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Automatic recognition of the color effect of yarn-dyed fabric by the smallest repeat unit recognition algorithm

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Abstract

In this paper, an effective method based on the smallest repeat unit recognition (SRUR) algorithm is proposed to inspect the color effect of yarn-dyed fabric automatically. This method consists of three main steps: (1) color pattern preliminary recognition; (2) weave repeat unit recognition; (3) color yarn repeat unit recognition. In the first step, the floats in the fabric are located by yarn position segmented with mathematical statistics of sub-images and the colors of all floats classified by the fuzzy C-means algorithm. The color yarn layout is recognized by statistical analysis and the color pattern is roughly generated. In the second step, the weave repeat unit is found based on the preliminary color pattern. The weave repeat unit is extracted from the incompletely recognized weave pattern matrix by the SRUR algorithm. In the last step, according to the weave repeat unit and the preliminary identified color pattern, the color yarn layout is rectified by the improved statistical analysis, and the color yarn repeat unit is finally obtained by the SRUR algorithm. According to the weave and color yarn repeat units, the color effect is produced. The experimental analysis proved that the proposed method can recognize color effects of yarn-dyed fabrics with satisfactory accuracy.

Keywords

yarn-dyed fabric, color effect, weave pattern, smallest repeat unit recognition algorithm, fuzzy C-means algorithm

The color effect of yarn-dyed fabric is an important parameter of yarn-dyed fabric, including (a) color yarn layout, (b) weave pattern, and (c) color pattern. It is necessary for yarn-dyed fabric to recognize its color effect automatically. In the color effect, the cycle size of the color warps or wefts is more than twice the size of the warp or weft repeat unit; the height of the color pattern is the lowest common multiple of the cycle size of the color wefts and the height of the weave repeat unit; and the width of the color pattern is the lowest common multiple of the cycle size of the color warps and the width of the weave repeat unit. However, traditional manual inspection methods are labor-intensive and time-consuming. Thus, with the development of computer and image processing technologies, computer-aided color effect recognition methods have gradually developed in textile engineering.[1–3]

To obtain the color effect of yarn-dyed fabric, it is important to segment the yarns and locate the floats correctly, because the inaccurate localization of floats easily leads to the incorrect recognition of the color and weave pattern.[4] The yarn segmentation methods can be categorized into two groups: frequency domain analysis-based and spatial domain analysis-based methods.[5] The former methods include Fourier transform-based[6–11] and wavelet transform-based[12,13] methods. The later methods include median filter-based,[14] gray projection-based,[15–18] correlation coefficient-based[14,17,18] and clustering analysis-based[17] methods. In the yarn-dyed fabric image, the color signals play a dominant role and the intensity signals decreasing from the yarn center to the interstices plays an inferior role. Therefore, it is difficult to localize yarns of the yarn-dyed fabric by these methods without

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any misjudgements.[18,19] In this paper, a novel yarn segmentation method based on mathematical statistics of sub-images is used to locate the yarn floats.

After acquiring the positions of yarn floats, the color effect of yarn-dyed fabric can be identified. For color effect recognition, there are three representative methods mainly. One method proposed by Xin and Hu[1] is to develop an active grid model. It is noted that the yarn-locating method can correctly detect the position of 99.8% of yarns and the color-information-based correction method can reduce the error rate to 3.6%. The second method, based on the fuzzy C-means (FCM) algorithm and woven fabric pattern database, is adopted by Pan et al.[2] The pattern-database-based method is time-consuming and unable to handle the more complicated fabrics. Furthermore, it does not take the misjudgments of float colors in color pattern into consideration. The latest method proposed by Zhou et al.[3] is the automatic feedback error-correcting color-weave pattern recognition algorithm. In the method, the color with the highest frequency in the column or row of color matrix is considered as the color of the warp or weft yarn of this column or row. Nevertheless, it may result in detecting yarn color layout with some misjudgments in single-system-mélange color fabrics.[15]

Therefore, a novel method based on the smallest repeat unit recognition (SRUR) algorithm is proposed to recognize and extract the smallest repeat unit from the incompletely recognized weave matrix and the color yarn layout vector with some misjudgments correctly. The method consists of three main steps: (1) color pattern preliminary recognition; (2) weave repeat unit recognition; and (3) yarn repeat unit recognition. In the first step, the yarn floats of the fabric image are located using the yarn segmentation method based on mathematical statistics of sub-images, and the colors of all yarn floats are classified using the FCM algorithm. The color yarn layout is confirmed by statistical analysis, and the preliminary color pattern is generated roughly. In the second step, based on the preliminary color pattern, the type of float is determined partly by the logical reasoning method. The weave repeat unit is extracted from the incompletely identified weave pattern matrix using the SRUR algorithm. In the final step, according to the weave repeat unit and the preliminary recognized color pattern, the color yarn layout is rectified by the improved statistical analysis, which improves the accuracy of the original statistical analysis proposed by Zhou et al.[3] The color yarn repeat unit is obtained using the SRUR algorithm. The color effect is produced by combining weave and color yarn repeat units.

This paper is organized as follows. The next section provides the detailed description about the SRUR algorithm that is the core of the paper, supported by the experiment of an incompletely recognized weave matrix. The next section takes a yarn-dyed fabric as an example to demonstrate the efficiency of the SRUR algorithm combining with the yarn segmentation method and the improved statistical analysis, which are also innovations of this paper. The final section offers the experimental discussion, algorithm analysis and method comparison.

Smallest repeat unit recognition algorithm

In this paper, the SRUR algorithm includes two main parts: matrix and vectorial repeat unit recognition. It is used to recognize and extract smallest repeat units from the incompletely recognized weave matrix and the color yarn layout vector, even with some misjudgments. We take one incompletely recognized weave matrix to explain the algorithm theory.

Repeat unit similarity calculation

One incompletely recognized weave matrix generated from Figure 1 is shown in Figure 2 whose original woven structure is plain (the size of the repeat unit is 2×2). In Figure 2, there are 10 rows or columns between two thick lines, the black blocks represent the weft floats and the corresponding value in the weave matrix is $P_{i,j} = 0$ ($i = 1, 2,.., N$, is the row number of the float, $j = 1, 2, \ldots, M$, is the column number of the float, $N \times M$ is the size of the incompletely recognized weave matrix); the white blocks represent the warp floats and the corresponding value in the weave matrix is $P_{i,j} = 1$; the gray blocks represent

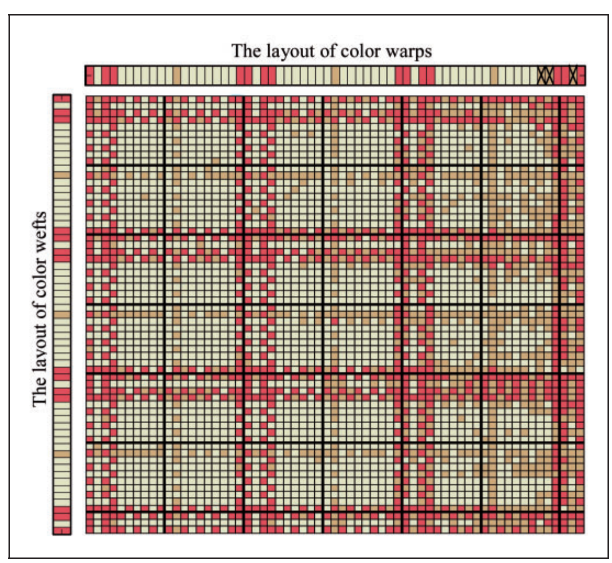


Figure 1. Preliminary color matrix and yarn layout.

