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Short Paper

Pairwise Matching of Stone Tools Based on Flake-Surface Contour Points and Normals

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Abstract

Stone tools constitute the main artifacts facilitating archaeological research of the Paleolithic era. The reassembly of stone tools is the most important research work for analyzing human activities of that period. In recent decades, large numbers of methods have been presented to solve various registration or matching problems for point clouds; however, few methods have been successfully applied to the matching of flakes, a type of stone tool. Therefore, we propose a new matching method for studying stone tools to improve archaeological research. Our method processes pairwise matching of stone tools based on contour points and mean normals of regions on all flake surfaces, according to the characteristics of the flake models. The sample experiments conducted in this study indicate that our new method achieves superior matching results for flakes, compared with the existing methods.

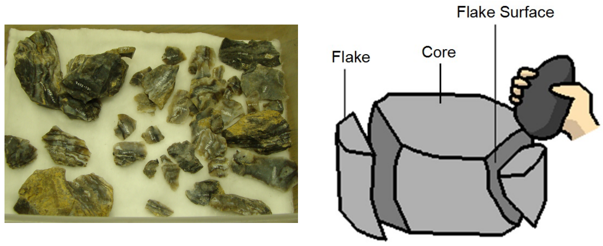
CCS Concepts

•***Computing methodologies*** → ***Point-based models; Shape analysis;*** •***Applied computing*** → ***Archaeology;***

1. Introduction

During the Palaeolithic era, a variety of stone tools such as cutting tools or weapons were fabricated. To create a stone tool, a rock is struck repeatedly with a pebble, and flake pieces of various sizes are obtained, as shown in Figure 1. Matching these flakes is an important task for analysis and categorization of excavated relics. The reassembly of stone tools allows their manufacturing process to be determined, and hence, conjectures can be made regarding human activities during the Palaeolithic era. Furthermore, reassembled archaeological materials have educational value as exhibition materials at history museums or schools.

Various matching methods have been developed in the past, for application to archaeological fragments or other types of data. However, a few algorithms have yielded satisfactory experimental results when applied to flakes, because of the following reasons: (1) Global matching algorithms yield unsatisfactory results, since a pair of flake surfaces require partial matching; (2) Descriptor-based methods struggle to extract features, because flake surfaces have less obvious regional features. Therefore, this paper presents a new method that is suitable for stone-tool flake matching.



(a) (b)

Figure 1: *(a) Excavated flake pieces. (b) Stone tool fabrication.*

2. Related Works

In point-cloud-based techniques, registration methods work to merge several data points obtained from different perspectives under a single model. In contrast, matching methods work to restore fragments according to multiple models. Nevertheless, the core algorithms of both approaches are extremely similar.

The most widely applied methods are Iterative Closest Point (ICP) [BM92, RL01] and Random Sample Consensus (RANSAC) [CHC99]. The defects of ICP are that correct correspondence is dependent on a satisfactory initial pose [RLF*], and the matching of partial overlap dose not work well. On the other hand, RANSAC is a robust method for managing partial overlaps; however, it has poor efficiency. Many researchers have proposed improved ICP [ZDL*16, CMBP15] and RANSAC [AMCO08, MAM14] methods. For example, the S-ICP [MAP15, BTP13] is introduced to solve practical implementation problems. Then, the Go-ICP [YLCJ16] is presented to study a globally optimal algorithm for solving the initialization problem. In this study, the pro-

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posed matching method is developed by enhancing the RANSAC algorithm to also accommodate flake models.

Moreover, Huang [HFG*06] et al. presented a system with good performance for automatic reassembly of broken 3D solids. Winkelbach and Wahl [WW08] proposed an efficient surface matching approach for reassembling broken solids using cluster trees. In addition, Altantsetseg [AMK14] et al. introduced a new descriptor that contains both feature points and curves for pairwise matching of broken fragments using Fast Fourier Transform (FFT). Song and Chen [SC15] developed a local voxelizer descriptor for surface registration that is constructed using a unique Local Reference Frame (LRF). Furthermore, Yang et al. [YCZ16] proposed a local feature statistics histogram (LFSH) for 3D point cloud registration. For flake models, however, the low curvature variation of the flake surface and the uniform point distribution blur the descriptor recognition and correspondence.

