New Objective Evaluation of Fabric Smoothness Appearance

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ABSTRACT

A new evaluation system is presented for measuring the smoothness appearance of fabric surfaces objectively and quantitatively. In this system, the contour of the fabric surface is measured with the stereo vision algorithm, and the data are then used to evaluate fabric smoothness by fractal geometry, which explicitly explains the degree of ruggedness of the fabric surface as a decimal fraction with precise grading. This study illustrates the stereo vision technique and its image processing for 3D measurements of surface contours using AATCC Test Method 124. The fractal dimensions of replicas are obtained by a fractal geometry algorithm such as reticular cell counting or cube counting. A new equation is established from a linear regression between the fractal dimensions of replicas and their grades. The experimental results show that the new grading based on 3D vision and the fractal dimension corresponds to a visual assessment of fabric smoothness with more accuracy and reliability. The new equation based on the fractal dimension should determine an objective rating of fabric smoothness that can substitute for the conventional subjective AATCC rating method for fabric smoothness and provide a quantitative reliable value to assess fabric smoothness with more accuracy and reproducibility.

Fabric smoothness is one of the most important properties of aesthetic appearance and the preference of end users. This property of garments is reflected in the criteria of a consumer's choice through the appearance of fabrics during ordinary wear. Thus, the ultimate smoothness of a garment after cleaning and during wear is one of the most important properties. The purpose of wash-and-wear fabrics is to reduce the need for ironing. Normally, areas that would ordinarily be ironed will be evaluated for smoothness. During texture and apparel processing in textile and related industries, fabric and garment manufacturers have made considerable efforts to improve the quality of fabric goods, surmounting undesirable ruggedness of fabric surfaces. With the advent of easy care finishes such as no-iron shirts and shape retention [2], laboratory procedures to evaluate the durability and efficiency of these finishes have had to be developed. Accurate evaluation of fabric smoothness will help determine the optimum processing conditions to overcome unwanted fabric properties.

Methods of evaluating fabric smoothness can be subjective or objective. The former method compares the fabric specimen after repeated home laundering with the six plastic AATCC replicas and is most widely used in industry [1]. This method allows observers to assign the numerical grade of the replica that most nearly matches the smoothness appearance of the test specimen. It is relatively simple and easy to perform, but it is subjective and sensitive to biases in perception. In particular, a specimen's embedded color and/or pattern does not result in consistent evaluations of fabric smoothness [11].

Some researchers have developed objective methods for automated evaluation of fabric smoothness using image processing technology and laser profiles [4, 10]. These methods cannot provide integrated information about fabric smoothness and are difficult to apply to all fabric types.

In this study, we have developed a new evaluation system using the stereo vision algorithm and fractal geometry, which includes a quantitative value to describe crinkled and random structures of fabric smoothness and which can be applied to all kinds of fabrics. The system also provides a unified topological parameter of surface smoothness. Stereo vision techniques can measure 3D coordinates of fabric contours to evaluate smoothness [8]. A computerized program based on the fractal algorithm calculates the fractal dimension of fabric smoothness to assign its grade [11]. A linear regression equation can be obtained from the relation plot between the fractal dimension of six replicas and the corresponding wrinkle grade. Fourteen fabric types are experimentally used to compare the conventional subjective method with the new objective method. The results show that the two methods have a good correlation and the new grading method provides much more detailed information on fabric smoothness than the subjective method. We propose new five- or ten-scaled grades for evaluating fabric smoothness with more linear grading steps and accuracy.

System Set-Up

The evaluation system involves a technique that uses the stereo vision algorithm, a 3D measurement method with two cameras, and the fractal algorithm. 3D vision is an optical image analysis apparatus for 3D measurements of fabric surface contours, and the fractal algorithm is an automatic computerized program to calculate the fractal dimension of fabric smoothness. Figure 1 shows the main components of the system as a schematic photograph; the components are described in detail as follows: Two charge couple device (CCD) cameras concurrently capture the images at the different angles. The pattern paper for calibration shown in Figure 4 is ready for the camera calibration processes. To easily acquire the corresponding points between a pair of images from the two cameras, this system uses two laser beam projectors to make specific patterns on a specimen. The X-Y table upon which a fabric specimen is laid can be moved in the x, y, and x/y directions in order to measure fabric surfaces in different regions. The controller commanded by the system regulates the position of the X-Y table with the back lighting turned on or off. Back lighting is needed when two cameras capture the scene of the calibration pattern paper. The main computer processes the captured images of the fabric to extract the required data using image processing techniques, and calculates a fabric grade or rating. Computerized software based on Windows 98 turns this system into an automatic integrated tool.

