Evaluating Fabric Smoothness Appearance with a Laser Profilometer

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ABSTRACT

Automated, objective, and reliable fabric evaluation methods are needed as alternatives to existing visual inspection methods. A new profilometer has been developed for assessing fabric smoothness appearance by using laser triangulation and image processing techniques. The profilometer consists of a laser line projector, CCD camera, rotating stage, computer, and special software. This paper reports the basic principle of laser triangulation, image processing techniques for extracting surface profiles, wrinkle characterization methods, and the results of a trial test. The profilometer can generate results that are consistent with human observers, and the patterns and colors of the fabric do not affect the measurements. In addition, the profilometer is essentially insensitive to patterns of wrinkle orientations. This new evaluation method also solves a problem encountered in research on other instrumental evaluation techniques—the ability to discriminate differences in fabrics whose smoothness appearance falls between AATCC Test Method 124 replicas SA-3 and SA-3.5.

One of the factors that influences the quality of garments is the ability of fabrics to recover from induced wrinkles or to retain a smooth appearance after repeated home laundering. Since the 1950s, many methods of assessing this property have been devised, one of the most widely used in U.S. being AATCC Test Method 124 [1]. This method allows fabrics to wrinkle by following standardized washing and drying procedures and then compares the fabric specimens with a set of six three-dimensional replica plates. Expert observers assign a rating or grade to the specimen whose smoothness appearance most closely matches the wrinkling characteristics of a photograph or replica.

There have been attempts to automate this characterization process using computers and imaging technology [2, 4, 8]. Computers acquire information from the specimens, compare the data with those obtained from the standard replicas, and produce ratings that are consistent with human graders. One way of acquiring surface data from a fabric specimen is for a laser probe to measure surface height variation [2]; these devices have excellent resolution in the order of microns. Because a laser makes one measurement at a time, a mechanical stage has to be used to scan the sample in the *X* and *Y* directions to obtain a surface map. However, this kind of scanning process makes data acquisition too slow to be suitable for industrial applications.

Another method uses a video camera with a lighting system [8]. These systems produce good resolution, but are sensitive to fabric color, *i.e.*, true wrinkling on darker colors is difficult to determine. Further, the system cannot analyze fabrics with constructed or printed designs. Moire imaging has been used to acquire fabric surface data; it is efficient and effective for characterizing wrinkling of certain fabric types, but its application is also limited by its ability to rate only fabrics without patterns or designs [4].

In the research described in this paper, we have focused on developing a new instrument for fabric smoothness (wrinkle) grading based on a laser triangulation technique. The measurement system consists of a laser line generator to project a stripe on a fabric specimen, a motor stage to rotate the sample, a video camera to grab images at certain rotation angles of the stage, and a computer to process the acquired data. Since the smoothness measurements are based on surface profiles, the instrument functions as a profilometer. Normally, laser profilometers are single-point devices, scanning surfaces point-by-point. The laser profilometer developed for this research projects a line along which hundreds of points are measured instantaneously; the advantage of using a line profilometer thus lies with its time efficiency.

To make the instrument suitable for a broad range of fabric types, colors, designs, etc., we have considered three practical issues during development: First, the necessity to obtain measurements insensitive to the orientation of fabric wrinkles, in particular, wrinkles that follow one main direction or are randomly oriented. Cameras or laser scanning mechanisms may produce different surface data when the orientation of wrinkles is dominant in one direction or when a fabric is placed at different angles relative to the lighting source. Second, the need to obtain measurements unaffected by the color of a fabric, its construction, its pattern, or any printed design. And third, the need to discern differences in smoothness appearance between AATCC replicas SA-3 and SA-3.5. SA-3.5 was added to the AATCC Test Method 124 to describe a fairly smooth, nonpressed appearance. Although replica SA-3.5 follows the visual assessment of smoothness over a complete set of replicas, its instrumental measurement of roughness disrupts the incremental differences over the full ranges of replicas. We will discuss this discrepancy in further detail. None of these issues had been addressed in earlier research.