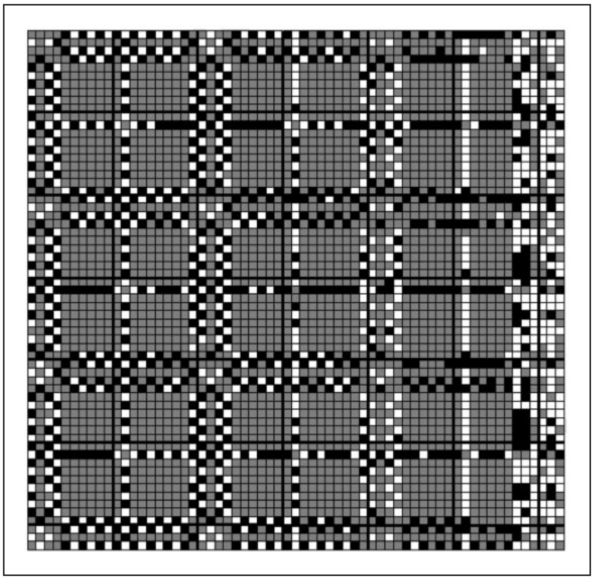


Figure 2. Incompletely recognized weave matrix.

the unidentified floats and the corresponding value in the weave matrix is $P_{i,j}=-1$. Through comparing the weave matrix with the original woven structure, the number of recognized floats is 1463, which accounts for 36.86% of the total floats, and the weave matrix includes 229 error-recognized floats, which accounts for 15.65% of the recognized floats. To extract the weave repeat unit from the incompletely recognized weave pattern matrix, the first step of our proposed method is to confirm the repeat unit size.

To confirm the repeat unit size, we propose S, including the similarity of the smallest repeat units along the horizontal (SX) and vertical (SY) direction, to characterize the similarity of every float in weave repeat units compared with other repeat units. S is in the interval [0, 1]. In order to calculate the similarity of the smallest repeat unit along the horizontal direction (SX), the weave matrix is divided into $fix(M/k)$ sub-matrices whose size is $N \times k$, where $k=2,3,\ldots,fix(M/3)$, $fix(value)$ is the roundness of *value*, especially when $k=1$, $SX_1=0$. The value of each float in the jth sub-matrix is compared with that in other $((j+1)$th, $(j+2)$th, $\ldots,fix(M/k)$th) sub-matrices from top to bottom and from left to right successively, where $j=1,2,\ldots,fix(M/k)-1$. The sub-matrices are compared $fix(M/k)\times(fix(M/k)-1)/2$ times, while the floats are compared $fix(M/k)\times(fix(M/k)-1)\times N\times k/2$ times. The calculation formula of SX is then obtained as below:

$$SX_k=\frac{1}{fix(M/k)\times(fix(M/k)-1)\times N\times k/2}\times\sum_{j=1}^{fix(M/k)}\sum_{i=j+1}^{fix(M/k)}\sum_{l=1}^{k}\sum_{m=1}^{N}(1-\Delta x) \quad (1)$$

$$\Delta x=\begin{cases}\left|P_{m,(j-1)\times k+l}-P_{m,(i-1)\times k+l}\right|, & P_{m,(j-1)\times k+l}\geq 0 \text{ and } P_{m,(i-1)\times k+l}\geq 0\\ 1, & P_{m,(j-1)\times k+l}=-1 \text{ or } P_{m,(i-1)\times k+l}=-1\end{cases} \quad (2)$$

The incompletely recognized weave matrix in Figure 2 has 63 columns, which represents that there are 63 warp yarns in the fabric.

In order to obtain the SX of the incompletely recognized weave matrix, we take SX_4 an example to illustrate the calculating process. When $k=4$, the incompletely recognized weave matrix is divided into 15 sub-matrices whose height and width are $N\times 4$. Its calculation process is shown in Figure 3. When $j=1$, the value of each float in the first sub-matrix is compared with that in other (2nd, 3rd, 4th, ..., 15th) sub-matrices from top to bottom and from left to right successively. When $j=2$, the value of each yarn float in the second sub-matrix is compared with that in other (3rd, 4th, ..., 15th) sub-matrices. Following the law, when $j=14$, the value of each yarn float in the 14th sub-matrix is compared with that in other (only 15th) sub-matrices. The sub-matrices are compared 105 $(15\times 14/2)$ times, while the floats are compared $420\times N$ $(15\times 14\times N\times 4/2)$ 2 times. The result of SX is shown in Figure 4.

To calculate the similarity of the smallest repeat unit along the vertical direction (SY), the incompletely recognized weave matrix is divided into $fix(N/k)$ sub-matrices whose size is $k\times M$, where $k=2,3,\ldots,fix(N/3)$. The value of each yarn float in the jth sub-matrix is compared with that in other $((j+1)$th, $(j+2)$th$,\ldots,fix(N/k)$th) sub-matrices, where $j=1,2,\ldots,fix(N/k)-1$. The sub-matrices are compared $fix(N/k)\times(fix(N/k)-1)/2$ times, while the floats are compared $fix(N/k)\times(fix(N/k)-1)\times N\times k/2$ times. The result of SY is also shown in Figure 4. The calculation formula of SY is as below:

$$SY_k=\frac{1}{fix(N/k)\times(fix(N/k)-1)\times M\times k/2}\times\sum_{j=1}^{fix(N/k)}\sum_{i=j+1}^{fix(N/k)}\sum_{l=1}^{k}\sum_{m=1}^{M}(1-\Delta x) \quad (3)$$

$$\Delta x=\begin{cases}\left|P_{(j-1)\times k+l,m}-P_{(i-1)\times k+l,m}\right|, & P_{(j-1)\times k+l,m}\geq 0 \text{ and } P_{(i-1)\times k+l,m}\geq 0\\ 1, & P_{(j-1)\times k+l,m}=-1 \text{ or } P_{(i-1)\times k+l,m}=-1\end{cases} \quad (4)$$

Repeat unit size detection

The size of the smallest repeat unit can be obtained according to S in Figure 4. The larger S_k is, the greater

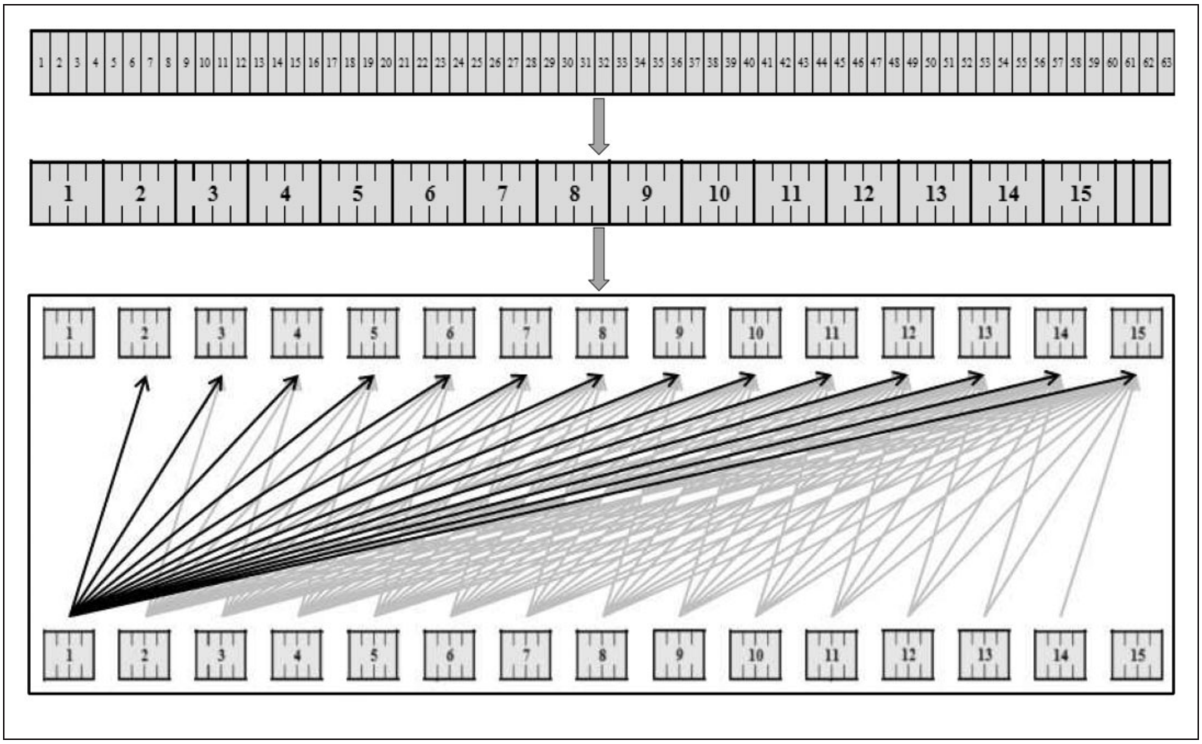


Figure 3. The calculation process of SX_4.

