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An Earthenware Reconstruction System Considering Color Pattern and Shape Similarities

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Abstract. This paper proposes an earthenware reconstruction system considering surface color and pattern of potsherds, in addition to contour shape. In general, most of potsherds have complex, irregular, and weathering contours because of rain, wind and so on. Reconstruction of earthenware, therefore, is attended with much difficulties. In our previous work, a system considering surface patterns has been developed, but there is some problems, for the surface patterns are just analyzed in grayscale in the system. In this paper, we discuss a color similarity approach, and then, we propose a joint detection method based on the approach. We have implemented the method into our earthenware reconstruction system, and we also report good performance results for some weathered potsherds.

1. Introduction

Reconstruction of earthenware offers significant knowledge: such as the era when it was used, ancestor's life style, and culture in the era. It is, however, too difficult for archaeologists to reconstruct earthenware, because of numerous excavated potsherds, weathering, and lack of parts. In order to reduce their task, we have developed an earthenware reconstruction system (e.g., KANOH *et al.*, 2000, 2001; SAKAMOTO *et al.*, 2003). In general, excavated potsherds have three dimensional shape. Thus earthenware should be reconstructed in three dimensions, and actually some research concerning three dimensional object recognition and matching are reported (e.g., PAPAIOANNOU *et al.*, 2001, 2002). We are taking our stand on that some earthenware shaped in three dimensions can be reconstructed in two dimensional images, if the earthenware consists of numerous potsherds, and if each of the potsherds is adequately flat and small. In this paper, at the beginning of our research, we consider reconstructing earthenware in two dimensions, such as plates, pot-lids and so on*. In solving jigsaw puzzles, one of the similar problems in two

*We also promote the research and development of three dimensional object reconstruction. Please refer to KATO (2000), SHIMAI (2001), and HASHIMURA (2002).

dimensions, some work has been reported by utilizing inherent properties of jigsaw puzzles (e.g., MIYACHI and MURATA, 1987; BUNKE and KAUFMANN, 1993; KOSIBA *et al.*, 1994; GOLDBERG *et al.*, 2004); 1) all pieces consist of four contours and 2) each contour has simple and clear shape. Earthenware reconstruction, however, can not utilize these properties because potsherds have complex and irregular contours. This requires an efficient joint detection method independent upon shape of potsherds. HORI (1999) has proposed a joint detection method independent upon shape of potsherds. The method, however, can detect joint only from two potsherds, and does not consider the case when the number of potsherds increases.

The existent systems by KANOH *et al.* (2000, 2001) detects segments, which may be a candidate of joint, from given potsherds by judging from one criterion: shape similarity among their contours. The system, therefore, cannot always detect the segments correctly for any weathered potsherds changed by rain, wind and so on. We have, therefore, proposed a joint detection method by YASUHARA *et al.* (2000) considering surface pattern in addition to contour similarity. For some potsherds, our system enhanced by the method is not still able to reconstruct earthenware from them. The method has no function for color similarity, for surface patterns are just analyzed in grayscale in the method. In this paper, we discuss a color similarity approach, and then, we propose a joint detection method based on the approach. We have also implemented an earthenware reconstruction system embedding the approach, and good performance results for some weathered potsherds are reported.

This paper is laid out as follows. Section 2 explains an outline of our earthenware reconstruction system. Section 3 describes a method for extraction of surface color and pattern of potsherd. Section 4 proposes the algorithm of joint detection considering color and shape similarities, and experimental results of our system are shown in Sec. 5.

2. System Outline

The section gives a brief description of our earthenware reconstruction system. Figure 1 shows an outline of the system. In the system, many given potsherds are reconstructed into some earthenware through the following procedures.

1) Detection of contour

The system detects contours from input color images of potsherds. In this procedure, we adopt the *g*-snake model proposed by LAI and CHIN (1993, 1995), which can extract a contour of any object from an observational image.