System Set-up

Triangulation is a technique that uses the known distance between a highly structured illumination source with a sensing element and the angle of the reflection pattern to measure the depth of a surface [3]. The profilometer developed for evaluating fabric smoothness uses the laser triangulation technique. Primarily, it has four components: a rotating platform, a laser light source, a CCD video camera, and a PC computer (Figure 1). The rotating platform, driven by a step motor, has a flat surface over which a fabric specimen is placed. The laser light source projects a single stripe of light over a specimen when triggered by a pulse signal. When the specimen is smooth, the projected line will be straight. Otherwise, the line will be curved or wrinkled, indicating the roughness of the surface. The CCD camera is connected to a computer with a frame grabber. The step motor controlled by the computer and the motor driver can be stopped at any angle to allow the camera to capture an image of the specimen, and the image contains one laser line that reflects the wrinkledness of the specimen at this angle. Customized software extracts projected laser line (profile) data from each image to measure roughness and other surface parameters.

Since this method measures wrinkling properties along a line projected over a specimen, we deemed it important to take multiple measurements of different sections of the specimen to obtain valid results. Other researchers have accomplished this by projecting multiple parallel lines over a specimen. For our research, we decided to project a single line, then rotate the specimen to take measurements at different angles. Our justification for this approach was that fabrics are sometimes wrinkled primarily in one direction or location. In such cases, measurements taken in one direction will yield biased results. It is therefore logical to obtain measurements from different angles and average them to achieve a better data set that describes smoothness regardless of wrinkle orientation.

Experimental Design

IMAGE PRE-PROCESSING

After the digital image is acquired, the gray-scale image is converted into a binary image. Since the laser stripe is a thick band (Figure 2a), we used its central axis to define a wrinkle. We obtained the central axis of a laser stripe by scanning an image vertically to locate its edges. We identified the middle point between the up and down edges on one vertical line as one central point. Figure 2b shows the surface profile of the fabric illuminated by the laser light source.

A fabric specimen to be analyzed cannot be flattened on the platform, so the laser profile across the specimen appears to be bent and needs to be leveled before measuring the wrinkle characteristics. Leveling is accomplished by finding a polynomial function that best fits the profile, then subtracting the fit curve from the pro-

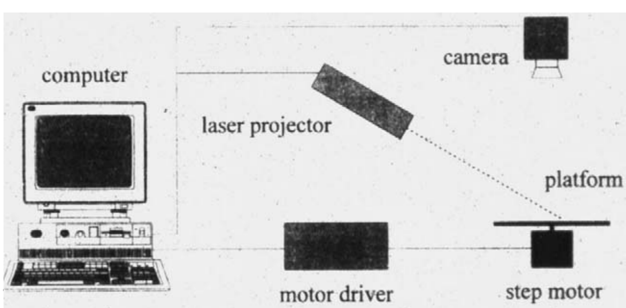

FIGURE 1. System set-up.

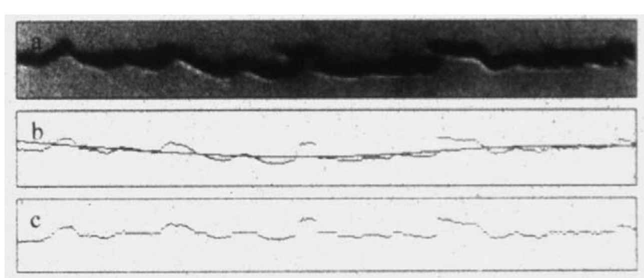

FIGURE 2. Curve thinning and fitting.

file [7]. The degree of the fitting function must be carefully chosen: If the degree is too low, large bumps or folds will not be effectively removed. On the other hand, if the degree is too high, it will filter out actual wrinkles. In these experiments, we determined the appropriate degree of the fitting curve to be seven. Figure 2b shows how a polynomial fit function follows the trend of the original curve, and Figure 2c shows the corrected curve based on this polynomial. This curve is ready for implementing the triangulation calculation.

WRINKLE CHARACTERIZATION

While attempting to establish levels of fabric wrinkling, we used three geometric factors to characterize wrinkle appearance: roughness, sharpness, and density.