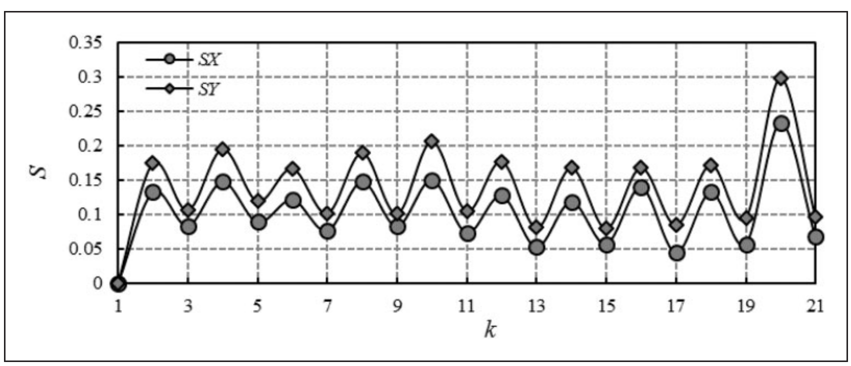


Figure 4. *S* generated from the incompletely recognized weave matrix.

the chance that k is the size of the smallest repeat unit. By investigating 10 samples of yarn-dyed fabrics, when the size of the smallest weave repeat unit is k, $S_{i \times k}$ is the local maximum value of all values of S_k ($i = 1, 2, \ldots, fix\ (L/k)$, where L is the length of S_k). According to the features of S, the right size of the smallest weave repeat unit is recognized with the following steps.

Step 1: If the maximum value of S is 1, the right size of the repeat unit is the minimum subscript k when $S_k = 1$, otherwise go to Step 2. This condition is shown in S of Figures 5(f) and 6(f).

Step 2: If $S_{i \times j} = \max([S_{(i-1) \times j+1},\ S_{(i+1) \times j-1}])$ and $S_{i \times j}$ are bigger than the mean value of S, where $j = 1, 2\ldots, fix\ (L/2)$, $i = 1, 2\ldots, fix\ (L/j)$, the right size of the repeat unit is j, otherwise go to Step 3. This condition is shown in S of Figures 4, 5(e) and 6(e).
Step 3: If $S_k = \max(S)$, the size of repeat unit is k. This condition is shown in S of Figure 7.

Applying the proposed steps into the S generated from incompletely recognized weave matrix in Figure 4, S meets the requirements: $\max(S) \neq 1$ and when $j = 2$, $S_{i \times j} = \max([S_{(i-1) \times j+1},\ S_{(i+1) \times j-1}])$, $i = 1, 2, \ldots, 10$. Therefore, the size of the smallest

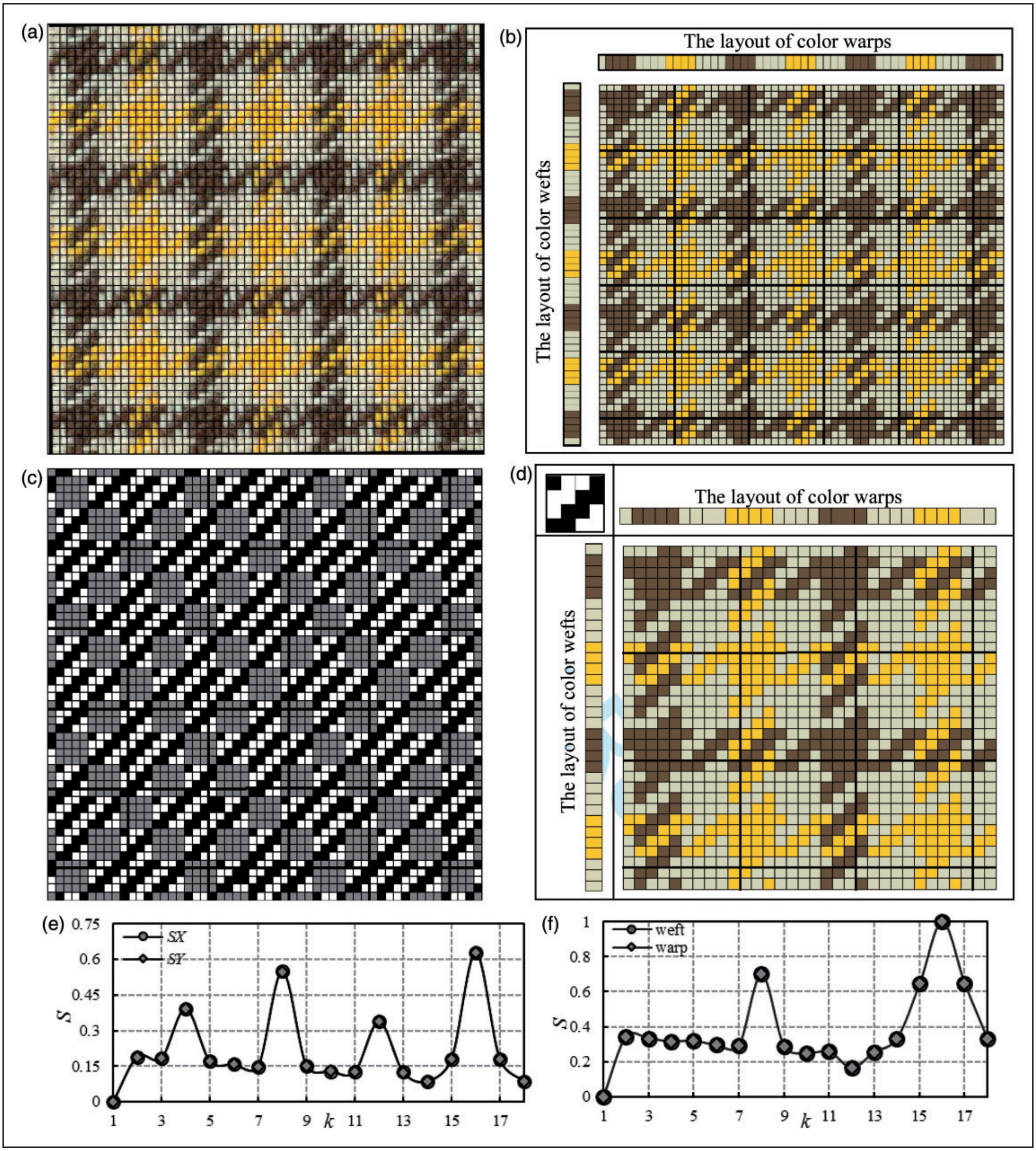


Figure 5. (a) Yarn segmentation result. (b) Preliminary color matrix and yarn layout. (c) Incompletely recognized weave matrix. (d) Color effect. (e) S generated from the incompletely recognized weave matrix. (f) S generated from the color yarn layout.

weave repeat unit in Figure 2 is 2×2. The recognized result is right as it represents the real situation.