2) Division of contour

Each of the contours is divided into some opened curves called *sub-contour* by the salient points. In this procedure, we adopt ROSENFELD and JOHNSTON's (1973) method for detecting these points. These sub-contours become candidates for joint.

3) Extraction of color pattern on the surface

For each of the sub-contours, the system extracts color patterns on the surface in the neighborhood of the sub-contour, and analyzes the patterns.

4) Joint detection

Firstly, for all pairs of sub-contours, similarities are evaluated by their color and pattern similarities, and then candidates for joint are screened by them. Secondly, the most similar pair is selected by similarity for not only surface pattern, but also contour shape.

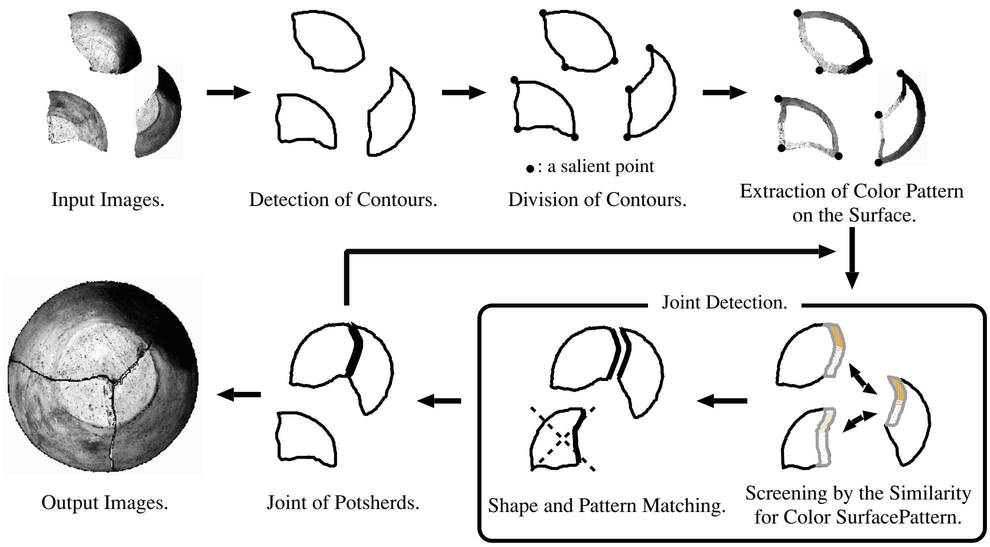

Fig. 1. An overview of the earthenware reconstruction system.

5) Joint

If the similarity of the selected pair satisfies some conditions, two potsherds having these sub-contours are joined, and then, contour shape and color pattern information of the new one potsherd is updated.
The series of procedures 4) and 5) is iterated until there is no pair for joint, and finally, the system outputs some images of reconstructed earthenware.

3. Extraction of Color Pattern on the Surface

Most of excavated earthenware have colors and patterns. It is obviously effective to utilize these attributes for joint detection. In this research, we utilize surface color and pattern on potsherds, standing on the following pattern analytical ground; in general, for a pair of potsherds which can be joined, surface color and pattern in the neighborhood of the joining segments are fairly similar.

For a given potsherd, we therefore consider a g-width cingular region along the inside of its contour, and calculate the average for color values extracted in g pixels along contour. As vigilant avoidance of noise in the neighborhood of the contour (e.g., chip, shade, and so on), we utilize average of colors in g-width cingular region. In this step, contour points from which colors are extracted are sampled at regular intervals from the salient point. Thus we can reduce dependence on noise, and robustness of surface pattern analysis is realized in our system. Surface pattern analysis based on color similarity, moreover, advances the performance of our system.

In this research, it is very important to quantify a color difference between surface patterns. Color patterns should be represented in such a way that salient chromatic properties are captured. Analysis based on color similarity requires a model of color stimuli, such that distances between colors correspond to human perceptual distances between colors. In this paper, our system adopts $L^*a^*b^*$, a model based on human perception of colors, which has uniform color space. Uniform color space has a convenient property for color distance, such that a color difference perceived by a human observer is approximated as the Euclidean distance between two points in the color space.

