocultural backgrounds, habits and other significant subjects. The stone tools are regarded as cutting tools or weapons made by striking or polishing rocks, and people in the Palaeolithic and Jomon periods made a variety of tools. However, the most of excavated relics are just stone tools in Japan because the weather in Japan is almost hot and humid and the ground soil is acidic. In this environment, the most organics, such as bones or woods, except stones are perished easily. Hence, lithic materials can be the main objects for tracing human activities in the ancient times[2].

To make a stone tool, the edge of a rock is struck repeatedly with a pebble, and flake pieces in various sizes are obtained as shown in Figure 1 (a). These pieces are called lithic materials and the flakes are the pieces peeled for adjusting the core shape. The core is the rock left as a raw material for a stone tool when flakes are peeled[2]. Refitting and reassembling lithic materials is a very important work to finish the excavated relics. In addition, by refitting lithic materials, the manufacturing process of stone tools can be restored and human activities in the ancient times can be conjectured. On the other hand, by reassembling lithic materials, not only the original form of relics but also specific human lives in the ancient times can be known. Furthermore, the reassembled lithic materials have educational values as exhibition materials at history museums[1].

However, it is extraordinarily difficult to finish and analyze excavated relics[1] as shown in Figure 1 (b). Although relics are measured by a scanner[3] and many problems can be solved



(a) (b)

Figure 1: a: Making of a stone tool;
b: An example of excavated lithic materials.

by computer algorithms rapidly and accurately, refitting lithic materials is still a complex and hard task and it may consume a lot of time and manpower. In Japan, even the conjoining status of lithic materials has been analyzed since 1960[4], no superb solution algorithms have been proposed yet for refitting lithic materials, especially for the mixture lithic materials with several different stone cores.

Therefore, in this paper, a new method is proposed for refitting mixture lithic materials by matching flake surfaces. In addition, the imitations of lithic materials were examined to show the new method could obtain good refitting results.

2 Related works

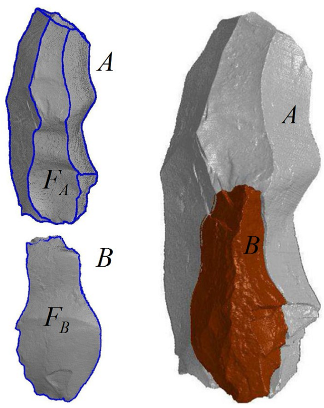
2.1 Previous works

Numerous algorithms have already been published about matching of geometric objects. Brown et al.[5] presented a system for matching fresco fragments to reassemble Theran wall paintings. This method requires feature extraction of surface curvature, whereas the flake surfaces of lithic materials are almost flat and smooth and the features that can be extracted are very limited. Huang et al.[6] presented a system with good performance for automatic reassembly of broken 3D solids. It is an excellent reference, but it is not entirely suitable for our research because the refitting of lithic materials has some unique principles[7], whose details are described in Section 3.3.

Chida et al.[8] proposed a rapid searching method of adjacent flake surfaces for lithic materials. The paper[8] dose not detail the simplification status, while their simplification could not obtain simplified results with the roughly same simplified standard for mixture lithic materials. Therefore, the matching method could not obtain good results with unified parameters for the mixture lithic materials. In addition, this method limited the search ranges of matching flake surface, while the search ranges are ambiguous for difference groups of lithic materials. In their mixture experiment, their method can obtain 83% correct results with top five flakes by D2, and 94% correct results with top ten.

2.2 Flake surfaces

Flake surfaces are fractures produced by peeling a stone into flakes. For example, Figure 2 (a) shows the flake surfaces of flakes A and B segmented by blue boundary lines. Flakes A and B can be matched into one flake as shown in Figure 2 (b), because the two corresponding flake surfaces F_A and F_B are produced at the same time. Therefore, flake surface matching is studied to solve the refitting issue of lithic materials. However, the previous method[8] only can solve the problems of pairwise matching or refitting lithic materials from a single stone core. With improving the previous methods, we improve the method[8] for refitting mixture lithic materials from multiple groups.