With regard to culture heritage applications, a previous survey [PPY*16] summarized a large number of analytical techniques implemented on the micro-, meso-, and macro-scale. In addition, the contour-line-based method has also been applied to 2D fragments [AO03, KDSK10] and Fresco fragments [BTFN*08, FSTF*11, TFBW*10, BV12].

3. Proposed Method

3.1. Overview

By analyzing flake matching scenarios, we observed that each flake pair was always matched as part of a contour line, regardless of whether partial or full overlap of the flake surfaces occurred. Consequently, we developed a new method based on contour points and normal vectors for pairwise matching of flakes. The input of our method is a pair of flake models from the point cloud. First, the normal vectors are calculated for each point. Second, each flake surface is segmented and uniformly downsampled; then, the contour points are extracted. Finally, the flake surface pair with the best matching is rapidly identified based on the contour points, and further matching is conducted using the nearest point sets.

3.2. Data Acquisition

Our data are acquired from a 3D surface reconstruction technique using four-directional measurement machine developed by Iwate University and LANG Co., Ltd. [AMCK11, CYKK15]. Hundreds of stone tools can be scanned at the same time and the surface feature is intact preserved, such as sharp edges, flake scars, benefiting from the highest 0.1 *mm* precision of laser scanner. Additionally, the stone tools are from archaeological researchers in the university and the Buried Cultural Property Investigation Center which we cooperated with.

3.3. Preparation Work

The preparation work of our method includes flake surface segmentation and contour point extraction for each flake, as shown in Figure 3. First, the normal vectors of the points are calculated via a least-square plane fitting estimation. The consistency and outward

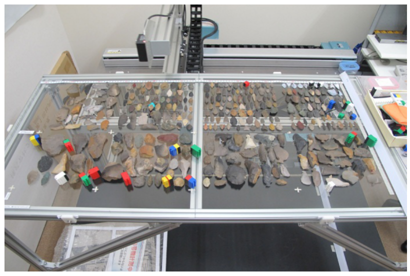
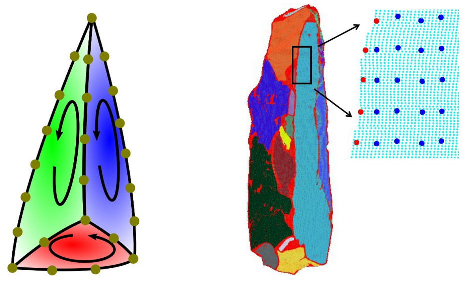


Figure 2: *Scanning Device*

directions of the normal vectors should be ensured. Then, a standard region growing algorithm is implemented on the flake to yield a set of flake surfaces. A flake, most likely possesses flake surfaces only, or has both flake surfaces and gravel faces. The flake surface is an almost flat or smooth surface that constitutes the fracture surface between two flakes. The gravel surfaces are intensely rough, because they correspond to the surface of the original rock. In our method, the gravel surfaces are divided into many trivial clusters, which are not used for matching.

To enhance the matching efficiency, the point numbers of the flake surface are reduced using the uniform downsampling algorithm. The sampling interval determines the efficiency and accuracy of the coarse matching. Then, the contour points are extracted using the convex hull algorithm. It is important to note here that the contour points are sorted in the counter-clockwise direction along the normal vector of the surface, to facilitate contour interception. In brief, one flake surface contains three point-set elements: the original $\{Op\}$, sampling $\{Sp\}$, and contour $\{Cp\}$ point sets.



(a) (b)

Figure 3: *Segmenting flake surfaces from a single flake. (a) The concept model is segmented into several surfaces indicated by different colors. The circular arrows show the ordering directions of the contour points. (b) An actual flake is segmented into several flake surfaces, where one color represents one flake surface. In the enlarged detail, the original, sampling, and contour points are shown in cyan, blue, and red, respectively.*