Coordinates of $L^*a^*b^*$ color space can be derived by the following transformation:

$$\begin{aligned}
L^* &= 116\left(Y/Y_0\right)^{1/3} - 16 && \text{for } Y/Y_0 > 0.008856,\\
L^* &= 903.3\left(Y/Y_0\right) && \text{for } Y/Y_0 \le 0.008856,\\
a^* &= 500\left[f\left(X/X_0\right) - f\left(Y/Y_0\right)\right], &&\\
b^* &= 200\left[f\left(Y/Y_0\right) - f\left(Z/Z_0\right)\right], &&
\end{aligned} \tag{1}$$

where XYZ are tristimulus values and they are transformed from RGB color models according to:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.393474 & 0.365252 & 0.191449 \\ 0.212350 & 0.701076 & 0.086444 \\ 0.018723 & 0.111834 & 0.957331 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \tag{2}$$

and where X_0, Y_0, Z_0 are the XYZ values of the reference white, and

$$\begin{aligned}
f(t) &= (t)^{1/3} && \text{for } t > 0.008856,\\
f(t) &= 7.787t + 16/116 && \text{for } t \le 0.008856.
\end{aligned} \tag{3}$$

Refer to BIMBO (1999) for more detail.

Definition 1 Color values on contour points

Let C be a potsherds, and let c be a sub-contour in C. We, then, consider the sequence of points $p(i)$ ($i = 0, \ldots, N-1$), which approximates c (e.g., contour points marked with ○ in Fig. 2). We, moreover, consider the cingular region along c, by considering sequence of points $g_i(j)$ ($j = 0, \ldots, g-1$) for each $p(i)$, which lie on surface in the neighborhood of c (e.g., surface points marked with ○ in Fig. 2). Then, the color value $CL_{p(i)}$ for $p(i)$ is composed of $L^*a^*b^*$ coordinate ($\tilde{L}^*_{p(i)}$, $\tilde{a}^*_{p(i)}$, $\tilde{b}^*_{p(i)}$), such that

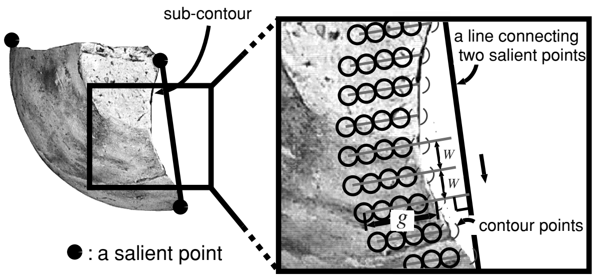

Fig. 2. Extraction of surface pattern.

$$\tilde{L}^*_{p(i)} = \frac{1}{g}\sum_{j=0}^{g-1} L^*_{q_i(j)},$$
$$\tilde{a}^*_{p(i)} = \frac{1}{g}\sum_{j=0}^{g-1} a^*_{q_i(j)}, \qquad (4)$$
$$\tilde{b}^*_{p(i)} = \frac{1}{g}\sum_{j=0}^{g-1} b^*_{q_i(j)},$$

where $L^*_{q_i(j)}$, $a^*_{q_i(j)}$, $b^*_{q_i(j)}$ are the $L^*a^*b^*$ values of the surface point $q_i(j)$, and where N means the number of points $p(i)$, and g means the width of cingular region along sub-contour c. ■

In this research, by the above definition, surface pattern in the neighborhood of the contour is represented as a sequence of color values.

4. Joint Detection

The section describes a method of joint detection which utilizes color similarity among surface patterns on potsherds. In the following section, we explain a method of evaluation of the similarity for surface pattern by utilizing our ground mentioned in Sec. 3. Then, we propose the algorithm of joint detection considering surface pattern similarity, in addition to contour shape similarity, in Subsec. 4.2.