(a) *Wrinkle roughness* is the measurement of the size of wrinkles with no consideration of their shape, and is characterized by four different quantitative measures [6]:

Arithmetic average roughness R_a:

$$R_a = \frac{1}{n} \sum |Z_i - m| \quad .$$

Root mean square roughness R_q:

$$R_q = \sqrt{\frac{1}{n} \sum (Z_i - m)^2} \quad .$$

In these two equations, Z_i is the height of the profile at the ith point, n is the number of points selected, and m is the height of the mean line that fits in the middle of the profile. Both these measures compute the average height of wrinkles from the mean line. R_q, also named the effective value of the profile, is more sensitive to occasional highs and lows, and is therefore more suitable for describing small, sharp wrinkles.

Ten-point height R_z: the average distance between the five highest peaks and the five lowest valleys on the curve.

Bearing length ratio t_p: a measure obtained by establishing a reference line parallel to the mean line at a predetermined height between the highest peak and the lowest valley of the profile. The line intersects the profile (see b_1, b_2, b_3, . . . in Figure 3), generating one or more subtended lengths; t_p is the ratio of the sum of the subtended length to the sampling length of the curve.

(b) *Wrinkle sharpness* k is the shape measure of a wrinkle, which describes the top point of the wrinkle that forms a definite peak. The ratio of the height to the width of a wrinkle is used to quantify sharpness (Figure 4), *i.e.*, $k = H/W$.

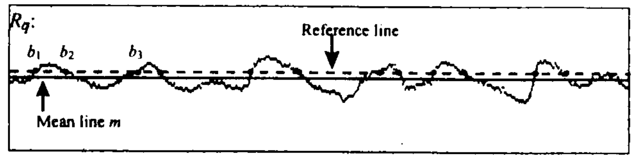

FIGURE 3. Illustration of bearing length ratio t_p.

(c) *Wrinkle density* can be quantified by the *peak-and-valley count PVc*, which is the number of peaks and valleys along the selected bandwidth symmetrical to the mean line of the profile (Figure 4). The selection of bandwidth is important to avoid tiny peaks and valleys that may correspond to noise signals.

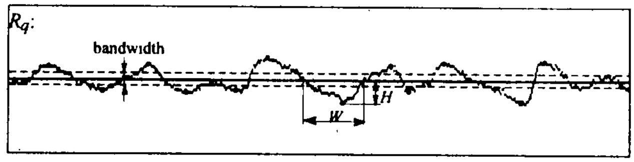

FIGURE 4. Illustration of sharpness k and peak-and-valley count PVc.

SYSTEM TESTING

Several factors can affect the output of the system. The incident angle of the laser stripe is a fundamental parameter of measurement. The shallower the angle, the more amplified the profile signal generated from the fabric surface. Figure 5 shows profiles obtained from the system at two different incident angles at the same location on a specimen. The profile at 8° of incident angle (Figure 5b) presents much clearer wrinkles than the one at 20° of incident angle (Figure 5a). While a smaller angle gives better resolution, it also causes the projected stripe to appear thicker and less sharp (see Figure 6b), and so shows the potential to compromise the accuracy of the data. In this research, the angles that yield the best results are in the range of 6°–8°.

As mentioned before, the system captures images as the platform rotates, and extracts one surface profile

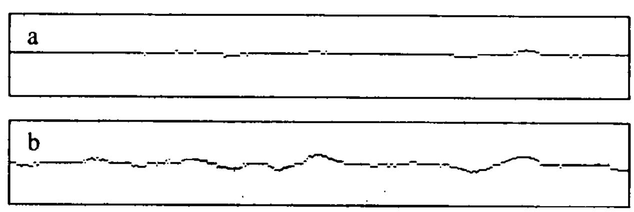

FIGURE 5. Profiles at two different beam angles on the same sample: (a) α = 20°, (b) α = 8°.