3.4. Pairwise Matching

A coarse-to-fine method is applied to all flake surface pairs for pairwise rigid registration. The surface with a smaller point number is set as the source surface S, while the one with the larger point number is set as the target surface T. Two 4-point sets $\{p_{i-n}, p_i, p_{i+n}, p_v\}$ and $\{p'_{i+n}, p'_i, p'_{i-n}, p'_v\}$ are constructed based on the contour points to compute the coarse rigid transform matrix M_a, which aligns S to T, as shown in Figure 4. The point p_i is a contour point on S and the two points p_{i-n} and p_{i+n} are separated from p_i by n. The normal vector v_i of point p_i is computed from the mean value of all the normal vectors of the points in the range r of p_i. The point p_v is on v_i, with distance r from p_i. Similarly, the first three points are constructed in the same manner on the target surface, whereas the point p'_v must be on the reverse extension line of v'_i. There are two reasons for the construction of the fourth point: (1) The two mean normal vectors v_i and v'_i represent the match of a partial edge region pair between two surfaces; (2) The fourth point is not on the same plane as the first three points.

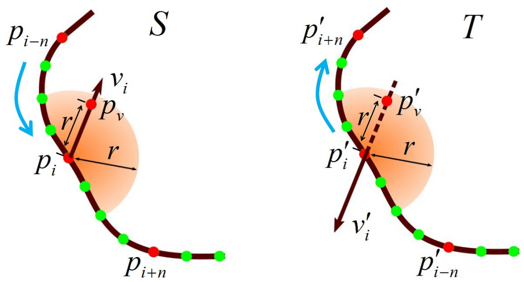


Figure 4: *Construction of 4 points for source S and target T surfaces.*

The point set $\{p\} \in \{Cp\}$ between p_{i-n} and p_{i+n} is transformed by M_a to measure the difference from $\{p'\}$. To improve the robustness of the error metric, point-to-region distances are employed instead of point-to-point distances, as shown in Figure 5. Furthermore, the error is computed using equation (1). We assume that two points are matched when the distance is smaller than $\frac{\sqrt{3}}{2}\xi_s$, where ξ_s is the sampling interval; therefore, two contour sections are considered to be approximately matched if equation (2) is satisfied. Subsequently, all points in $\{Sp\}$ are transformed, and the number of points that satisfy equation (3) are calculated. The best matching position is indicated by the largest number.

$$\xi(p, p') = \sum_{j=i-n}^{2n+1} \left(\sum_{k=1}^{K} \|p_j - p'_k\|^2\right) \tag{1}$$

$$\xi(p_i, p'_i) <= \frac{1}{2}\xi_s \cdot \sum_{k=1}^{K} \sqrt{2 + (k - \frac{1+(-1)^k}{2})^2} \tag{2}$$

$$\begin{cases} d(Sp_i, Sp') = min\{Sp_i - Sp'_j\} <= \frac{\sqrt{3}}{2}\xi_s, & (3) \\ d(Op_i, Op') = min\{Op_i - Op'_j\} <= \frac{\sqrt{3}}{2}\xi_s, & (4) \\ d(Op'_i, Op) = min\{Op'_i - Op_j\} <= \frac{\sqrt{3}}{2}\xi_s. & (5) \end{cases}$$

The next step is fine matching with the ICP algorithm. First, the original points set O_p is transformed by M_a, and the number of near points is computed using equations (4) and (5) for both S and T. The ICP algorithm is applied to the pair of near points to obtain the fine matching transform matrix M_b. Finally, the final matching transform matrix M is calculated as $M_a \times M_b$.

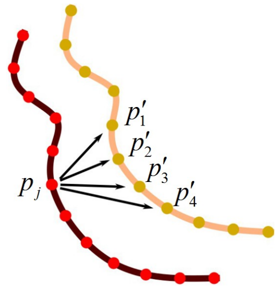


Figure 5: *Matching two contour sections ($K = 4$).*

4. Results

We implemented our proposed method using the C++ programming language on a PC with an Intel Core i7-4790 CPU and 8.00GB memory. Figure 6 compares the experimental results for pairwise partial matching of flakes obtained with the SHOT descriptor [STDS14], S-ICP algorithm, and the proposed method. The two flakes examined in the experiment are shown in Figure 6(a), with the flake surfaces extracted and colored blue and red. Figures 6(b) and 6(c) show the SHOT and S-ICP results, respectively. The key-points correspondences with the SHOT descriptor are disordered, since the flake surface features are indistinct. The S-ICP algorithm also struggles to yield an accurate result, even though the initial position is adjusted manually. In contrast, our proposed method achieves a superb result, as shown in Figure 6(d). These experimental results demonstrate that our method is more suitable for flake models, which the existing methods struggle to resolve.