3D MEASUREMENT BY STEREO VISION ALGORITHM

Principles of Stereo Vision

The stereo vision technique requires a preliminary step to calibrate the camera, which is the process of determining the internal camera geometric and optical characteristics (intrinsic parameters) and/or the 3D position and orientation of the camera frame relative to a certain world coordinate system (extrinsic parameters). Finally, 3D information from the computer image coordinates is entered. This requires a set of image points whose world coordinates are known and the computational procedures used to obtain the camera parameters with these known points. In this study, we use a pinhole camera model with four transformation steps from 3D world coordinate to camera coordinate, as adopted by Tsai [8]. Figure 2 illustrates the basic geometry of the camera model where $P(x_W, y_W, z_W)$ is the 3D coordinate of the object point in the 3D world coordinate system and (x, y, z) is the 3D coordinate in the 3D camera coordinate system. (X, Y) is the image coordinate system centered at O_1 and (X_u, Y_u) is the image coordinate in the pinhole camera model. (X_d, Y_d) is the actual image coordinate due to lens distortion. Figure 3 shows the schematic diagram of the transformation processes from 3D world coordinate to camera coordinate in the projective geometry shown in Figure 2, where parentheses are the parameters to be calibrated, R is the rotation matrix, T is the translation vector, f is the effective focal length, k_1, k_2 are the distortion coefficients, and s_x is the image scale factor. Through this model, we implement the camera calibration using the calibration pattern paper offering a set of image points (X_{fi}, Y_{fi}) whose world coordinates (x_{wi}, y_{wi}, z_{wi}) are known, where $i = 1, \ldots, n$, n is the total number of calibration points.

The 3D information can be obtained from the corresponding points in two images of the same scene, taken from different viewing positions. A world coordinate that means the same point in each image of the two cameras is spatially calculated by searching for an intersecting point between two camera projection vectors made by the two world coordinates. One is the world coordinate

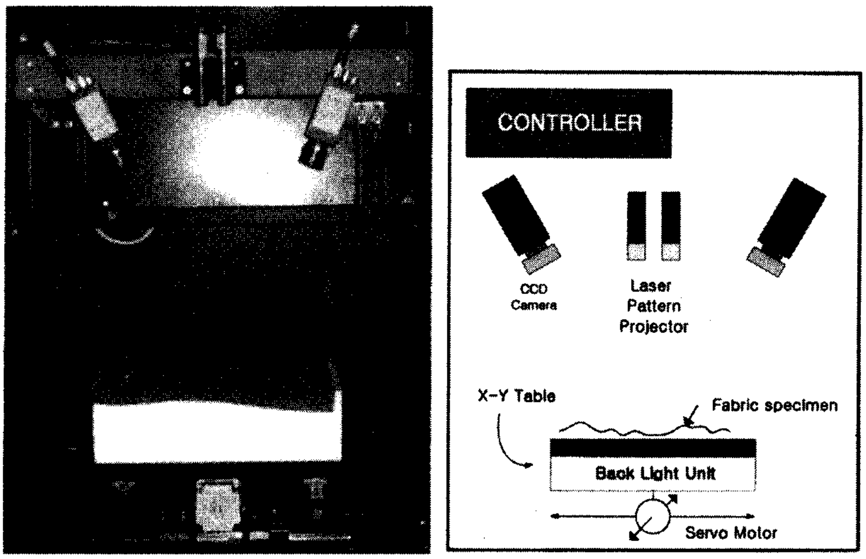

FIGURE 1. Photograph and schematic diagram of the system.

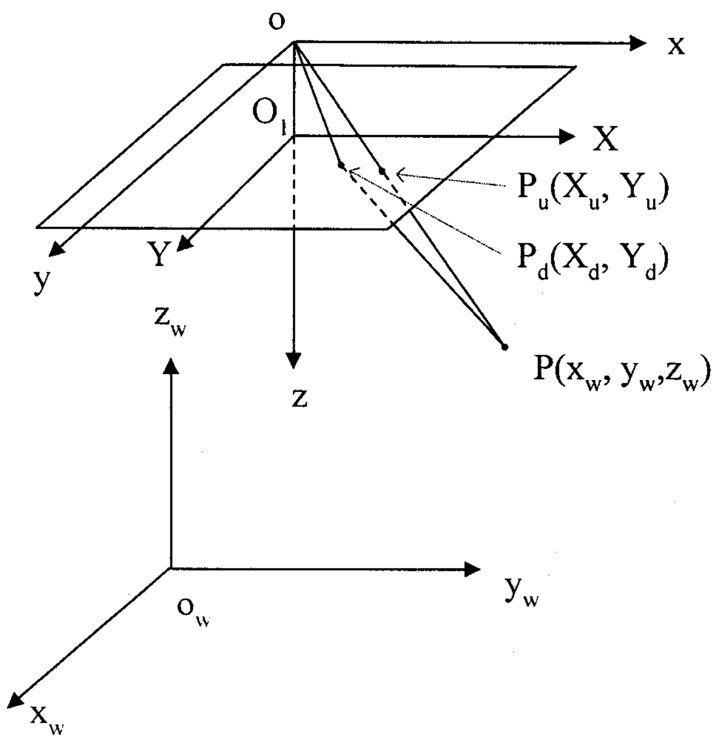

FIGURE 2. Camera geometry with perspective projection and lens distortion.