Repeat unit extraction

According to the size of the smallest weave repeat, it can be extracted from the incompletely recognized weave matrix. Based on the right size of the smallest weave repeat ($h \times w$), the weave matrix is divided into $n \times m$ weave repeat units ($n = fix\ (N/h)$, $m = fix\ (M/w)$). The types of floats are confirmed by the comprehensive judgment of the all weave repeat units. In an ideal weave matrix without any misjudgments, the types of $n \times m$ floats in the same position of all weave repeat

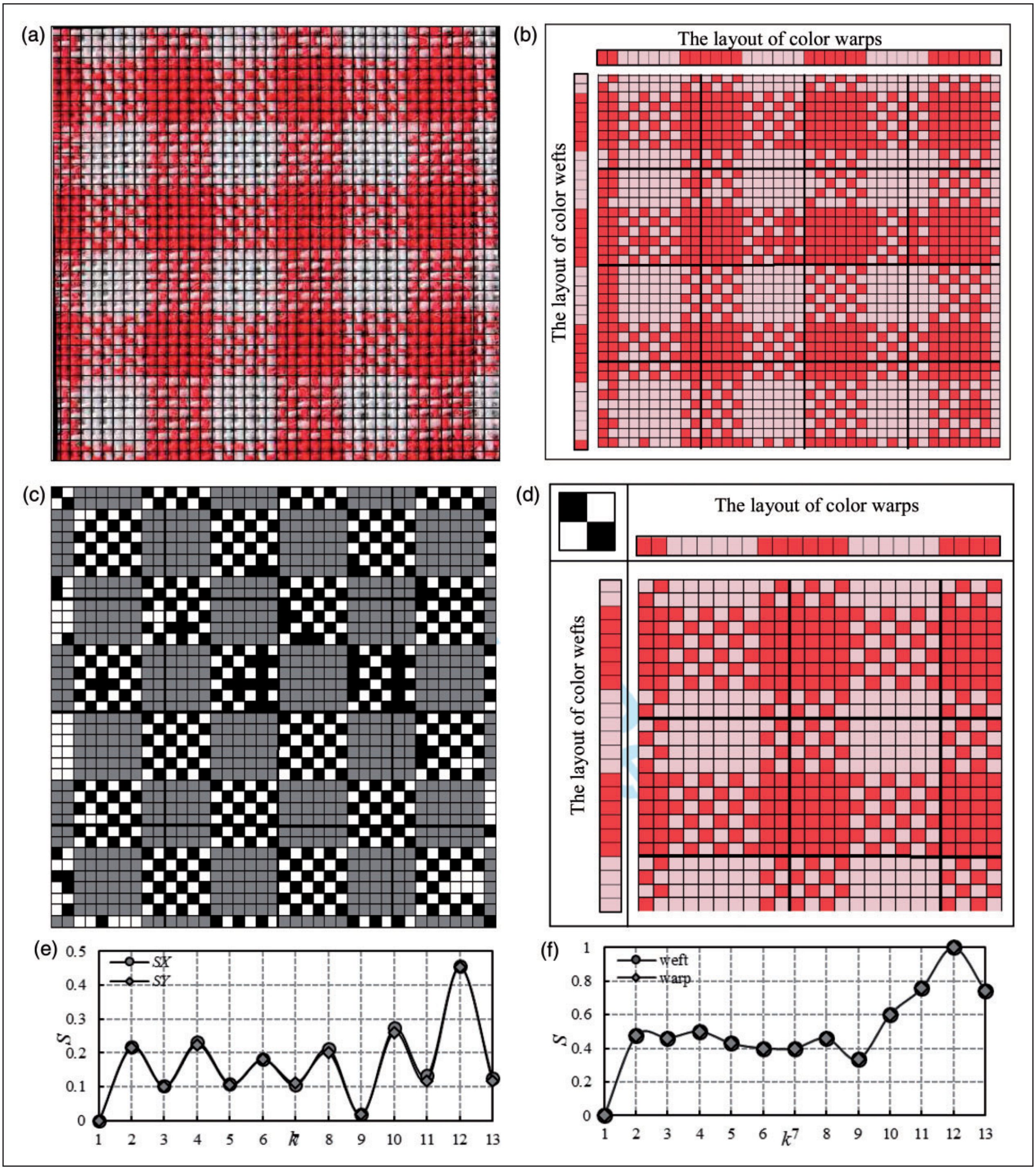


Figure 6. (a) Yarn segmentation result. (b) Preliminary color matrix and yarn layout. (c) Incompletely recognized weave matrix. (d) Color effect. (e) *S* generated from the incompletely recognized weave matrix. (f) *S* generated from the color yarn layout.

units should be the same. Whereas there are some unidentified and error-recognized floats in the incompletely recognized weave matrix, the type of float is usually the type with the highest frequency in these $n \times m$ floats. Thus, by calculating the proportion of float types (0 or 1) appearing in $n \times m$ floats, the type having the highest frequency value is considered as the type of the float. According to the

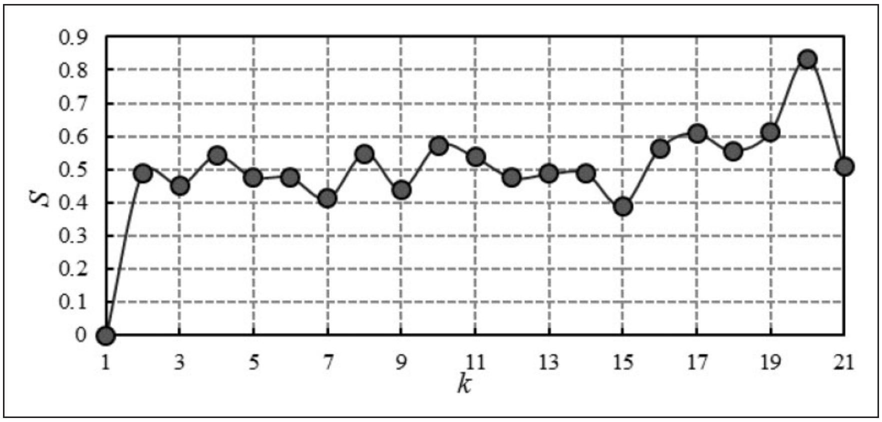


Figure 7. *S* generated from the color yarn layout vector.

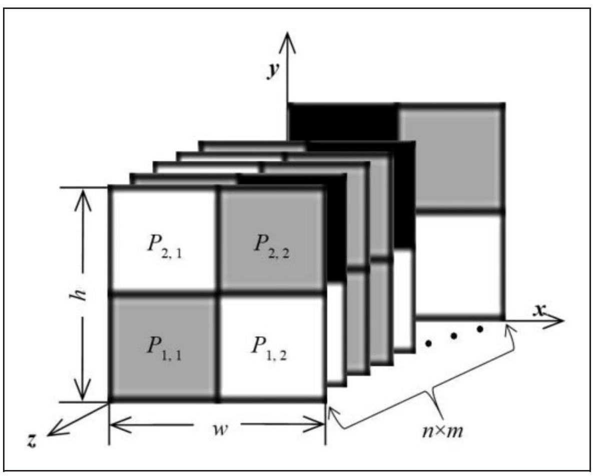


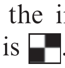
Figure 8. The comprehensive judgment diagram.

above comprehensive judgment, the specific formulas are as below:

$$F_0 = \sum_{k=1}^{n}\sum_{g=1}^{m} \Delta x, \Delta x = \begin{cases} 1, & P_{i+(k-1)\times h, j+(g-1)\times w} = 0 \\ 0, & P_{i+(k-1)\times h, j+(g-1)\times w} \neq 0 \end{cases} \tag{5}$$

$$F_1 = \sum_{k=1}^{n}\sum_{g=1}^{m} \Delta x, \Delta x = \begin{cases} 1, & P_{i+(k-1)\times h, j+(g-1)\times w} = 1 \\ 0, & P_{i+(k-1)\times h, j+(g-1)\times w} \neq 0 \end{cases} \tag{6}$$

where $i = 1, 2, \ldots, h$, $j = 1, 2 \ldots, w$, $k = 1, 2, \ldots, n$, $g = 1, 2, \ldots, m$. If $F_0 > F_1$, $U_{i,j}$ is 0. If $F_0 < F_1$, $U_{i,j}$ is 1. U is the matrix of the weave repeat unit.

There are 31×31 weave repeat units in the incompletely recognized weave matrix of Figure 2 ($n = fix$ (63/2), $m = fix$ (63/2)). The comprehensive judgment diagram is shown in Figure 8. In Figure 8, we do not take the unidentified floats into consideration. When $i = 2$ and $j = 2$, the black blocks have the highest frequency value in $n \times m$ floats, which means that $U_{2,2} = 1$. Following the law, $U_{1,1} = 1$, $U_{1,2} = 0$ and $U_{2,1} = 0$. Therefore, the weave repeat unit in the incompletely recognized weave matrix of Figure 2 is . The recognized result is right as it represents the real situation.