(a) (b)

Figure 2: Matching by flake surfaces

3 New method

3.1 Algorithm overview

The input to our algorithm is a set of stone tool point clouds measured by [3]. Based on the pipeline of the method[8], we improve their algorithm for mixture lithic materials. The algorithm is executed in the following procedure:

1. Each point cloud is segmented for obtaining flake surfaces. Automatic segmentation is applied in place of the semi-automatic method.
2. Each flake surface is simplified to reduce the number of point cloud. New simplification is employed based on point clouds that can control simplified flake surfaces via the same evaluation with the matching method. The input flake surfaces are improved by the new segmentation and simplification, and a premise is provided for refitting mixture lithic materials with the same threshold parameter.
3. From each flake surface of stone cores, the matching algorithm is used to search the best matching surface and the transform matrix is computed. For the mixture lithic materials, all flake surfaces instead of partial ones are computed until find the best matching surface is found with the D2 order.
4. All flake surfaces belonging to one stone tool with the matched surface are transformed by the matrix.
5. The new flake surfaces of the matched stone tools are reconstructed.
6. The matching process is repeated until all stone tools are matched.

Thus, point clouds of all lithic materials are refitted by the transform matrices.

3.2 Segmentation and simplification of flake surfaces

In our method, the algorithm of region growing segmentation is applied to obtain flake surfaces. The two parameters, angle threshold of normal vector θ and curvature threshold c, are used to get a superb segmentation result. The greater values of θ and c lead to the smaller number of flake surfaces. The gravel surfaces (that belong to the original rock, not to a flake surface) and the flake surfaces whose number of points is smaller than 1/20 of the original points are removed. They are not put into flake surfaces that will be matched.

Matching of the original point clouds requires a large amount of computing time due to the large number of points, which makes the simplification process necessary. The point cloud simplification based on curvature[9] is employed to simplify the flake surfaces. Matching will fail if the features of adjacent flake surfaces are changed by simplification. While, in this method, the features can be maintained by comparing with the original shapes. Parameter α of the distance threshold is set to control the number of simplified points, and the greater α leads to the smaller number of simplified points. Furthermore, the successful rate of mixture matching is raised because the same evaluation as matching process is applied in this simplification. In this paper, the algorithm of fast triangulation[10] is applied to reconstructed polygon meshes for simplified flake surfaces. The polygon meshes will be used to evaluate simplification result and matching process.

3.3 Mixture matching

In our previous research[8], it was extremely difficult to control every flake surface in the same simplified degree with other simplification algorithm, and this led to large simplified differences among the groups. Thus, matching method described in [8] cannot be applied for mixture lithic materials. While the simplification method[9] in this research can obtain simplification results in the same evaluation value for all flake surfaces, the minimal simplified errors are maintained between the original point clouds and the simplified ones by computing the same normalized distance as matching evaluation. Depending on favorable segmentation and simplification results, lithic materials can be refitted with mixture materials of several groups at once.

Additionally, there are three properties to make lithic material refitting different from other fractured object reassembling, as shown in Figure 3. The first property is that there is a time difference in generation of multiple flakes from a single core[7]. In other words, lithic material refitting is not an operation to match two flakes arbitrarily. It must follow an order. Suppose flake A is peeled first and then flake B is peeled, as an example. In the viewpoint that the flakes are peeled from a rock one by one and the rest is the stone core, the flakes should be matched with the stone core in reverse order. The second property is that most of flake surfaces used for matching are flat and smooth since the selected stone can be divided sharply[2]. According to this property, it is not suitable to use the general matching algorithm based on surface features. The third property is that one flake surface may be divided into several pieces. For example, in order to match flake A, flake B should be matched with the core to get flake surface F_C by combining flake surfaces F_1 and F_2. Thus, the matched flake surfaces must be reconstructed to search the next surface.

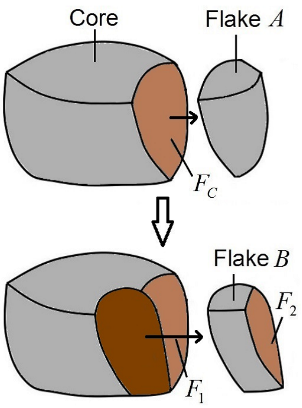


Figure 3: A case of making a stone tool(flake A is peeled first and flake B next).

In our method, the stone cores are specified manually and the matching process begins on flake surfaces of a stone core. As the data is mixed with multiple stone cores in our research, the stone cores are refitted in succession. Each flake surface of a core is matched with each flake surface of flakes to search the best matching flake surface later. In order to reduce the number of tasks for matching, shape distribution D2[11] of each flake surface is computed, and the matching order is sorted by the Manhattan Distance of each pair. Figure 4 shows the result of D2 distribution computation for four different flake surfaces by a spot chart. The black, red, blue and green points show the D2 shape distribution of meshed flake surfaces 1, 2, 3 and 4 respectively. We can see the shape of flake surface 1 is similar to 2, and different from 3 and 4. The difference between flake surfaces 1 and 2 is significantly less than the difference between 1 and 3 or 4. Therefore, the sorted matching order could improve the efficiency of our matching process.