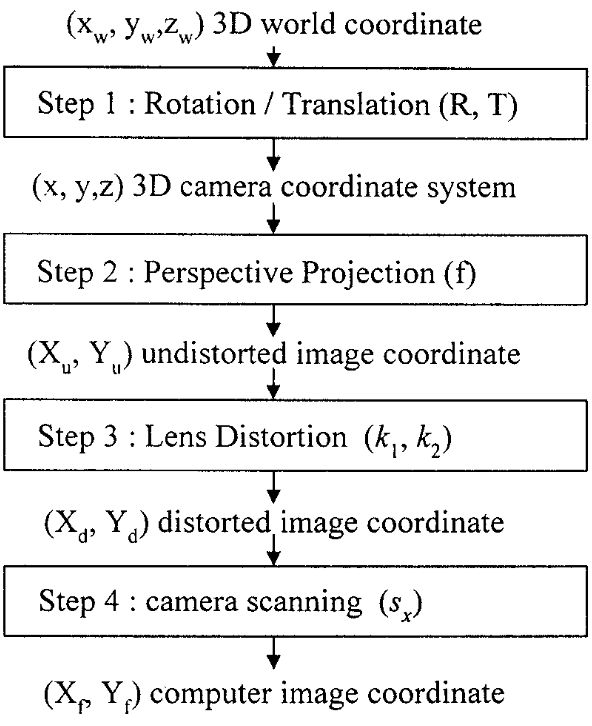

FIGURE 3. Four transformation steps from 3D world coordinate to computer image coordinate.

of the lens center, and the other is the world coordinate of the concerned image point. Therefore, the preliminary camera calibration is needed to calculate the position vectors of each lens center mounted on the two cameras and the projection vectors of those cameras [8].

Image Processing for Camera Calibration

The calibration pattern contains 48 black squares, making a total of 192 corner points for camera calibration, and is laid upon the *X-Y* table of this system. We obtain the 3D coordinates of every black square corner in the calibration paper, which we use as input values to the calibration process, by the direct measurement method. The same calibration pattern under illumination is obtained as images with two CCD cameras. To determine the computer image coordinates for the calibration points, two cameras acquire color images of the calibration pattern, these images are converted into gray scale images, then applied to a threshold value adopted from a histogram algorithm [3] to convert binary images, and the edge points in the binary images are then extracted (Figure 4). Consequently, the bottom images of Figure 4 show the results of superimposing dots on the corners of all the squares that are extracted as computer image coordinates for the calibration points. With the extracted image coordinates and the measured 3D world coordinates of the calibration points, we process the four transformation steps, as shown in Figure 3, to compute the calibration parameters.

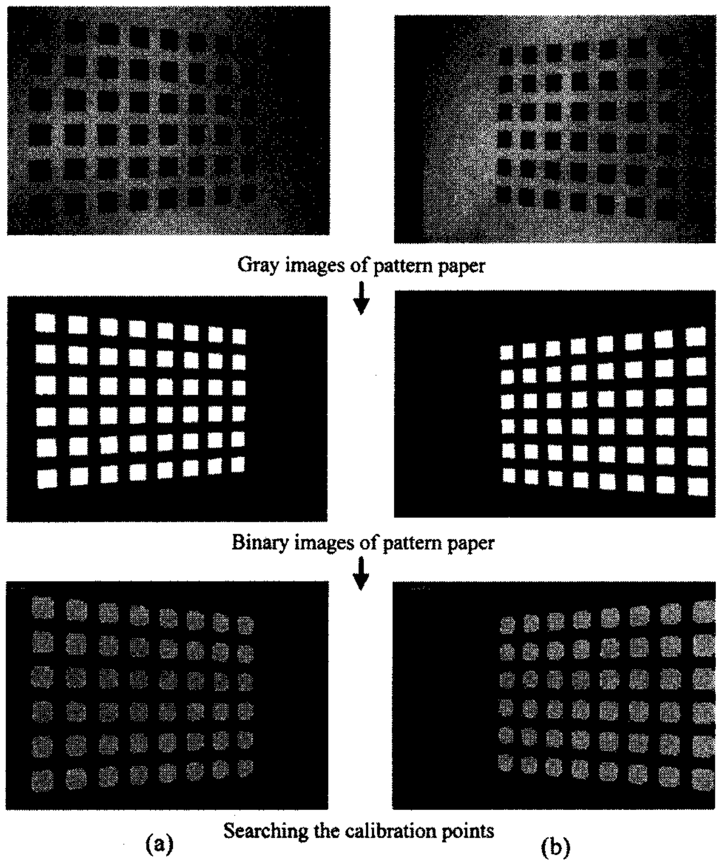

FIGURE 4. Image processing procedures for obtaining calibration points: (a) left camera image, (b) right camera image.