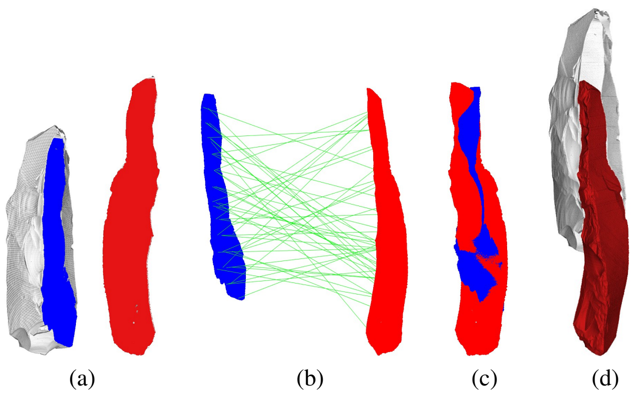


Figure 6: *(a) Two original flakes (Length = 72.0mm, 80.8mm). (b) Correspondences with SHOT descriptor (green lines). (c) The S-ICP registration result ($p = 0.4$, iterations $= 100$). (d) Matching result yielded by our proposed method.*

Three other flake pairs were also tested, and the results are shown

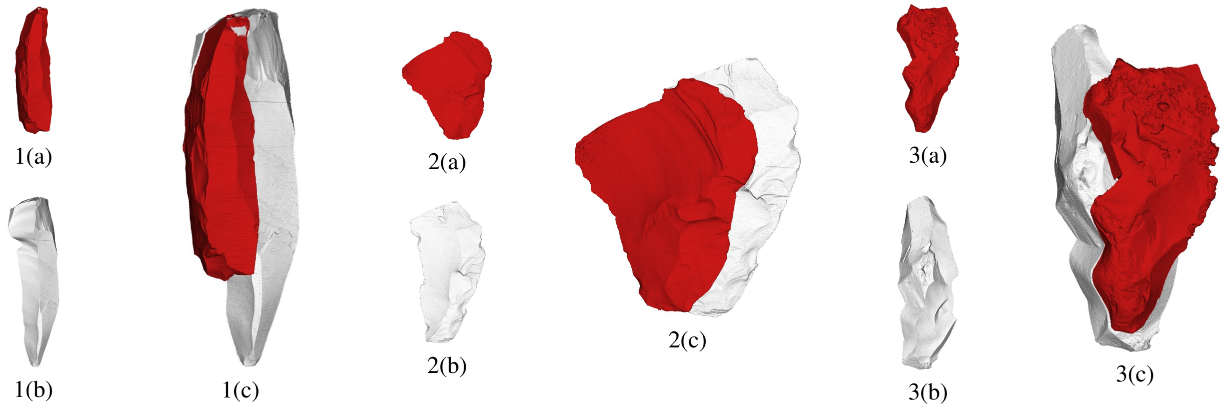


Figure 7: *(a) (b) Two original flakes. (c) Matched flakes.*

Table 1: *Flake matching performance of our proposed method (Unit of length and time: mm, s).*

Flake	Length	Point number	Flake surface number	Pre-work time	Matching time	Total time
1(a) / 1(b)	72.0 / 100.3	263,112 / 382,861	4 / 3	6.3 / 10.6	96.5	113.4
2(a) / 2(b)	63.0 / 69.4	406,674 / 345,481	3 / 3	12.1 / 9.7	51.4	73.2
3(a) / 3(b)	64.5 / 80.6	272,038 / 319,595	2 / 4	15.0 / 11.5	44.8	71.3