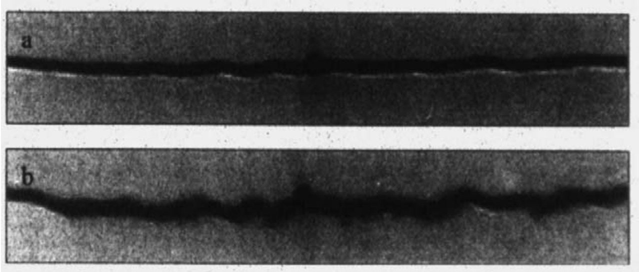

FIGURE 6. Laser stripes at different incident angles: (a) $\alpha = 20°$, (b) $\alpha = 8°$.

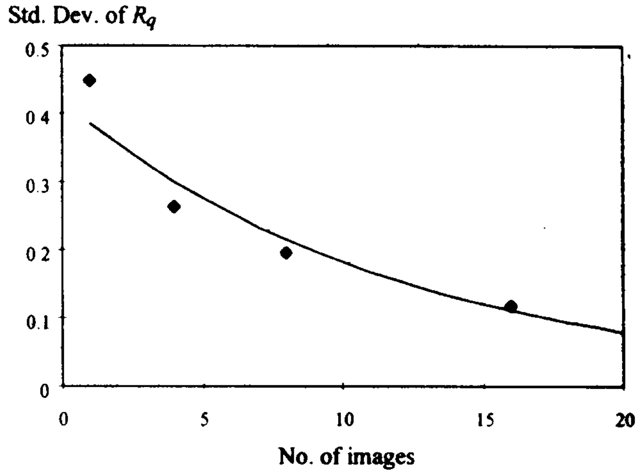

FIGURE 7. Standard deviation of the R_q parameter with respect to the number of images.

from each image representing the wrinkled appearance of a specimen in a particular direction. The parameters calculated from each profile are averaged to produce an estimate that minimizes the bias of the wrinkle orientation. We investigated the question of how many images are needed to obtain reliable results. Using R_q as an example, we measured a specimen by grabbing multiple images at equal intervals in a complete revolution, repeating the procedure five times. Lower standard deviations in R_q suggested a higher precision of measurement. The angle intervals used in the experiment were 180°, 90°, 45°, and 22.5°. Figure 7 shows that the standard deviation of the R_q decreases exponentially as the number of images increases. The more images are measured, the more precise the results become. However, the sampling scheme requires more time to complete one cycle. The decreasing rate of standard deviation slows down when the number of images increases. Considering both precision and time efficiency, we determined that sixteen equally spaced stripes (images) per sample are the optimal number to produce reliable results.

Having chosen the best incident angle of the laser source and the optimal number of images per specimen, we investigated the repeatability of the measurement system. We measured three parameters, R_q, PVc, and k, of the AATCC Smoothness Appearance replicas SA-1–SA-5, and measured each replica ten times. Figure 8 shows the variations of the three parameters for each of the replicas (denoted by black bars). Of the three parameters, the average roughness R_q was most repeatable. The variations in the repetitive tests are most likely explained by the laser stripe illumination of different sites of the specimen.

GRADING EQUATIONS FROM AATCC REPLICAS

Figure 8a shows that the roughness R_q of SA-3.5 does not fit the trend of the measurements of the other of replicas in the set. We measured the wrinkle parameters of all the AATCC smoothness appearance replicas ten times. The same phenomenon occurred in other roughness parameters. In order to build SA grading equations based on measurements of the replicas, we temporarily excluded replica SA-3.5 from the calculations. The average roughness data of ten measurements on each replica are displayed in Figure 9. There we can see exponential trends between roughness data and the SA grades of the replicas. The logarithmic equations