Image Processing for Real Samples

It is necessary to calculate the 3D world coordinate with the stereo vision algorithm from which we obtain the matched points from each real sample image of the two cameras. To easily obtain the matched points of a pair of images captured from the two cameras, this system uses two laser beam projectors modulated to make thirty-three vertical lines and as many horizontal ones upon a specimen. Each camera sequentially captures the vertical and horizontal projecting lines, which form the contour in accordance with a specimen surface. Two images from one camera are converted to gray scale images and then binary images by applying a threshold value that can be set by analysis of intensity histograms. The laser lines in the binary image are thinned and the broken lines are connected. Two reconstructed line images are combined to obtain the image coordinates of the cross-lines, which are used as corresponding points. Two images from the other camera are processed according to previously mentioned procedures. Ultimately, a pair of CCD cameras, installed at a slant on the ceiling of the chamber, acquires one pair of images from two pairs of images, which include the corresponding image coordinates before running the stereo vision algorithm. The two cameras also similarly capture two pairs of images whenever the X-Y table moves to the x, y, or x/y direction. The movement distance is 75 mm, and the X-Y table is shifted nine times in order to measure larger range specimens more accurately. Therefore, we obtain nine pairs of images including the matched image coordinates, which means the specimen size is 225 × 225 mm.

Figures 5 and 6 illustrate the image processing procedures for searching the cross-points with two images captured by one camera and the flow chart as procedures to obtain the 3D data file.

This system finds 1089 corresponding points between the left and right images. When moving the X-Y table, we find the remaining (1089 × 9) points from nine pairs of images. These 9801 image coordinates are merged into a data file and computed to obtain 3D world coordinates using stereo vision algorithm. Figure 7 shows the topographical representation of AATCC smoothness replicas as a solid model using a coded program.

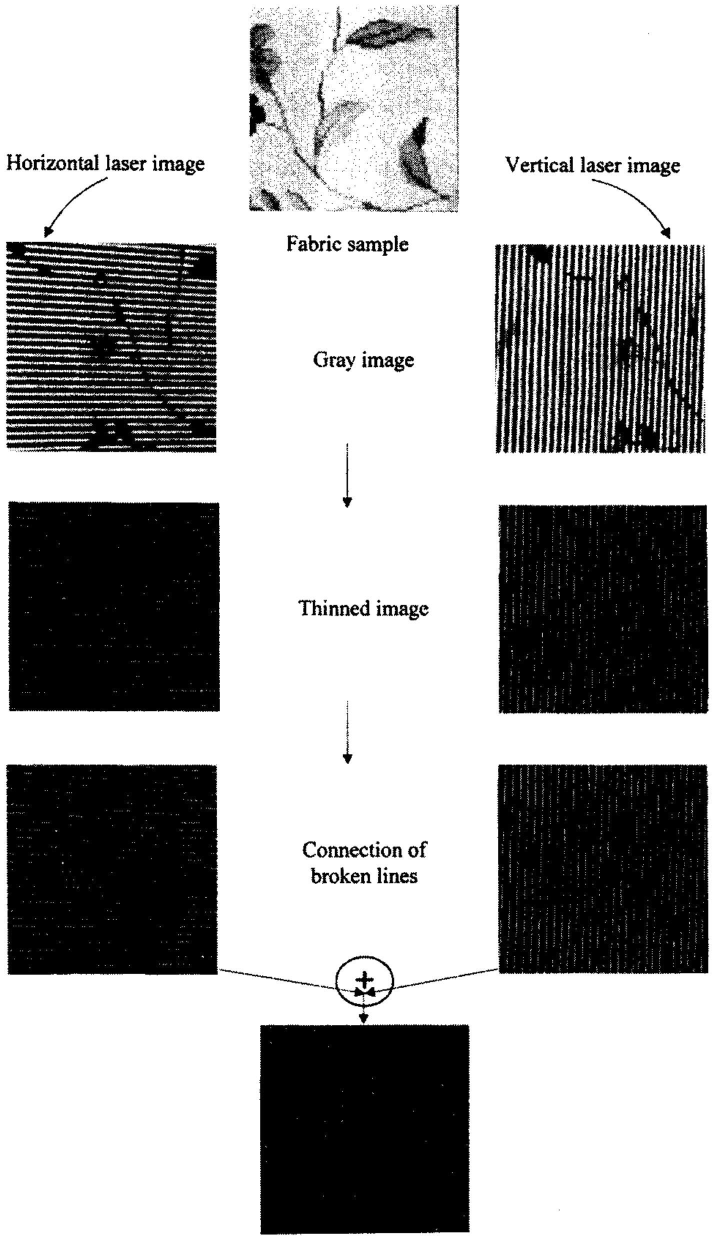

FIGURE 5. Image processing procedures of laser line images to extract the cross points in two images obtained by one camera.

Characterizing Fabric Smoothness Appearance

Fabric surface roughness is characterized by analyzing or measuring the altitude of the different points of the surface by image processing techniques or a laser profilometer [10]. Statistical analyses of the random functions that reflect the altitude, such as correlation function, height distribution, and power spectrum density, are often made to assess the surface ruggedness of fabric. In this study, we have used a different approach with the fractal dimension to evaluate fabric smoothness or roughness as an integrated descriptor, which has already proven more concise and convenient [5, 11].