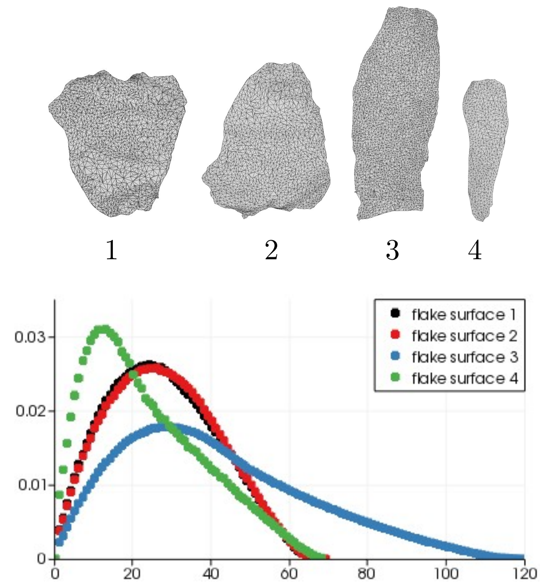


Figure 4: D2 distribution on four flake surfaces.

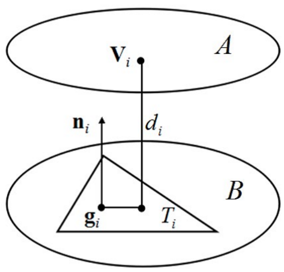


Figure 5: Computing method of normalized distance.

Normalized distance D[12] is applied for finding the best matching flake surfaces. It provides a standard to measure the difference between two flake surfaces on a unit area. Normalized distance D of each pair is calculated as equations (1) and (2), and the best matching flake surface is judged by a value smaller than threshold parameter d. Figure 5 shows the computing method of normalized distance. In the equations and Figure 5, $\mathbf{V}_i$ is a point on flake surface A, T_i is the triangle on flake surface B closest to $\mathbf{V}_i$, $\mathbf{n}_i$ is the normal vector of T_i and $\mathbf{g}_i$ is the geometric center of T_i. Then distance d_i between $\mathbf{V}_i$ and T_i can be calculated by equation (1). D is computed by the sum of $(d_i)^2$, dividing mesh area S of flake surface B like equation (2).

$$d_i = (\mathbf{V}_i - \mathbf{g}_i) \cdot \mathbf{n}_i \tag{1}$$

$$D = \frac{1}{S}\sum_{i=1}^{n}(d_i)^2 \tag{2}$$

Our pairwise matching algorithm is proposed in the following steps and Figure 6:

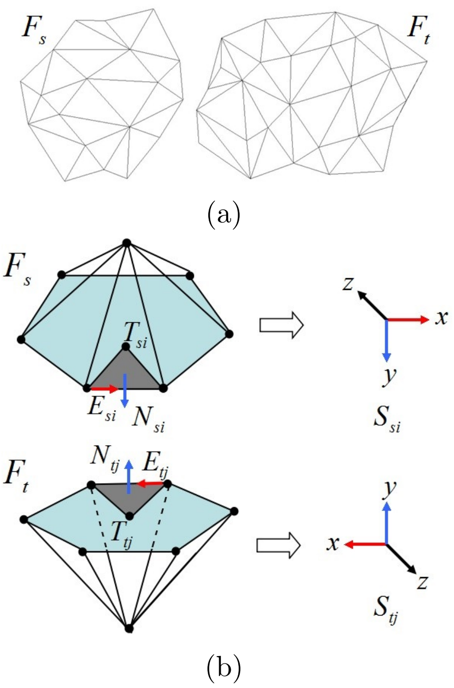


Figure 6: Matching algorithm.