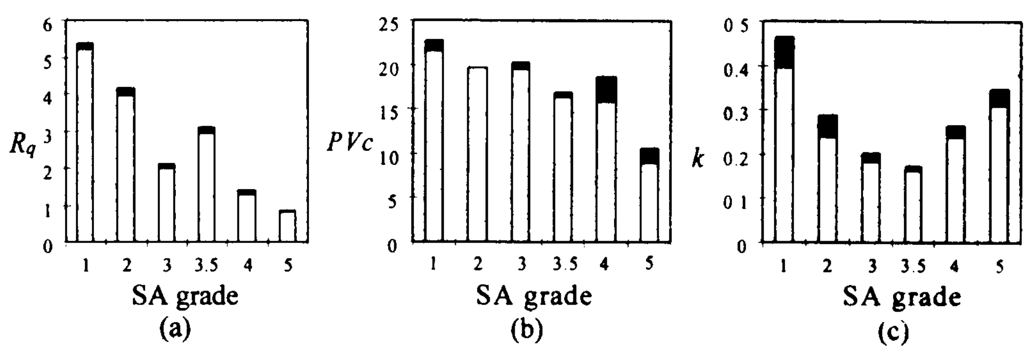

FIGURE 8. Repeatability of R_q, PVc, and k for each AATCC replica.

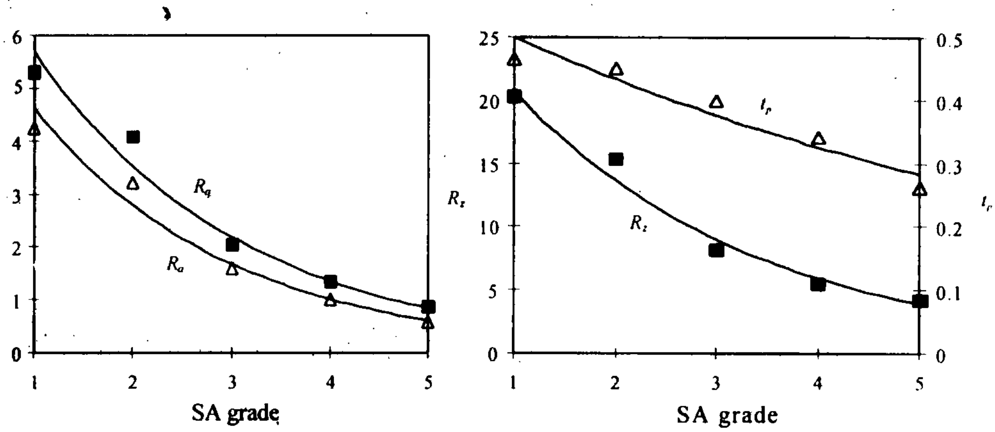

FIGURE 9. Exponential behavior of the four roughness parameters with respect to the replica grades, excluding SA-3.5.

corresponding to the exponential regression of the roughness data in Figure 9 are

$$SA = -1.972\,(\ln R_a - 2.037) \quad ,$$

$$SA = -2.092\,(\ln R_q - 2.215) \quad ,$$

$$SA = -2.403\,(\ln R_z - 3.446) \quad ,$$

$$SA = -7.013\,(\ln t_p + 0.551) \quad .$$

The roughness parameters appear to be good estimates for assigning smoothness appearance (SA) grades of a fabric specimen, except in the range between SA-3 and SA-3.5 due to the disturbance of SA-3.5. The average of the SA values calculated from these four equations seems to produce a better instrumental smoothness rating. The averaging may reduce the rating differences between the instrument and observers. As shown in Figure 8a, the replica SA-3.5 does not fit in the exponential curves. In fact, SA-3.5 has roughness data comparable to those at SA = 2.5. The roughness data are not sufficient for discerning grades of smoothness appearance in the range of 2.5–3.5. Since SA-3.5 represents a surface that has soft, rounded lumps rather than flat wrinkles when compared to SA-3, the measurements in wrinkle density (PVc) and sharpness k help differentiate specimens when roughness data fall into the 2.5–3.5 range. From Figures 8b and c, we find that SA-3 has higher PVc and k values than SA-3.5. Therefore, a two-step approach is needed for rating smoothness appearance: First, compute the roughness parameters R_a, R_q, R_z, and t_p. If these values are outside the range SA-2.5 to SA-3.5, then use the exponential regression curves shown above to obtain an SA grade. The final grade can be computed by averaging the four roughness estimates. Second, if the roughness parameters fall in the SA-2.5 to SA-3.5 range, compare the wrinkle density PVc and sharpness k of the sample with the values of replica SA-3 (PVc = 19.94, k = 0.193). If both parameters are larger than or equal to those of SA-3, the SA rating should be between SA-2.5 and SA-3. Since the exponential curves approximately fit roughness data in this range, the grade obtained from the roughness equations can be used. Otherwise, an SA grade should be calculated by using the straight line connecting the points corresponding to replicas SA-3 and SA-3.5 in Figure 10a or 10b.