PRINCIPLES AND METHODS OF FRACTAL GEOMETRY

Fractals occupy a borderline between Euclidean and complete randomness. A fractal dimension is so convenient that we must be careful when we use it to characterize the object. Many objects in nature, *e.g.*, clouds and

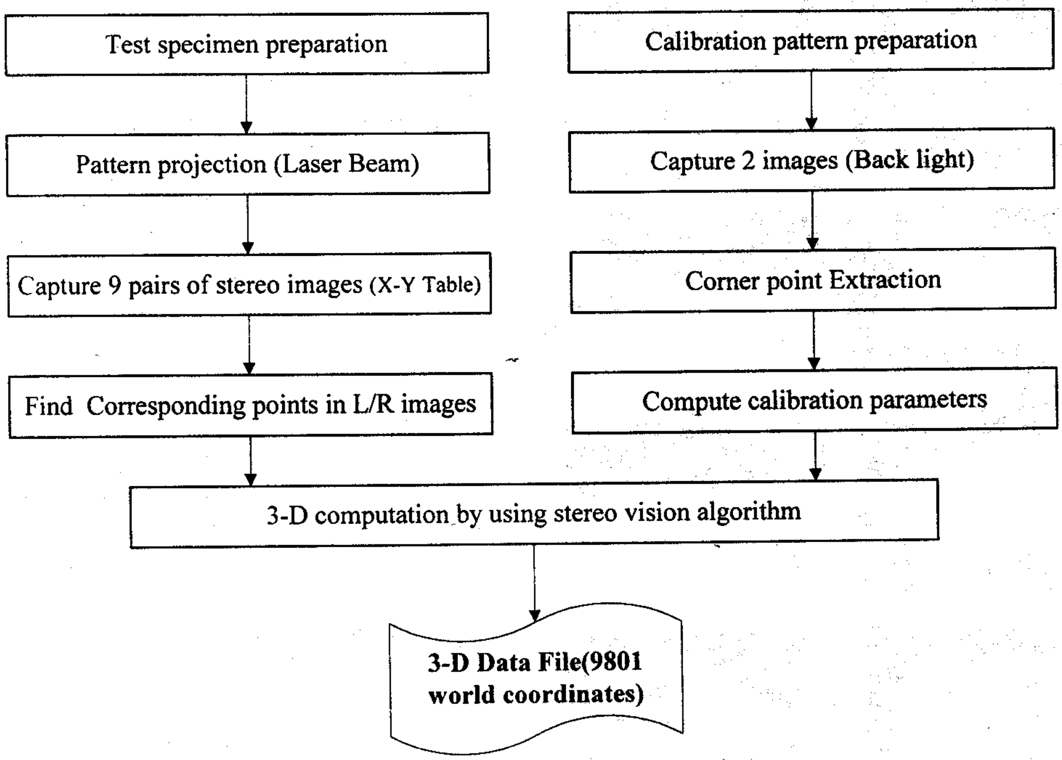

FIGURE 6. Flow chart of overall procedures to obtain the 3D data file in the system.

coastlines, have complex shapes that confuse us when we want to describe their shapes quantitatively. From the fractal point of view, we can find a self-similar structure in them, and we can then characterize their shapes with the fractal dimension. Consider a cross-sectional profile of a fabric surface enclosed by a rectangle. Divide the rectangular region into square boxes with side lengths r. Let $N(r)$ be the number of boxes that the profile enters.

The formula expressing the relationship between r and $N(r)$ is

$$N(r) \sim r^{-D} \quad ,$$

where D is a fractal dimension. Practically, when $N(r)$ is plotted against r on a double logarithmic scale, the graph is almost linear with a slope $-D$. We can obtain the fractal dimension from the slope of the graph [6, 7]. If we are interested in globally describing the shapes of objects quantitatively, we can associate D values with their complexity. We should emphasize that D is a descriptive, quantitative measure, which represents an attempt to estimate a single-valued number for a property (complexity) of an object.

To calculate the fractal dimension of a specimen surface by reticular cell counting, a cut is made along the x or y direction to obtain the function $z(x)$ or $z(y)$. We fix the representative rectangular box that includes the total range of the cut function, and then count the number of intersecting subrectangles and the function varying the scale size of a subrectangle from a long one to a short one. The scale size is experimentally chosen to have good linearity, $R^2 = 0.99$, when a line is fitted into the plot of log $N(r)$ versus log r (Figure 8). In this research, we calculate the fractal dimension by the cube counting method, where nine scales of a cube size are changed from 4 to 1.1 mm. The cube counting method is similar to the box counting method. Unlike the application of the fractal algorithm to gray image intensities, calculating the geometrical fractal dimension by the amplitude of the fabric surface largely depends on the scale size of the box or cube because the amplitude of the fabric surface ranges from 5 to 0 mm. If the scale size were too long or short, the correlation coefficient of the fitted line would not be high and give a meaningless value.

In earlier work (Kang and Lee [5]), we reported simulation results showing that the rougher the surface, the larger the fractal dimension. The theoretical value of the fractal dimension is from 2 to 3. In the case of a fractal dimension 2, the surface implies a perfectly smooth plane, and approaching 3, it implies the rugged surface.