1. Set a polygon mesh with the smaller area as source mesh F_s, and the one with the larger area as target mesh F_t.
2. For meshes F_s and F_t, search their edge line sets E_s and E_t and edge triangle sets T_s and T_t. For each pair of E_{si} and E_{tj}, obtain vectors V_{si} and V_{tj} in counterclockwise direction for normal vectors N_{si} and N_{tj} of triangles T_{si} and T_{tj}.
3. Construct local coordinate systems S_{si} and S_{tj}. For S_{si}, set the direction of edge vector V_{si} to the x axis, that of normal vector N_{si} to the y axis, and that of $V_{si} \times N_{si}$ to the z axis. Then, match local coordinate system S_{si} to S_{tj} and compute transform matrix M_a. In addition, transform F_s with M_a to get $F_s\prime$.
4. Search the nearest triangle in F_t for each triangle of $F_s\prime$ by their barycenter. Calculate the sum of distances between each barycenter pair d_c. Select $F_s\prime$ with the minimum value of d_c. Search the nearest triangle T_i from F_t for each point P_i from $F_s\prime$. Get point $P_i\prime$ by projecting P_i in T_i and construct point set $P\prime$.
5. Calculate fitting transform matrix M_b by matching point set P of $F_s\prime$ to $P\prime$.
6. Finally, matching transform matrix M is computed by $M_a \times M_b$.

Thus, the source flake could be matched with the target flake by transform matrix M.

3.4 Flake surface reconstruction

In order to reconstruct the original flake surface, the divided flake surfaces should be detected and made into one flake surface after matching two flakes. Figure 7 shows the reconstruction of flake surfaces F_a and F_b, where the two matched flake surfaces are shown in darker gray. The flake surfaces are reconstructed in the following procedure:

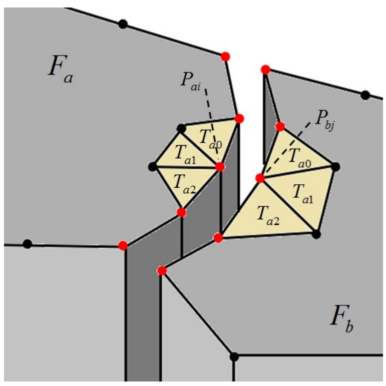


Figure 7: Searching reconstruction flake surfaces.

1. For each pair of flake surface F_a and F_b of two matched flake surfaces sets, search nearest

point P_{bj} from F_b for each point P_{ai} from F_a. If the distance between P_{ai} and P_{bj} is shorter than distance threshold d_r, they are put into the corresponding point pair set P_c.

2. For each point in P_c, search the triangles that belong to the point. For point P_{ai} on F_a, triangle set T_{ai} on F_a can be obtained. Then, compute mean vector V_{ai} from all normal vectors of the triangles in T_{ai}.
3. Calculate the angle between each vector pair V_{ai} and V_{bi}. If both angles are smaller than angle threshold θ_r, the flake surface pair F_a and F_b should be reconstructed to one flake surface.

4 Results and limitation

4.1 Experimental results

We have implemented the new method using C++ and PCL[13], and examined the method in a PC with Intel Core i7-4790 CPU and 8.00GB memory. The data of 43 lithic material imitations were examined in our experiment, shown in Figure 8. $No.01$ and $No.20$ shown with black thick frames are the stone cores. The 43 data could be refitted into two groups by our new matching algorithm in the order of $No.01$ and $No.20$.

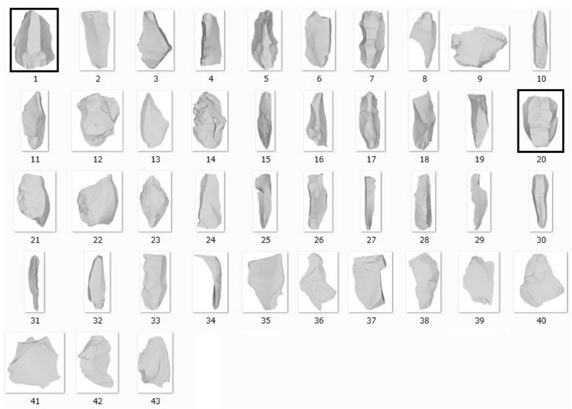
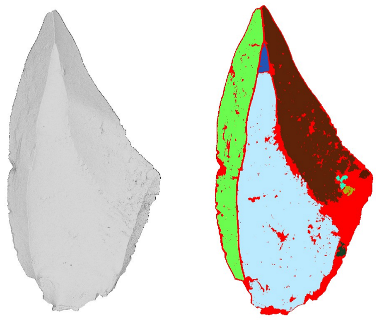


Figure 8: 43 experiment data.