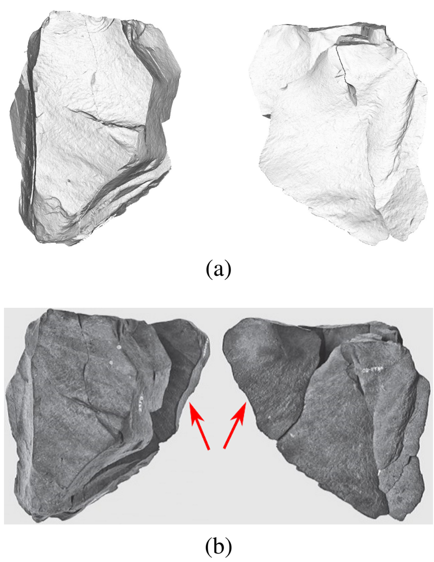


Figure 8: *(a) The screenshots of front and back view of matching result. (b) The pictures of actual assembly of stone tools.*

in Figures 8. In this figure, parts (a) and (b) show two original flake models, and part (c) shows the matched models. The detailed results are shown in Table 1. In these experiments, the scanning interval of the original point clouds was 0.1 *mm*, and the sampling interval ξ_s was set to 1.0 *mm*. The parameters for computing the transform matrix were set to: $n = 8$ and $r = 2.0$. These matching results indicate that our method yielded excellent results for various flakes. The segmentation and downsampling employed in our method reduced the number of points necessary for the calculation efficiency. Furthermore, the short execution time proved that our method can efficiently process a large number of point clouds. Figure 7 shows an example of a matching assembly of seven stone tools, six stone tools are obtained superb results. The stone tool which cannot be matched is shown by the red arrows, since it has no adjacent surfaces with the others. The limitations of the proposed method are that the parameter n, the length of matching contour line, is difficult to determine; it affects the efficiency and results of the algorithm. Besides, our method may not obtain correct results if the adjacent surface is cramped.

5. Conclusion and Future Work

In this paper, we proposed an efficient method for pairwise matching flake models, in which the matching matrix is computed by constructing 4-points based on the contours and normals of the flake surfaces. In addition, we proposed an error function to measure the difference between two uniformly sampled contour lines. The experiments results indicated that our new method has beneficial applications for archaeological research.

In future work, our proposed method will be applied as an archaeological assistant system to identify and match fragments of massive stone tools. Through a large number of tests on excavated relics, not only is our method improved but also new archaeological discoveries are made since the matching result of stone tools greatly affects the analysis of manufacturing technique and relationship between each site.

Acknowledgement

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References

[AMCK11] ALTANTSETSEG E., MURAKI Y., CHIBA F., KONNO K.: 3d surface reconstruction of stone tools by using four-directional measurement machine. *International Journal of Virtual Reality 10*, 1 (2011). 2

[AMCO08] AIGER D., MITRA N. J., COHEN-OR D.: 4-points congruent sets for robust pairwise surface registration. *ACM Transactions on Graphics (TOG) 27*, 3 (2008), 85. 1

[AMK14] ALTANTSETSEG E., MATSUYAMA K., KONNO K.: Pairwise matching of 3d fragments using fast fourier transform. *The Visual Computer 30*, 6-8 (2014), 929–938. 2

[AO03] ADAMEK T., O'CONNOR N.: Efficient contour-based shape representation and matching. In *Proceedings of the 5th ACM SIGMM international workshop on Multimedia information retrieval* (2003), ACM, pp. 138–143. 2

[BM92] BESL P. J., MCKAY N. D.: Method for registration of 3-d shapes. In *Robotics-DL tentative* (1992), International Society for Optics and Photonics, pp. 586–606. 1

[BTFN*08] BROWN B. J., TOLER-FRANKLIN C., NEHAB D., BURNS M., DOBKIN D., VLACHOPOULOS A., DOUMAS C., RUSINKIEWICZ S., WEYRICH T.: A system for high-volume acquisition and matching of fresco fragments: Reassembling theran wall paintings. In *ACM Transactions on Graphics (TOG)* (2008), vol. 27, ACM, p. 84. 2

[BTP13] BOUAZIZ S., TAGLIASACCHI A., PAULY M.: Sparse iterative closest point. In *Computer graphics forum* (2013), vol. 32, Wiley Online Library, pp. 113–123. 1

[BV12] BELENGUER C. S., VIDAL E. V.: Archaeological fragment characterization and 3d reconstruction based on projective gpu depth maps. In *Virtual Systems and Multimedia (VSMM), 2012 18th International Conference on* (2012), IEEE, pp. 275–282. 2