Results and Discussion

Figures 7 and 9 show the solid models of AATCC smoothness replicas and their fractal dimensions using the acquisition data whose 3D world coordinates are calculated by the stereo vision method. Figure 9 explains

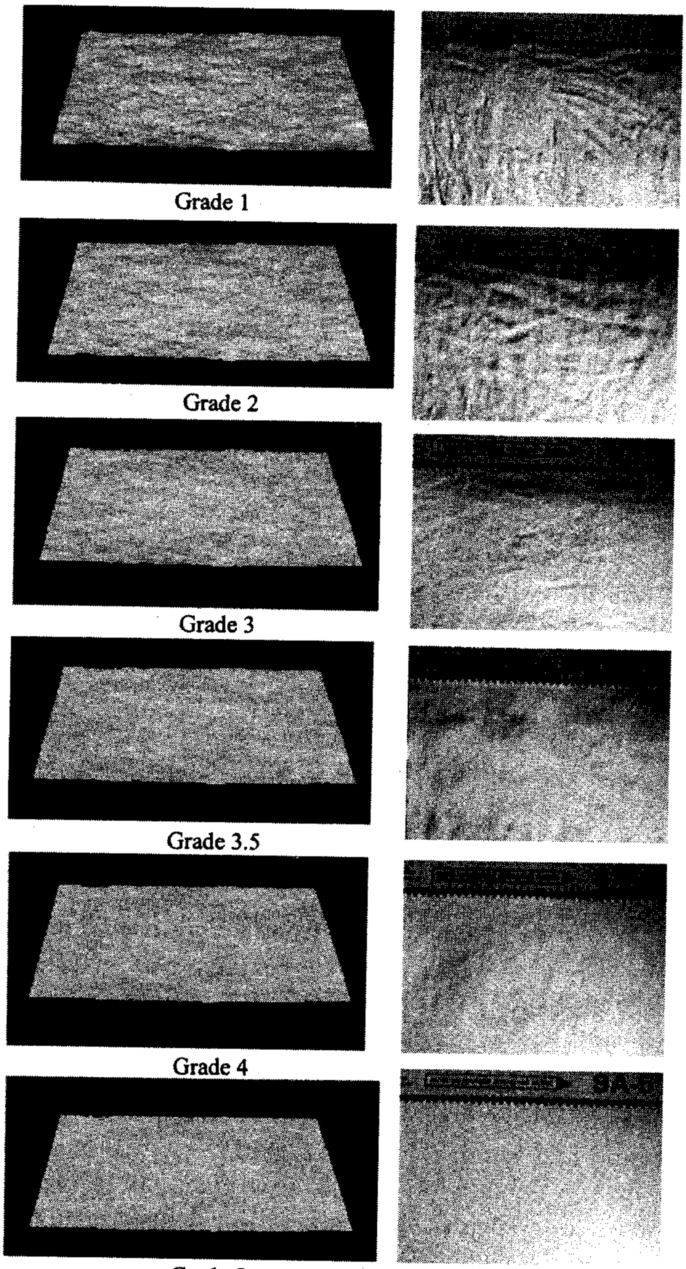

FIGURE 7. 3D surface shape reconstruction using stereo vision technique and real images of AATCC smoothness appearance replicas.

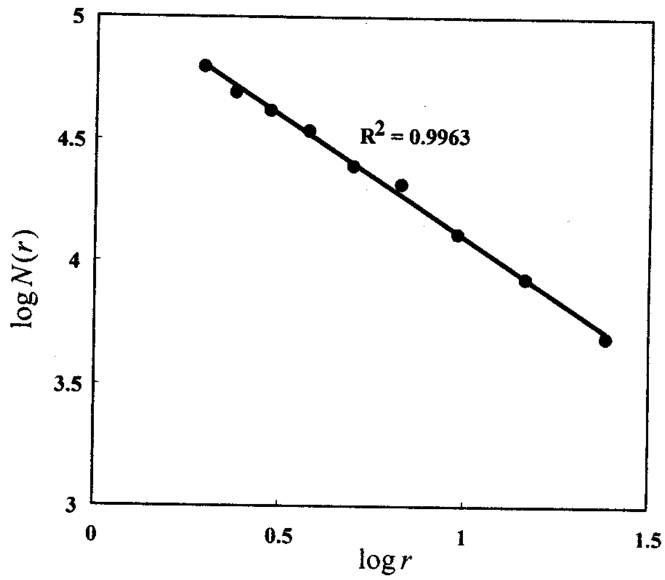

FIGURE 8. A curve between log $N(r)$ and log r to confirm the fractal relationships of fabric smoothness.