4.1. Similarity evaluation for surface color and pattern

In our joint detection method, a similarity between two surface patterns is calculated in $L^*a^*b^*$ color space. Comparing the similarities of colors for all sub-contours, our system screens the candidates for joint.

Definition 2 Color difference between sub-contours

Let C and D be potsherds, and let c and d be sub-contours in C and D respectively. Further let $p_c(i)$ $(i = 0, ..., N - 1)$ and $p_d(j)$ $(j = 0, ..., M - 1)$ be sequences of points approximating

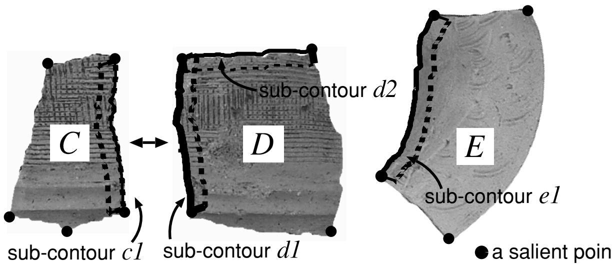

Fig. 3. Three potsherds: match and mismatch.

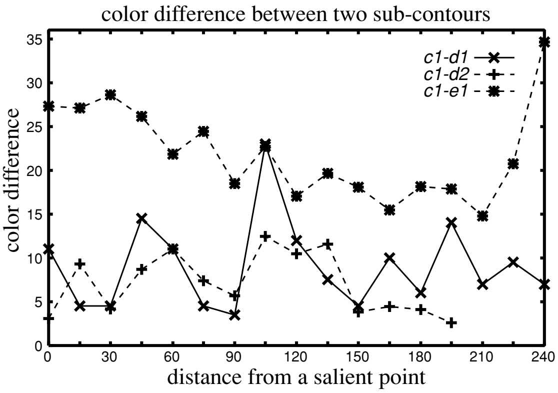

Fig. 4. The color difference between surface patterns.

c and d, respectively (see Definition 1). Then, the color difference $\varepsilon_{c,d}^{clr}$ between c and d is defined as follows:

$$\varepsilon_{c,d}^{clr} = \frac{1}{S}\sum_{i=0}^{S-1}\Delta E_{c,d}(i) \quad (i = 0,1,\ldots,S-1), \tag{5}$$
$$S = \min(N, M),$$

where $\Delta E_{c,d}(i)$ is a color distance between $p_c(i)$ and $p_d(i)$. The $\Delta E_{c,d}(i)$ is expressed as the length of a vector such that

$$\Delta E_{c,d}(i) = \left|\overrightarrow{CL_{p_c(i)}CL_{p_d(i)}}\right|, \tag{6}$$

where $CL_{p_c(i)}$ and $CL_{p_d(i)}$ are color values for $p_c(i)$ and $p_d(i)$ in $L^*a^*b^*$ color space, respectively (see Definition 1). ■