[CHC99] CHEN C.-S., HUNG Y.-P., CHENG J.-B.: Ransac-based darces: A new approach to fast automatic registration of partially overlapping range images. *IEEE Transactions on Pattern Analysis and Machine Intelligence 21*, 11 (1999), 1229–1234. 1

[CMBP15] CHEN E. C. S., MCLEOD A. J., BAXTER J. S. H., PETERS T. M.: Registration of 3d shapes under anisotropic scaling. *International Journal of Computer Assisted Radiology and Surgery 10*, 6 (2015), 867–878. URL: http://dx.doi.org/10.1007/s11548-015-1199-9, doi:10.1007/s11548-015-1199-9. 1

[CYKK15] CHIBA F., YOKOKOYAMA S., KANEDA A., KONNO K.: Development of network-type archaeological investigation system. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 40*, 5 (2015), 99. 2

[FSTF*11] FUNKHOUSER T., SHIN H., TOLER-FRANKLIN C., CASTAÑEDA A. G., BROWN B., DOBKIN D., RUSINKIEWICZ S., WEYRICH T.: Learning how to match fresco fragments. *Journal on Computing and Cultural Heritage (JOCCH) 4*, 2 (2011), 7. 2

[HFG*06] HUANG Q.-X., FLÖRY S., GELFAND N., HOFER M., POTTMANN H.: Reassembling fractured objects by geometric matching. In *ACM Transactions on Graphics (TOG)* (2006), vol. 25, ACM, pp. 569–578. 2

[KDSK10] KLEBER F., DIEM M., SABLATNIG R., KAMPEL M.: Proposing features for the reconstruction of marble plates of ephesos. In *Virtual Systems and Multimedia (VSMM), 2010 16th International Conference on* (2010), IEEE, pp. 328–331. 2

[MAM14] MELLADO N., AIGER D., MITRA N. J.: Super 4pcs fast global pointcloud registration via smart indexing. In *Computer Graphics Forum* (2014), vol. 33, Wiley Online Library, pp. 205–215. 1

[MAP15] MAVRIDIS P., ANDREADIS A., PAPAIOANNOU G.: Efficient sparse icp. *Computer Aided Geometric Design 35* (2015), 16–26. 1

[PPY*16] PINTUS R., PAL K., YANG Y., WEYRICH T., GOBBETTI E., RUSHMEIER H.: A survey of geometric analysis in cultural heritage. *Computer Graphics Forum 35*, 1 (2016), 4–31. 2

[RL01] RUSINKIEWICZ S., LEVOY M.: Efficient variants of the icp algorithm. In *3-D Digital Imaging and Modeling, 2001. Proceedings. Third International Conference on* (2001), IEEE, pp. 145–152. 1

[RLF*] ROURE F., LLADÓ X., FOREST J., PRIBANIC T., SALVI J.: An experimental benchmark for point set coarse matching. 1

[SC15] SONG P., CHEN X.: Pairwise surface registration using local voxelizer. 2

[STDS14] SALTI S., TOMBARI F., DI STEFANO L.: Shot: Unique signatures of histograms for surface and texture description. *Computer Vision and Image Understanding 125* (2014), 251–264. 3

[TFBW*10] TOLER-FRANKLIN C., BROWN B., WEYRICH T., FUNKHOUSER T., RUSINKIEWICZ S.: Multi-feature matching of fresco fragments. In *ACM Transactions on Graphics (TOG)* (2010), vol. 29, ACM, p. 185. 2

[WW08] WINKELBACH S., WAHL F. M.: Pairwise matching of 3d fragments using cluster trees. *International Journal of Computer Vision 78*, 1 (2008), 1–13. 2

[YCZ16] YANG J., CAO Z., ZHANG Q.: A fast and robust local descriptor for 3d point cloud registration. *Information Sciences 346* (2016), 163–179. 2

[YLCJ16] YANG J., LI H., CAMPBELL D., JIA Y.: Go-icp: a globally optimal solution to 3d icp point-set registration. *IEEE transactions on pattern analysis and machine intelligence 38*, 11 (2016), 2241–2254. 1

[ZDL*16] ZHANG C., DU S., LIU J., LI Y., XUE J., LIU Y.: Robust iterative closest point algorithm with bounded rotation angle for 2d registration. *Neurocomputing 195* (2016), 172–180. 1