Experimental details

In the experiment, the SRUR algorithm is proposed to identify the color effect of yarn-dyed fabric. The yarn segmentation method based on the mathematic statistics of sub-images is applied to localize the yarn floats. The FCM algorithm is used to recognize the preliminary color pattern, and then the proposed SRUR algorithm is combined with the logical reasoning method to identify the weave repeat unit. The proposed SRUR algorithm and the improved statistical analysis are adopted to inspect the color yarn repeat units and produce the color effect finally.

Color pattern preliminary recognition

Fabric image acquisition and preprocessing. A Microtek S400 flat scanner is used to digitize a reflective color fabric image. The resolution is set at 1200 DPI. The experiments are operated in the software MATLAB 2013a, and the computer doing experiments is equipped with the Win7 Ultimate System, CPU Intel® Core™i3 and 2.00 GB memory. To reduce the color differentiation on the fabric appearance, the capture region is chosen far from the edge and the surface of the fabric should be clear.

Because of the fabric placement, the slant of the fabric cannot be avoided during the image acquisition. The slant of the fabric can affect the yarn segmentation results greatly. To realize the precise measurement of fabric parameters, the Hough transform method is used to detect the high-precision skew angle of yarn and rotate the fabric image into an ideal state.[20] A yarn-dyed fabric sample with the size of 980 pixels $\times$ 816 pixels, as shown in Figure 9, is used to validate the effect of the method. The real size of yarn-dyed fabric sample is $2.07 \times 1.73\,\mathrm{cm}^2$.

Yarn floats location. In order to inspect the placements of the yarn floats, mathematical statistics of sub-images is adopted to segment the yarns.[21] The method consists of two main steps: rough measurement and precise measurement. In the step of rough measurement, the projection curve of value in the Hue Saturation Value (HSV) color model is obtained successively.[22] The number of weft yarns in the sample fabric image is N_{weft} by counting the number of peaks in the weft curve roughly. The height of the sub-image is $fix(M/N_{weft} \times \beta)$ pixels ($M \times N$ is the size of the yarn-dyed fabric image), where β is a parameter to control the height of the sub-images. So the whole fabric image is divided into $M/fix(M/N_{weft} \times \beta)$ sub-images whose size is $fix(M/N_{weft} \times \beta)$ pixels $\times$ N pixels.

In Figure 9, the number of weft yarns in the sample fabric image is 63 by counting the number of peaks in the weft curve roughly. After many experiments, β was determined to be 1.5, which gave an optimal yarn segmentation result. Hence, the height of the sub-image is $fix(816/63 \times 1.5)$ pixels, and the whole fabric image is divided into 42 sub-images whose size is 19 pixels $\times$ 816 pixels. The projection method is applied to all the sub-images respectively and the projection curves of all sub-images after smoothing using the locally weighted regression (LOESS) algorithm[23–25] are shown in Figure 10.

The probability distribution map of peaks is obtained by processing the projection curves of all sub-images, as shown in Figure 11. In Figure 11, the gray squares represent the peak locations in the projection curves of Figure 10. The peak locations corresponding to the same yarn center-main line make up a straight line roughly. The locations of the yarn center-main lines can be located by detecting every straight line. The frequency curve is generated by accumulating the probability distribution map of peaks along the vertical direction. After smoothing using the LOESS

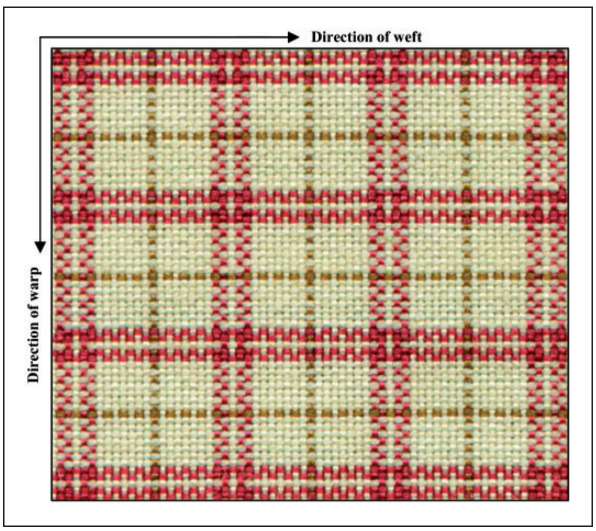


Figure 9. The original yarn-dyed fabric sample.

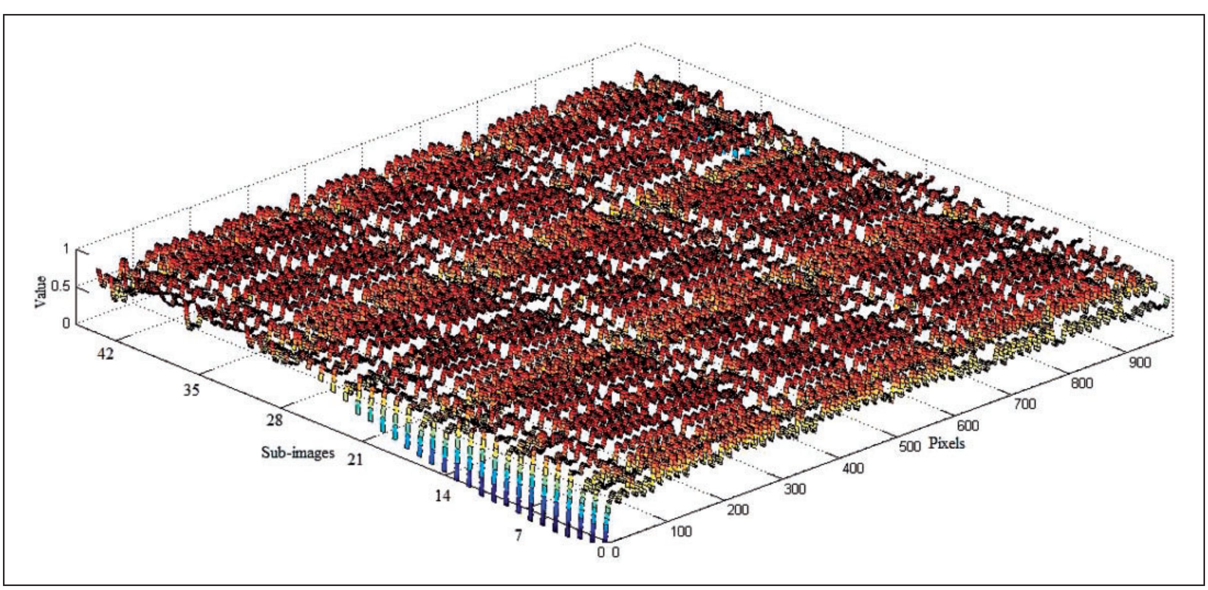


Figure 10. Projection curves of fabric sub-images corresponding to the warp yarns.

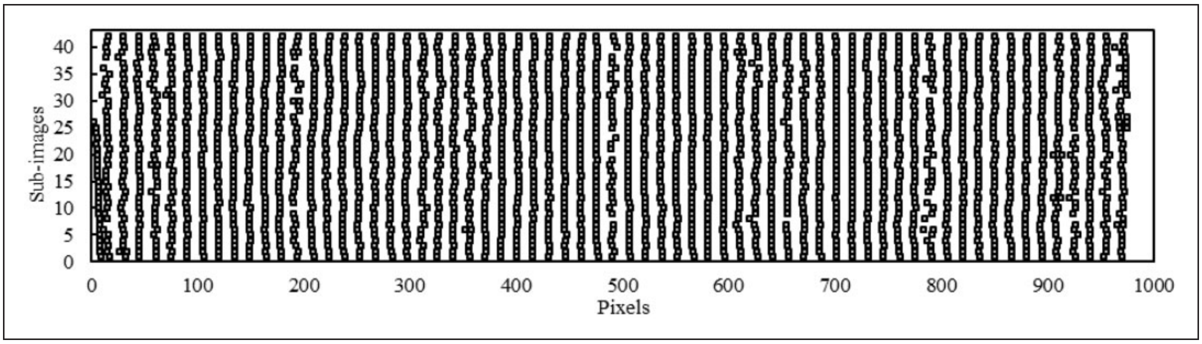


Figure 11. The probability distribution map of peaks corresponding to the warp yarns.