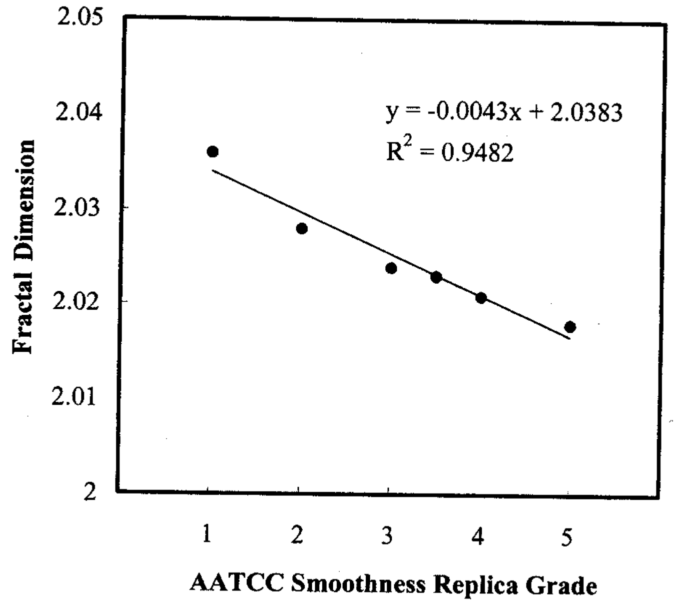

FIGURE 9. Plot between the fractal dimension and AATCC smoothness replica.

the results that have a low correlation among the fractal dimensions of each replica. Especially significant differences exist between replicas 1 and 2. A visual discernment of replicas 3, 3.5, and 4 makes a considerable effort to distinguish subtle differences in surface smoothness so that observers may make different visual smoothness ratings. Though there are small differences in the fractal dimensions that correspond well to small changes in surface smoothness, they are consistent with the visual smoothness replicas.

We offer new five- or ten-scale ratings (TJK grading) based on a linear equation to fit the line into the plot between the fractal dimensions of six replicas and their corresponding wrinkle grades. The rating equation makes the evaluation of fabric smoothness more objective and the interval between the grades equable, which can take the place of the conventional subjective AATCC standard replica method:

$$
\begin{aligned}
G_s(5 \text{ scale}) \\
&= \frac{5-1}{2.0-2.034}(FD-2.0)+5 \quad && \text{if} \quad 2.0 < FD \leq 2.034 \\
&= 5.0 && \text{if} \quad FD \leq 2.0 \\
&= 1.0 && \text{if} \quad 2.034 < FD
\end{aligned}
$$

TABLE I. Properties of fourteen fabric samples and their grades.

Fabric samples	Color	Weave	Density		AATCC grade (five observers)	TJK grade, 5-scale	TJK grade, 10-scale
			Ends/inch	Picks/inch			
Cotton 1(C1)	creamy	satin	102	84	2.8	2.6	5.3
Cotton 2(C2)	dark gray	plane	102	102	2.0	1.8	3.6
Cotton 3(C3)	floral print	plane	127	84	1.4	1.7	3.3
Linen 1(L1)	black and dark blue	plane	84	64	1.8	1.9	3.8
Linen 2(L2)	beige and dark brown	plane	64	64	1.0	1.1	2.3
Nylon/cotton1 (N/C1)	white	plane	64	64	3.6	4.2	8.5
Nylon/cotton2 (N/C2)	floral print	twill	64	51	4.4	4.6	9.2
Nylon	white	plane	127	84	5.0	5.0	10.0
Silk	creamy and light green	plane	152	84	5.0	5.0	10.0
Polyester(T)/C1	white	satin	102	84	1.8	2.0	4.1
Polyester(T)/C2	white	twill	102	64	1.6	1.9	3.8
Polyester(T)/C3	dark gray	plane	64	64	3.4	4.0	8.1
Wool 1(W 1)	creamy	twill	84	64	5.0	5.0	10.0
Wool 2(W 2)	beige and dark brown	plane	64	51	4.2	4.8	9.6

or

$$G_s(10 \text{ scale})$$

$$\begin{aligned} &= \frac{10-1}{2.0-2.034}(FD-2.0)+10 && \text{if} \quad 2.0 < FD \le 2.034 \\ &= 10.0 && \text{if} \quad FD \le 2.0 \\ &= 1.0 && \text{if} \quad 2.034 < FD \quad , \end{aligned}$$

where G_s is a new rating of fabric smoothness appearance and FD is the measured fractal dimensional value obtained from the 3D stereo vision. The fraction values of five-scale gradings are enough to assess fabric smoothness appearance rather than the six-scale grades of the AATCC smoothness appearance grade. A ten-scale grading is double the value of the five-scale grading, so we can classify fabric smoothness appearance in detail.

The sample materials, which consist of several colors and patterns, are listed in Table I. Figure 10 shows that the new grading method is similar to AATCC subjective grading. We are often confused when assessing the grade of fabric smoothness with the AATCC grading method, especially when surface smoothness does not exactly match one of the AATCC replicas. But our new grading