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JDCS: Joint Detection Algorithm Considering Surface Color and Shape Similarity
   Input S:       a set of sub-contours
   Output ANS:    an answer (p1, p2)        (in success)
                  : false                   (in failure)
begin
  R := S;
  Q := φ;
  for each a ∈ S                            % screening by the length of
   begin                                    % sub-contours
    R := R \ {a};                           % delete a from R
    for each b ∈ R
     if (−α < (|b|−|a|)/|a| × 100 < α) then Q := Q ∪ {(a, b)};
   end
  for each (a, b) ∈ Q
   begin
    color := cs(a, b);
     if (color < β)                         % screening by the similarity for
      then Q := Q \ {(a, b)};               % color surface pattern
     else
      begin
       score := ss(a, b)·color/δ;           % evaluation by the similarity for
       if (score < γ)                       % shape and pattern
        then Q := Q \ {(a, b)};
      end
   end
  if (|Q| ≥ 1)                              % |Q| denotes the number of elements in Q
   then ANS := (p1, p2) ∈ Q | ss(p1, p2)·cs(p1, p2)
                    ≥ ss(a, b)·cs(a, b) for all (a, b) ∈ Q;     % in success
  else ANS := false;                                            % in failure
end.
```

Fig. 5. The joint detection algorithm.

Example 1 Figure 3 shows three potsherds, C, D and E. The C and D are to be joined with their sub-contours c_1 and d_1 adjoining. Figure 4 shows the color difference for c_1-d_1, c_1-d_2 and c_1-e_1. The results indicate that color difference does not always perform strict matching, but screening function for a large number of joint candidates. ■

More similar two sub-contours are, $\varepsilon_{c,d}^{clr}$ gets nearer to zero. It follows that $\varepsilon_{c,d}^{clr} = 0$ when the color patterns on the surfaces in the neighborhood of c and d are the same. In our system, we, therefore, define the surface pattern similarity between sub-contours as follows.

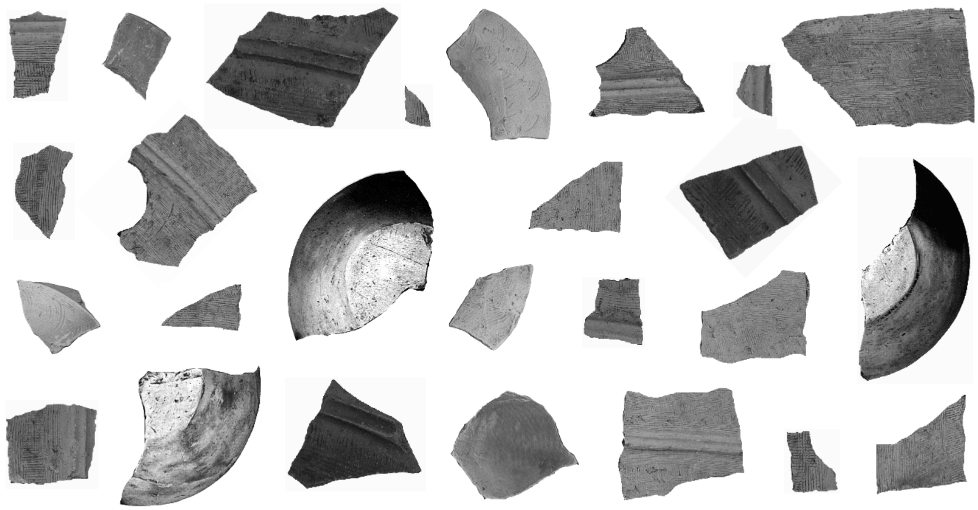

Fig. 6. Input images.

Definition 3 Color similarity between sub-contours