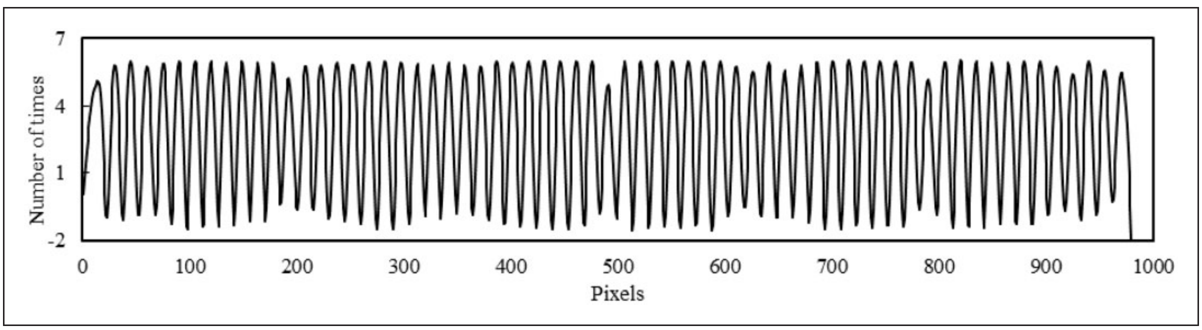


Figure 12. The frequency curve corresponding to the warp yarns after smoothing.

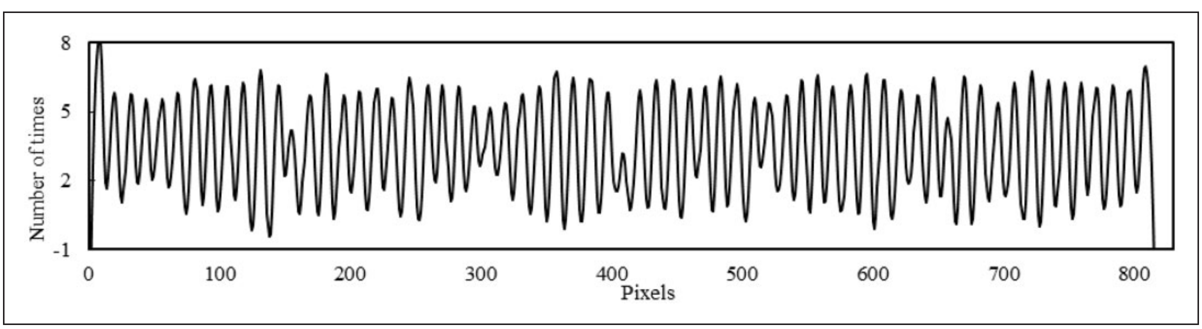


Figure 13. The frequency curve corresponding to the weft yarns after smoothing.

algorithm, the frequency curves corresponding to the warp yarns are shown in Figure 12. In Figure 12, the valleys in the frequency curves correspond to the positions of the yarn interstices in the fabric image.

Using the same method, the frequency curve after smoothing corresponding to the weft yarns is shown in Figure 13. Based on the positions of the warp and weft yarn interstices, the yarn segmentation results are shown in Figure 14. The fabric in Figure 14 consists of 63×63 yarn floats.

Float colors classification. The fabric image is converted into Lab color model from the RGB color model.[26] The color features are extracted from the floats in the Lab color model. The floats are classified by the FCM algorithm according to the float color features.[27] The color pattern is obtained from the float classification results. The color feature used to characterize and classify the floats is shown as below:

$$V = \left(\bar{L}, \bar{a}, \bar{b}\right) \tag{7}$$

The color features of the float are easily weakened by the pixels in the border of the float according to the definition of feature V, because the color of the pixels in the border of float is influenced by the color of the

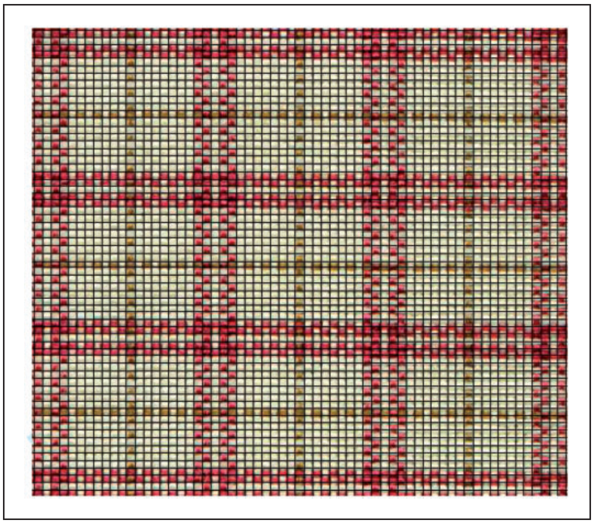


Figure 14. Yarn segmentation results of the yarn-dyed fabric.

adjacent yarn. In order to eliminate the influence of the border pixels, the mean value of L, a and b of nine pixels in the center of each float is calculated as the float characteristic feature:

$$\bar{L} = \frac{1}{9}\sum_{i=-1}^{1}\sum_{j=-1}^{1} L_{x_0+i,y_0+j}, \quad \bar{a} = \frac{1}{9}\sum_{i=-1}^{1}\sum_{j=-1}^{1} a_{x_0+i,y_0+j},$$
$$\bar{b} = \frac{1}{9}\sum_{i=-1}^{1}\sum_{j=-1}^{1} b_{x_0+i,y_0+j} \tag{8}$$

where (x_0, y_0) is the center position of the yarn float.

Color yarn layout preliminary recognition. According to the preliminary recognized color pattern, the color yarn layout is confirmed by statistical analysis.[3] In an ideal color matrix without any misjudgments, the warp or weft yarn color of a column or row is usually the color with the highest frequency in this column or row. Hence, by calculating the proportion of colors appearing in each row and column, the color having the highest frequency value is considered as the color of each weft and warp yarn. The discriminated formula is as below:

$$J_j = mode\left(C_{1,j}, C_{2,j}, \ldots, C_{N,j}\right) \tag{9}$$

$$W_j = mode\left(C_{i,1}, C_{i,2}, \ldots, C_{i,M}\right) \tag{10}$$

where J, W are the color types of the warp and weft yarns, respectively, $mode$(vector) is the number that has the highest frequency in the vector and C is the color matrix whose size is $N \times M$. $i = 1, 2, \ldots, N$, $j = 1, 2, \ldots, M$.

After that, the preliminary color matrix and yarn color layout are obtained as shown in Figure 1. In Figure 1, the number of floats with color misjudgment is 744 and the error rate is 18.75%. Weft color yarn layout is detected without misjudgments, but warp color yarn layout is detected with three misjudgments, as shown in Figure 1 (marked by 'X').

Weave repeat unit recognition

Yarn-dyed fabric consists of different color warps and wefts that are interlaced at right angles to each other. Thus, according to the color yarn layout and the preliminary recognized color matrix, the cross-states of yarn floats can be determined partly by the logical reasoning method.[2,3]

In a color matrix C with $N \times M$ floats, the colors of each warp yarn from left to right are denoted as weft color W_i ($i = 1, 2, \ldots, N$), and the colors of weft yarns from top to bottom are denoted as warp color J_j ($j = 1, 2\ldots, M$). Then each element $P_{i,j}$, in weave pattern matrix P can be inferred by the logical reasoning method as follows:

1. if $C_{i,j}$ is identical with the corresponding weft color W_i, but different from the corresponding warp color J_j, it should be a weft float with $P_{i,j} = 0$;
2. if $C_{i,j}$ is identical with the corresponding warp color J_j, but different from the corresponding weft color W_i, it should be a warp float with $P_{i,j} = 1$;
3. if the weft color W_i of the yarn float is identical with the corresponding warp color J_j, $P_{i,j}$ cannot be inferred.

The incompletely recognized weave matrix corresponding to Figure 1 is shown as Figure 2. The weave repeat unit is extracted from the matrix using the SRUR algorithm. It can be seen that the weave pattern of the yarn-dyed fabric is plain.