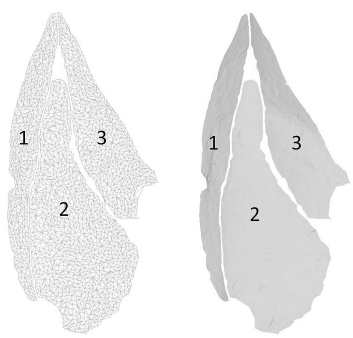
Figure 9 shows the segmentation results of $No.13$ by point clouds. The flake surfaces are displayed in different colors. The red points do not belong to any flake surfaces. There are about 833 thousand points, the execution times are about 95 seconds, and four flake surfaces are segmented for matching. From this figure, we can clearly see that the flake surfaces of stone tool models are segmented precisely and integrated.



$No.13$ ($\theta = 1.5$, $c = 1.0$)

Figure 9: Results of segmentation.

Figure 10 shows the constructed meshes and faces of three simplified flake surfaces of $No.13$. Distance threshold parameter α is set to 3.0. For the three flake surfaces from left to right, the number of the original point clouds, the number of the simplified point clouds, simplified rate, execution times and normalized distance are shown in the Table 1. The normalized distances show that the simplified results are very close to the original point clouds, and we can see that the contour lines are almost identical. Thus, the simplified flake surfaces can be used for matching very well. Furthermore, the simplified process can drastically reduce the computing time of matching.



(a) Mesh (b) Face

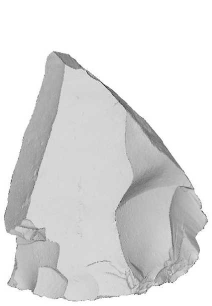
Figure 10: Results of Simplification.

Through the process of segmentation and simplification, the 43 data are divided into 169 flake

Table 1: Results of Simplification.

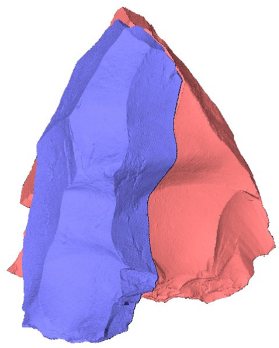
Flake	1	2	3
Original number	78119	167834	86643
Simplified number	591	1095	628
Simplified rate	0.76%	0.65%	0.72%
Execution time	4.4s	11.5s	5.8s
Normalized distance	0.090	0.066	0.067

surfaces for mixture matching algorithm. Figure 11 shows the result of pairwise matching of two stone tools $No.1$ and $No.7$. Figure 12 shows a case of matching where some matched flake surfaces must be reconstructed into one flake surface to match with the next one. Three flake surfaces of stone tools $No.8$, $No.13$ and $No.18$ are reconstructed to match with $No.19$.



(a) $No.1$

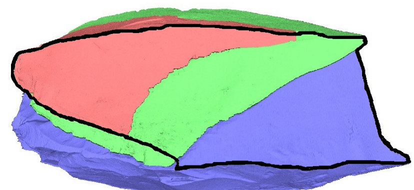
(b) $No.7$



(c) Result of matching

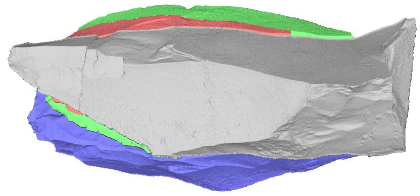
Figure 11: Result of pairwise matching.

Tables 2 and 3 show the details of matching groups 1 and 2. In the tables, *Number* indicates the flake surfaces matched currently, where the digits are the number of stone tools, and the alphabets are the number of flake surfaces produced from the same stone tool. *Order* indicates the sorted order of flake surfaces for searching the



(a) Reconstructed flake surfaces of $No.8$, $No.13$ and $No.18$.

(b) Target flake $No.19$.



(c) Result of matching.

Figure 12: Result of reconstruction.

best matching flake surface by D2. Long execution time is required for calculating the fitting transform matrix for each pair, and a large number of pairs need to be computed. For example, the execution time is 1007.9 seconds for searching the best matching flake surface $06A$ in the group 1. The average matching time is about 32.5 seconds for each pair, while 31 times of matching are required. All flake surfaces are matched starting from the two stone cores $No.01$ and $No.20$. The threshold parameter of normalized distance d is set to 0.06 to judge the best matching flake surface. Finally, sixteen stone tools are matched in group 1, and twelve are matched in group 2. Flake E cannot be matched by our method, and the details are described in Section 4.2. Figure 13 shows the results of the final matching for groups 1 and 2 and the pictures of imitations matched by hands.