Let *C* and *D* be potsherds, and let *c* and *d* be sub-contours in *C* and *D* respectively. Further let $\varepsilon_{c,d}^{clr}$ be the color difference between *c* and *d* calculated by Definition 2. Then, the color similarity between *c* and *d* is defined by the following equation:

$$cs(c,d) = \frac{1}{\varepsilon_{c,d}^{clr}}. \tag{7}$$

■

4.2. JDCS: Joint Detection Considering Surface color and shape similarity

In order to reconstruct earthenware from potsherds whose shape have changed for an extremely long time, we propose the algorithm of joint detection considering surface pattern similarity, in addition to contour shape similarity. Figure 5 shows the algorithm. In this figure, *S* and *R* denote sets of sub-contours, *Q* denotes a set of pairs of sub-contours, *a*, *b*, *c*1, and *c*2 denote sub-contours, and $|a|$ denotes the length of *a*. In the algorithm, $cs(a, b)$ returns the value of surface pattern similarity (see Definitions 2 and 3), and $ss(a, b)$ returns the value of similarity for contour shape (refer to KANOH (2000) and UESAKA (1985)). JDCS returns the most similar pair of potsherds and their corresponding sub-contours from given set of potsherds.

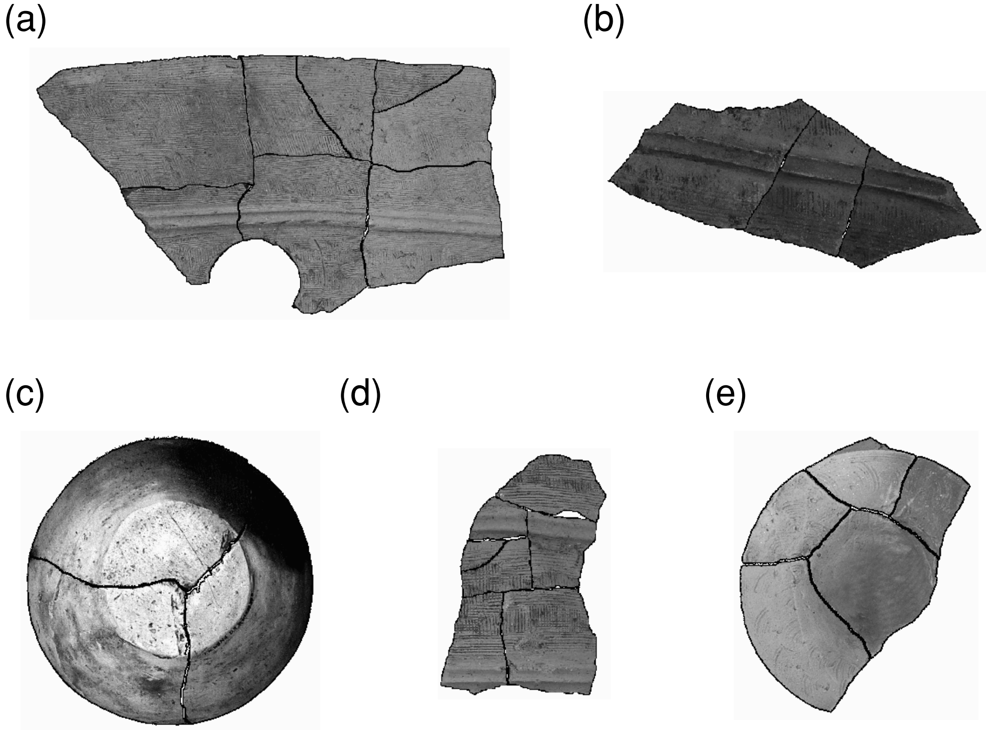

Fig. 7. Output images by our system.

5. Experimental Results

We have implemented the algorithm in our earthenware reconstruction system, and, in order to verify effectiveness of the system, we have made some experiments of reconstruction of earthenware from excavated potsherds. In the experiments, we have obtained images of potsherds by a camera mounted right above them and three lights with uniform light intensity. The images are digitized in 800×600 pixels and 24 bits color levels. We have implemented earthenware reconstruction system in C++ on a PentiumIV 3.0CGHz running Solaris 9 PC.

In one of the experiments, we have given 26 potsherds shown in Fig. 6 to our system. The result is shown in Fig. 7. In this experiment, parameters for extraction of surface pattern, $g = 15$ and $w = 15$ (see Sec. 3), and parameters for joint detection, $\alpha = 3$, $\beta = 12$, $\delta = 12$, and $\gamma = 0.035$ (see Fig. 5). The