Yarn repeat unit recognition

Color yarn layout correction. The misjudgments in the preliminary recognized color yarn layout should be corrected. The color of the weft or the warp floats is the same as that of the corresponding weft yarn or warp yarn separately. Hence, the color that appears most frequently in the weft or the warp floats is considered to be the color of the weft or the warp yarns. The yarn layout can be rectified by this improved statistical analysis:

$$YJ_j = mode\left(C_{k1,j}, C_{k2,j}, \ldots, C_{kn,j}\right) \tag{11}$$

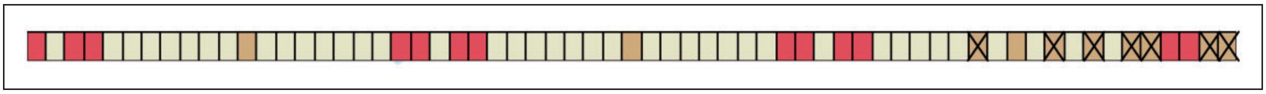


Figure 15. Color yarn layout vector with some misjudgments.

$$YW_i = mode\big(C_{i,k1}, C_{i,k2}, \ldots, C_{i,kn}\big) \qquad (12)$$

where YW, YJ are the color types of the weft and the warp yarns. $\{C_{k1,j}, C_{k2,\ j}, \ldots, C_{kn,j}\}$ is the color set of the warp floats in the jth column and $\{C_{i,k1}, C_{i,k2}, \ldots, C_{i,kn}\}$ is the color set of the weft floats in the ith row.

The preliminary recognized color warp and weft yarn layouts are shown in the left and top position of Figure 1, respectively. The layout of color weft yarn is detected without misjudgments and it does not need to be corrected. The corrected layout of the color warps is shown in Figure 15. Nevertheless, the number of misjudged warp yarns after correcting increases from 3 to 7, because the color-misjudged floats are too many and concentrated in the close warp yarns of the fabric image. However, theoretical analysis and experiments conducted during the present study indicate that the improved statistical analysis can correct the color yarn layout.

Color yarn repeat unit extraction. Color yarn repeat unit recognition can be seen as the special case of weave repeat unit recognition from the incompletely recognized weave matrix. The color yarn layout vector takes the place of the incompletely recognized matrix during the recognition process. The corrected layout of the color warp vector with seven misjudgments in Figure 15 (marked by 'X') has over three yarn repeat units. There, the color yarn repeat unit can be extracted using the SRUR algorithm.

When calculating the similarity of the smallest color yarn repeat unit, N in Equation (1) is 1 in the color yarn layout vector. The results of S generated from the color yarns layout vector are shown in Figure 7. According to the curve and the features of S in Figure 7, the size of yarn repeat units is identified as 20 by the proposed recognition steps of repeat unit size detection.

After obtaining the right size of color yarn repeat units, the yarn layout vector is divided into n yarn repeat units. The yarn repeat unit can be also extracted by the proposed comprehensive judgment of the all yarn repeat units:

$$Q_i = mode\big(Y_i, Y_{c+i}, \ldots, Y_{(n-1)\times c+i}\big) \qquad (13)$$

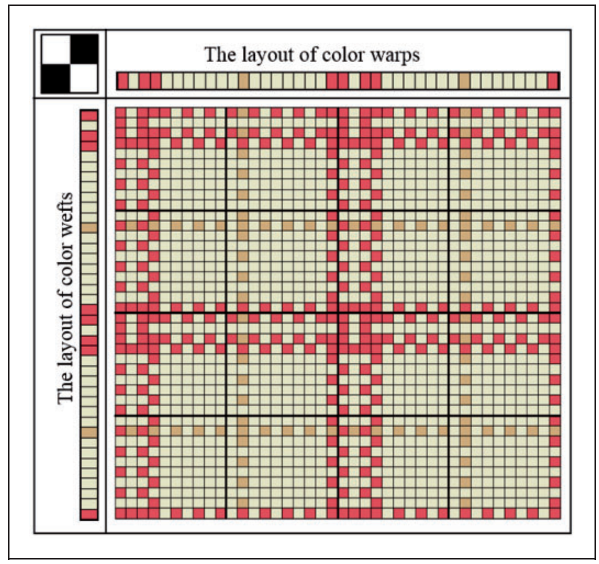
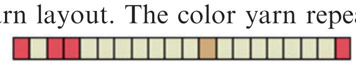


Figure 16. Color effect of the yarn-dyed fabric.

where $i = 1, 2, \ldots, c,\ n = fix(L/c)$, c is the size of the color yarn repeat unit and Q is a repeat unit of color yarn layout. The color yarn repeat unit is recognized as .

The weft and warp color yarn repeat units are extracted from the preliminary recognized layout of the color wefts and warps using the SRUR algorithm. Based on weave and color yarn repeat units, the color effect of the yarn-dyed fabric is constructed as shown in Figure 16. In Figure 16, the color warp and weft yarn layouts are in the left and top position, respectively, the weave repeat unit is in the left-top position and the color effect is in the right-bottom position. The flow chart of the algorithm is shown in Figure 17.

Results and discussion

Experimental discussion

In this section, two different actual yarn-dyed fabrics are used to illustrate the effectiveness of the proposed method. The fabric in Figure 5 is a 2/2 twill yarn-dyed fabric containing three color pattern repeat units. Its yarn segmentation results are shown in Figure 5(a). It consists of 54 wefts × 54 warps. After processing using the FCM algorithm, all floats are divided into

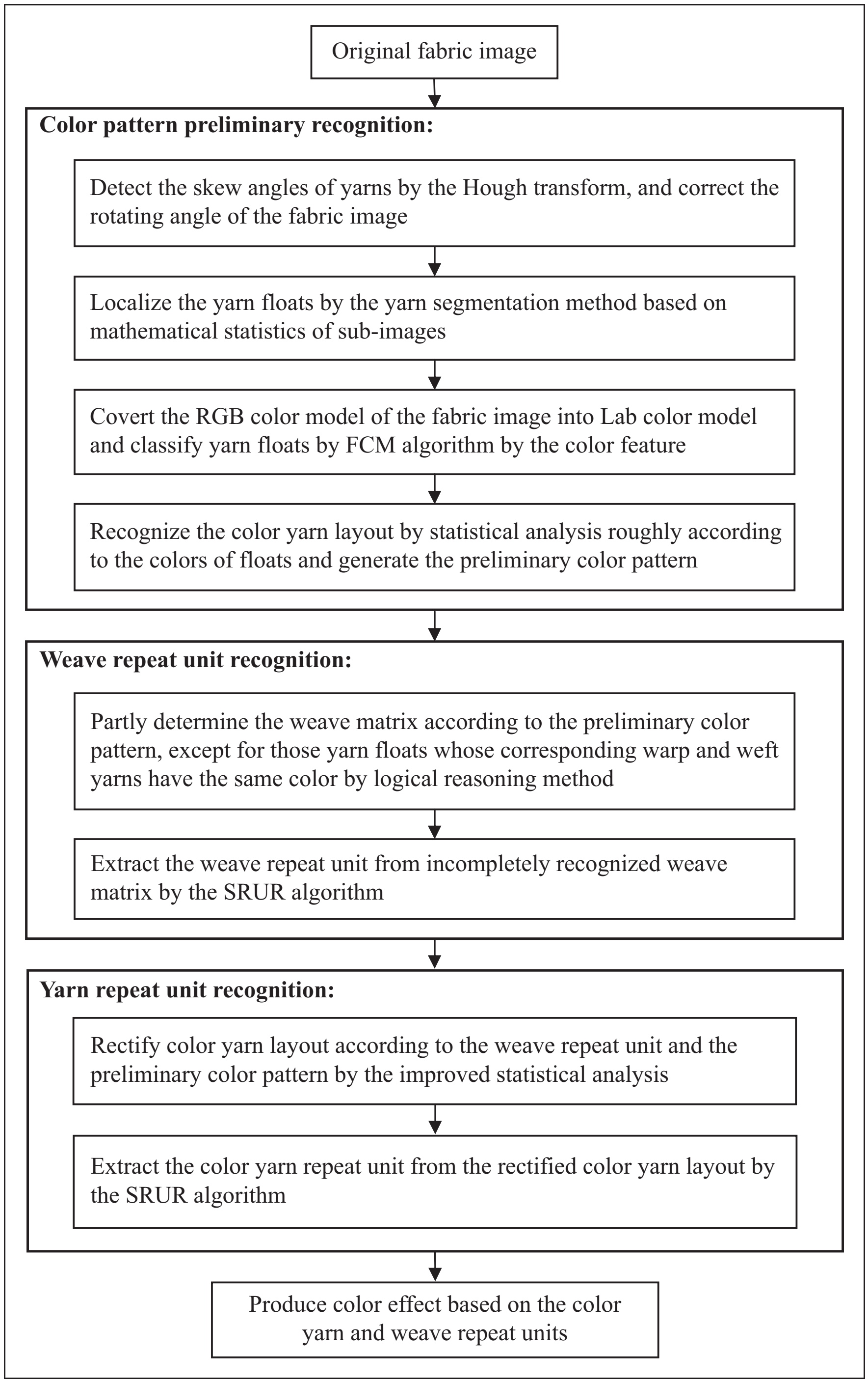


Figure 17. Flow chart of the proposed method.