4.2 Limitation

Figure 14 shows an example where our method cannot match. The two red circles show the corresponding points of matching. The two flake sur-

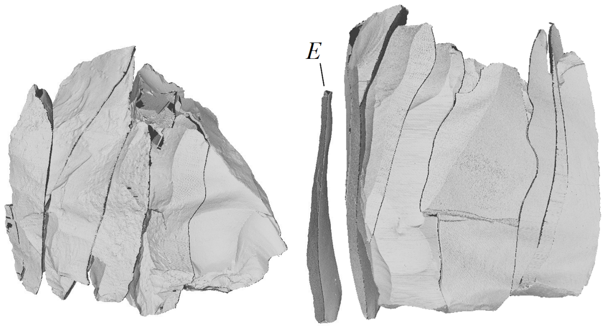
Table 2: Matching of group 1.

Number	Order	Normalized distance	Time
01A-12B	1/163	0.0248339	121.0s
└ 06A	31/160	0.0565872	1007.9s
└ 10B	45/156	0.0253672	1758.9s
└ 07B	1/152	0.0429291	88.6s
⋯	⋯	⋯	⋯
└ 04B	45/113	0.0148311	140.3s
Total	15846.5s		

Table 3: Matching of group 2.

Number	Order	Normalized distance	Time
21A-25D	30/99	0.0348425	992.8s
└ 34A	3/94	0.0071474	19.5s
└ 33A	7/91	0.0219804	47.6s
└ 07E	7/86	0.0580872	376.2s
⋯	⋯	⋯	⋯
└ 35D	4/59	0.0130739	142.9s
Total	4399.5s		

(a) Matched flakes of two groups.



(b) Matched results by our new method.

Figure 13: Results of final matching and actual pictures.

faces overlap partially (shown by the gray diagonal lines), and the one with the larger area shown in the right cannot be completely cover the other. Because of this, the minimum distance of the two flake surfaces could not be computed correctly. Our method results in an error for such flake surfaces. The incidence rate of such case depends on the condition of lithic materials, and there is only one in this experiment.

5 Conclusions and further work

In this paper, we proposed a new method for refitting mixture lithic materials by matching flake surfaces. Several characteristics were designed in our algorithm according to the principles of lithic material refitting. The experiment results could show that our new method could obtain precise refitting results for mixture lithic materials. In the further works, we will study more efficiency matching algorithms. Moreover, we will study the matching method for flakes that are matching each other on a extremely small part.

Acknowledgements

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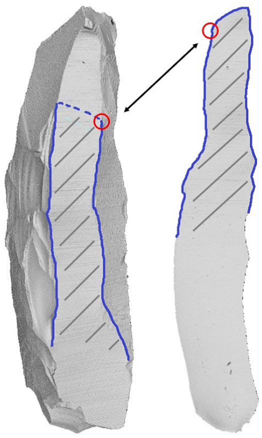

Figure 14: Limitation of our method.

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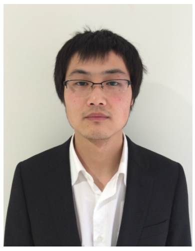
Xi Yang



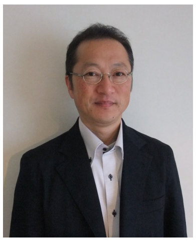
Xi Yang is currently a Ph.D student in Faculty of Engineering at Iwate University. He received the BE degree in College of Information Engineering from Northwest A&F University in 2012. He received the ME degree in Faculty of Engineering at Iwate University. His research interests include geometric modeling and computer graphics.

Katsutsugu Matsuyama

Katsutsugu Matsuyama is currently an assistant professor at Iwate University. His research interests include computer graphics, information visualization and interactive systems. He received

BE, ME, DE degrees in computer science from Iwate University in 1999, 2001 and 2005, respectively. He was a research associate at Future University-Hakodate from 2005 to 2011.

Kouichi Konno



Kouichi Konno is a professor of Faculty of Engineering at Iwate University. He received a BS in Information Science in 1985 from the University of Tsukuba. He earned his Dr.Eng. in precision machinery engineering from the University of Tokyo in 1996. He joined the solid modeling project at RICOH from 1985 to 1999, and the XVL project at Lattice Technology in 2000. He worked on an associate professor of Faculty of Engineering at Iwate University from 2001 to 2009. His research interests include virtual reality, geometric modeling, 3D measurement systems, and computer graphics. He is a member of IEEE.