parameter setting of g and w is to reduce the computational cost of surface pattern extraction. Reconstruction performance is not influenced very much. On the other hand, the parameters for joint detection strongly influence the reconstruction performance. The automatic parameter setting of β, δ and γ is open problem of our system. In this particular example, the result indicates that our system

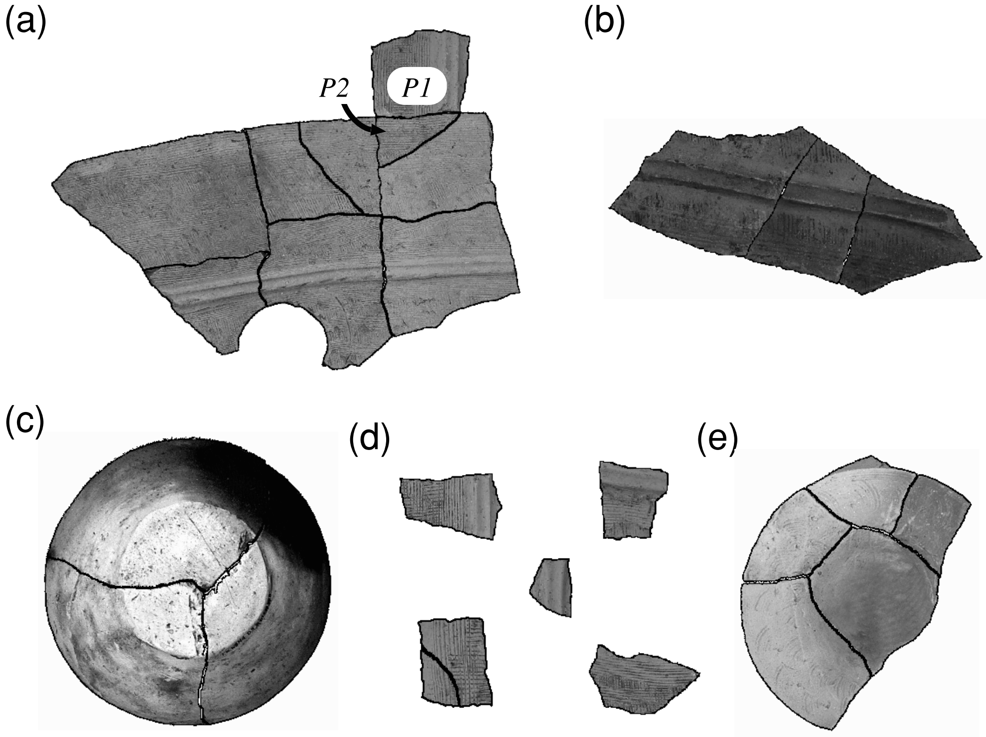

Fig. 8. Output images by the system using only contour shape similarity.

can correctly and completely reconstruct 5 pieces of earthenware from given potsherds. Total execution time was 35.05 (sec.) and 4993 pairs of sub-contours were examined for the first joint detection.

In order to compare our system with the existent systems, we have also given the potsherds shown in Fig. 6 to two system; one is the system using only shape similarity proposed by KANOH (2000), another is the system considering shape and pattern similarities in grayscale by YASUHARA (2000). In the comparisons, parameters for the system by KANOH (2000) are $\alpha = 3$ and $\gamma = 0.03$. Parameters for the system by YASUHARA (2000) are the same with our present system except $\beta = 230$ and $\delta = 20$*.

5.1. *Effectiveness of our surface pattern analysis*

Figure 8 shows the result of the reconstruction by the system by KANOH (2000). In this particular example, sub-contours in potsherds often have few features of curvedness and their shapes are, thus, fairly similar one another. The system, therefore, selected the wrong

*These large differences about β and δ are due to the consideration of the variance of brightness, in addition to the average, for surface pattern similarity, in the system by YASUHARA *et al.* (2000).

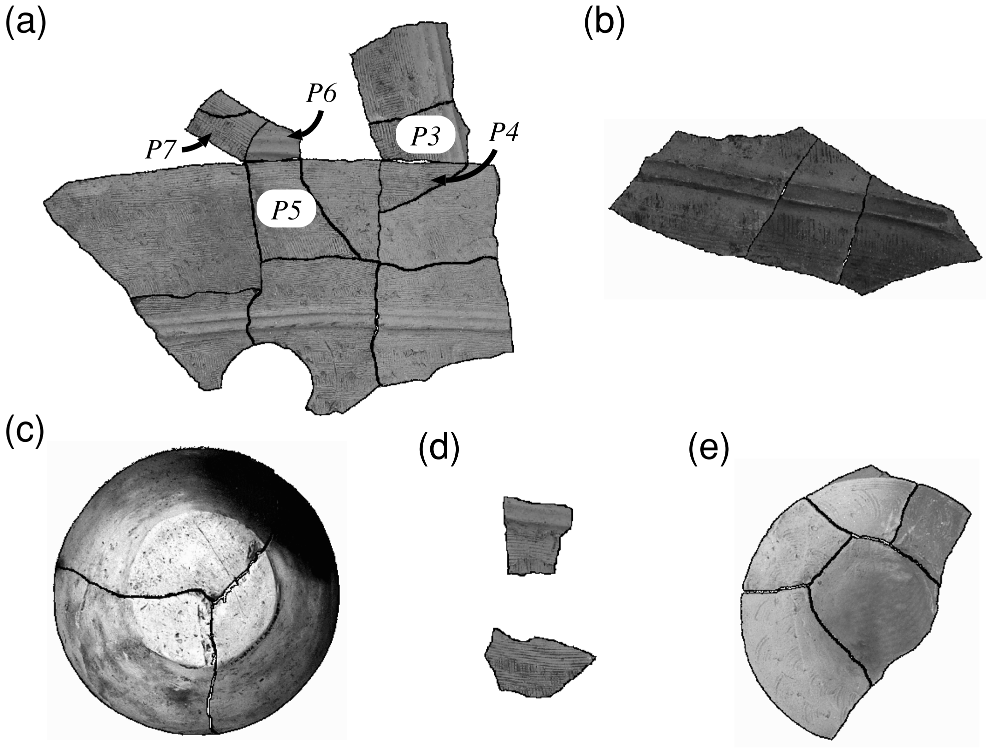

Fig. 9. Output images by the system using pattern and shape analysis in grayscale.

pair of potsherds (*P*1, *P*2), and joined them incorrectly (see earthenware (a) in Fig. 8), because their sub-contours *p*1 and *p*2 were fairly similar in shape. On the other hand, our system, considering surface pattern, joined correctly their potsherds (see Fig. 7), because our system screened wrong pairs, such as (*p*1 , *p*2), by evaluating surface pattern similarity.