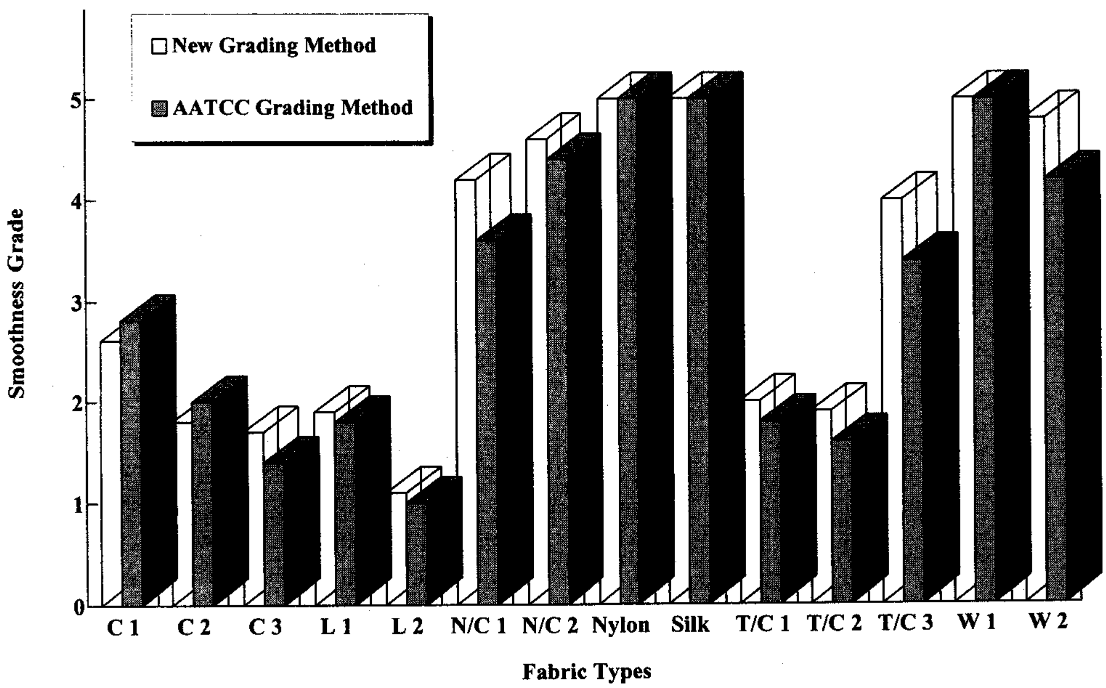

FIGURE 10. New smoothness grade and AATCC smoothness grade for 14 fabric samples.

method can provide interval values between two replicas. We conclude from the results in Figure 10 that the grade difference between the two methods is almost within one grade, and the new method can depict more detailed smoothness degrees of fabric surfaces with decimal fractions.

Conclusions

In this paper, we propose a new five- or ten-scale rating of fabric smoothness measurements that is enough to discern subtle differences in fabric smoothness appearance. This rating has equal intervals with the smoothness appearance of the fabric, unlike the AATCC replicas.

We have developed an integrated system for measuring fabric surface smoothness contours with a stereo vision algorithm and the fractal dimension. Most fabrics with different colors or patterns can be evaluated with the stereo vision system, except for those fabrics that absorb laser beams. Unlike previous studies that have several parameters for evaluating fabric smoothness, the fractal dimension of the fabric surface provides a comprehensive descriptor for fabric smoothness. New five- or ten-scale rating methods may substitute for the conventional subjective AATCC method, and this system can use other surface evaluations such as wrinkles, seam puckers, or plain strain.

Literature Cited

1. AATCC Test Method 143-1992, AATCC Technical Manual, vol. 69, 249–253, 1994.
2. Cheng, H., and Kai, S., Easy-care Finishing of Silk Fabrics with a Novel Multifunctional Epoxide, *J. Soc. Dyers Colour.* **114**(12), 359–362 (1998).
3. Gonzalez, R. C., and Woods, R. E., "Digital Image Processing," Addison-Wesley, NY, 1993.
4. Kang, T. J., Cho, D. H., and Whang, H. S., A New Objective Method of Measuring Fabric Wrinkles Using a 3-D Projecting Grid Technique, *Textile Res. J.* **69**(4), 261–268 (1999).
5. Kang, T. J., and Lee, J. Y., Objective Evaluation of Fabric Wrinkles and Seam Puckers Using Fractal Geometry, *Textile Res. J.* **70**, 469–475 (2000).
6. Mandelbrot, B., "The Fractal Geometry of Nature," W. H. Freeman, NY, 1983.
7. Smith, T. G., Lange, G. D., and Marks, W. B., Fractal Methods and Results in Cellular Morphology—Dimensions, Lacunarity and Multifractals, *J. Neurosci. Meth.* **69**, 123–136 (1996).
8. Tsai, R., A Versatile Camera Calibration Technique for High-Accuracy 3D Machine Vision Metrology Using Off-the-shelf TV Cameras and Lenses, *IEEE J. Rob. Auto.* **RA-3**(4), 323–344 (1987).
9. Weng, J., Cohen, P., and Herniou, M., Camera Calibration with Distortion Models and Accuracy Evaluation, *IEEE Trans. Anal. Machine Intell.* **14**(10), 965–980 (1992).
10. Xu, B., Cuminato, D. F., and Keyer, N. M., Evaluating Fabric Smoothness Appearance with a Laser Profilometer, *Textile Res. J.* **68**(12), 900–906 (1998).
11. Xu, B., Quantifying Surface Roughness of Carpets by Fractal Dimension, *Clothing Textiles Res. J.* **15**(3), 155–161 (1997).

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