three clusters. The preliminary recognized color matrix and yarn layout are shown in Figure 5(b). The weave matrix in Figure 5(c) is generated from Figure 5(b).

The SRUR algorithm is used to calculate the similarities along the horizontal direction (SX) and vertical direction (SY), as shown in Figure 5(e). In Figure 5(e), regardless of SX and SY, the S meets the requirements: $\max(S) \neq 1$, and when $j = 4$, $S_{i \times j} = \max([S_{(i-1) \times j+1}, S_{(i+1) \times j-1}])$, $i = 1, 2, 3, 4$, the right size of the smallest weave repeat unit is 4×4. The smallest repeat unit is 2/2 twill, as shown in the left-top position of Figure 5(d). The color yarn layout is recognized accurately and does not need correcting. The SRUR algorithm is used to calculate the similarity including the color warp and weft yarn layout, as shown in Figure 5(f). In Figure 5(f), $\max(S)=1$ and 16 is the minimum value making $S_k=1$, and the right size of the warp and weft yarn repeat units is 16×16. The smallest repeat unit is obtained using the SRUR algorithm. Based on the weave and the color yarn repeat units, the color effect of the yarn-dyed fabric is identified as shown in Figure 5(d).

The fabric in Figure 6 is a plain yarn-dyed fabric containing three color pattern repeat units. Its yarn segmentation results, the preliminary recognized color matrix and yarn layout, the incompletely recognized weave matrix, S generated from incompletely recognized weave matrix and S generated from the color yarn layout are shown in Figure 6(a), (b), (c), (e), (f), respectively. It consists of 39 wefts $\times$ 39 warps. The right size of weave repeat unit is 2×2 and the right size of color warp and weft yarn layout is 12×12. Through the SRUR algorithm, the color effect of the yarn-dyed fabric image is identified as shown in Figure 6(d).

Algorithm analysis

In this paper, the proposed SRUR algorithm can be used to extract the color yarn repeat unit from the color yarn layout with some misjudgments and weave repeat unit from the incompletely recognized weave matrix even with some misjudgments. The fabric images in Figures 5, 6 and 11 are used to analyze the robustness of this algorithm, including the percentages of recognized floats in the weave matrix, error-recognized floats in the recognized floats and error-recognized warps and wefts in the color warps and wefts, as shown in Table 1. In the table, the smallest weave repeat unit is extracted from the incompletely recognized weave matrix only with 36.86% recognized floats and 15.65% error-recognized floats in the recognized floats using the proposed algorithm. The smallest color yarn repeat unit is extracted from the color yarn layout with 4.76% error-recognized yarns. The experimental data demonstrates that the proposed SRUR algorithm has a good robustness when recognizing the weave and color yarn repeat units for yarn-dyed fabrics.

Method comparison

The SRUR algorithm combining with the yarn segmentation method and the improved statistical analysis are the important and original parts of the proposed method. In the section, in order to demonstrate the advantages of our method, two other methods proposed by Pan et al.[2] and Zhou et al.,[3] respectively, are used to make a comparison with our method.

The methods of Pan et al.[2] and Zhou et al.[3] and our method to recognize the color effect of yarn-dyed fabric follow a similar procedure: (1) a fabric image is captured; (2) the fabric image is pre-processed, including noise removal, image enhance and image correction; (3) the yarns of the fabric image are segmented and the yarn floats are localized; (4) the color of every yarn float is identified by a clustering algorithm; (5) the color of every weft and warp yarn is confirmed and the color yarn layout is obtained; (6) the weave matrix is recognized incompletely using the logical reasoning method; (7) the weave matrix is detected; (8) the weave and color yarn repeat units are recognized and extracted.

The biggest difference between these methods is whether the method can recognize weave and color yarn repeat units from uncompleted weave matrix and color yarn layout respectively in different situations, as shown in Table 2. The weave repeat unit recognition method of Pan et al.[2] is based on the pattern database, which is time-consuming and unable to handle an uncompleted weave matrix with misjudgments. The *Su* index-based period extraction method is proposed by Pan et al.[2] to recognize the color yarn repeat unit, but it does not take the misjudgments of the color yarn layout into consideration. Therefore, it cannot recognize the repeat unit from color yarn layout with misjudgments. An automatic feedback error-correcting color-weave pattern recognition algorithm has been created by Zhou et al.[3] to recognize the completed weave matrix from the incompletely recognized weave matrix even with some misjudgments. Nevertheless, they just focus on the first seven steps of the color effect recognition and do not study the color yarn

Table 1. The robustness analysis of the SRUR algorithm

Yarn-dyed fabric	Size of the weave matrix	Recognized floats in the weave matrix (%)	Error-recognized floats in the recognized floats (%)	Error-recognized warps in the color warps (%)	Error-recognized wefts in the color wefts (%)
Figure 5(a)	54×54	63.10	0.27	0	0
Figure 6(a)	39×39	50.03	5.52	0	0
Figure 11	63×63	36.86	15.65	4.76	0

Table 2. The comparison results of different methods

Method	Recognizing repeat unit from incompletely recognized weave matrix		Recognizing repeat unit from color yarn layout	
	without misjudgments	with misjudgments	without misjudgments	with misjudgments
Method in Pan et al.[2]	Yes	No	Yes	No
Method in Zhou et al.[3]	Yes	Yes	No	No
Method based on SRUR	Yes	Yes	Yes	Yes

SRUR: smallest repeat unit recognition.

repeat unit and recognition and extraction. Particularly in the section of *yarn repeat unit recognition*, the original statistical analysis proposed by Zhou et al. is improved with high accuracy to detect the color yarn layout.

In our method, the weave repeat unit can be extracted from the incompletely recognized weave matrix with some misjudgments; furthermore, the color yarn repeat unit can be extracted from the color yarn layout with some misjudgments. The computational time of our method is only around 1 minute (Matlab code), which is smaller than that of Pan et al.[2] (3–5 minutes, C++ code).

Conclusion

In the present paper, the SRUR algorithm is proposed to avoid misrecognition in automatic recognition of the color effect of yarn-dyed fabric. The SRUR algorithm is the core of this paper. It not only can be used to extract color yarn repeat unit from the color yarn layout with some misjudgments, but also can be used to extract the weave repeat unit from the incompletely recognized weave matrix with some misjudgments.

Based on the SRUR algorithm, the color effect of yarn-dyed fabric is recognized. This method consists of three main steps: color pattern preliminary recognition, weave repeat unit recognition and color yarn repeat unit recognition. The yarns are segmented and the preliminary color pattern is detected. The proposed SRUR algorithm is combined with the logical reasoning method and the improved statistical analysis to identify the weave and the color yarn repeat units. The color effect is produced finally.

The experimental results prove that the proposed algorithm has a good robustness. The SRUR algorithm can be used to extract the smallest weave repeat unit from the incompletely recognized weave matrix only with 36.86% recognized floats and even 15.65% error-recognized floats in the recognized floats, and the color yarn repeat unit from the color yarn layout with 4.76% error-recognized yarns. The proposed method can recognize the color effects of yarn-dyed fabrics with greater accuracy.

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