5.2. *Effectiveness by using color pattern similarity*

Figure 8 shows the result by the system by YASUHARA (2000). The result indicates that the system also joined some potsherds incorrectly, for example, the pairs of potsherds (*P*3, *P*4), (*P*5, *P*6), and (*P*6, *P*7) shown in Fig. 9, because pairs of sub-contours in the two potsherds might seem both similar each other in grayscale. On the other hand, our system can quantify color distance between surface patterns of sub-contour in $L^*a^*b^*$ color space, and can also consider pattern similarity in color. In this particular example, our system, thus, can detect exactly the pair of potsherds which can be joined, and can reconstruct correctly (see Fig. 7).

It should be noticed that the correctness of reconstruction results is verified by some archaeologists' judgment, and they give adequate value to the efficiency and nearly correctness of our system when a large number of potsherds are given.

6. Concluding Remarks

This paper proposed a method of joint detection considering surface pattern similarity, in addition to contour shape similarity. The method was enhanced, so as to utilize color information effectively for surface pattern analysis for earthenware reconstruction. We implemented the method into our earthenware reconstruction system, and made some experiments. Our system obtained good performance for reconstruction from some weathered potsherds. The joint detection in our system is based on local matching: similarity analysis between two fragments. Reconstruction should be, however, considered global matching, too. In future work, as a global evaluation, we will dedicate to recognition of surface pattern as texture and will propose a joint detection method considering the orientation and the color painting on the surface of potsherds. From the practical standpoint, we will also introduce the surface pattern analysis into three dimensional earthenware reconstruction system in forthcoming papers.

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