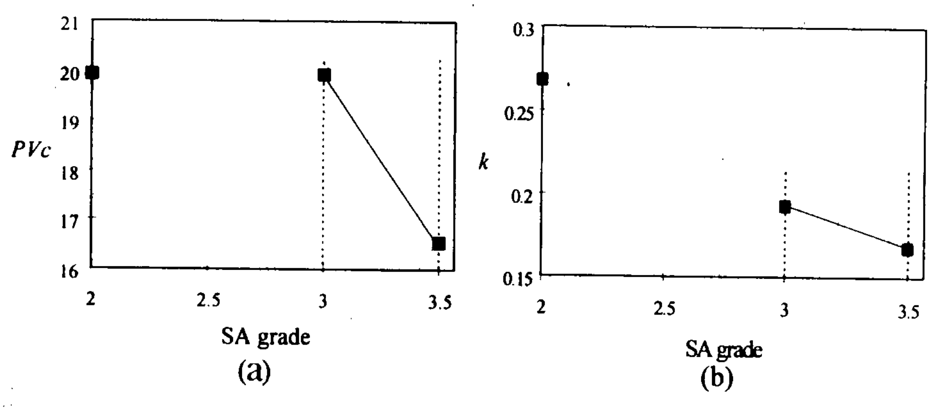

FIGURE 10. SA grades based on PVc and k measurements.

TABLE I. Wrinkle measurements of the samples.

Specimen	R_a	R_q	R_z	t_p	PVc	k
1	1.211	1.592	5.975	0.352	15.375	0.164
2	1.438	1.840	7.613	0.392	19.875	0.227
3	1.192	1.576	6.263	0.355	16.250	0.157
4	1.187	1.545	6.281	0.373	17.375	0.149
5	1.286	1.715	6.150	0.363	15.250	0.155
6	1.093	1.446	5.763	0.345	16.813	0.191
7	1.849	2.391	10.125	0.411	22.250	0.287
8	2.049	2.619	10.200	0.404	20.250	0.215
9	2.357	3.032	12.088	0.421	20.810	0.305

TRIAL TEST

We laundered a set of nine specimens by following the procedures specified in AATCC Test Method 124 [1]. The specimens were then rated by three observers and by the profilometer system. Table I shows the initial measurements of wrinkle roughness, density, and sharpness obtained from the samples. Table II shows the SA ratings from visual inspection (ratings assigned at 0.5 increments) and from the instrument measurements. In Table II, O1, O2, and O3 are the ratings of the three observers. SA_v is the average of the three observers' ratings. SA_{Ra}, SA_{Rq}, SA_{Rz}, SA_{tp}, SA_{PVc}, and SA_k are the ratings based on the wrinkle parameters, and SA_m is the final machine rating generated from the formulas discussed above.

In Table I, samples 1 through 6 clearly fell into the SA-3 to SA-3.5 range of roughness, and accordingly in Table II, we formulated the final grades for these six samples by averaging the grades obtained from wrinkle density (PVc) and sharpness (k). Samples 7, 8, and 9 fell outside the SA-3 to SA-3.5 range, and therefore their final grade was just the average of the grades obtained from the four roughness parameters R_a, R_q, R_z, and t_p. By comparing visual ratings (SA_v) with machine ratings (SA_m), we saw that the two sets of SA ratings were comparable to each other. From Figure 11, the correlation between the two sets of ratings was fairly high ($r^2 = 0.913$). The difference in the SA ratings of any of these specimens did not exceed 0.5. We should point out that the visual and instrumental inspections of the samples were not done at the same time; the visual inspection was done several months earlier than the instrument ratings. Wrinkles on the samples could have been disturbed or changed more or less during that period, though we took great caution in storing and handling the samples.

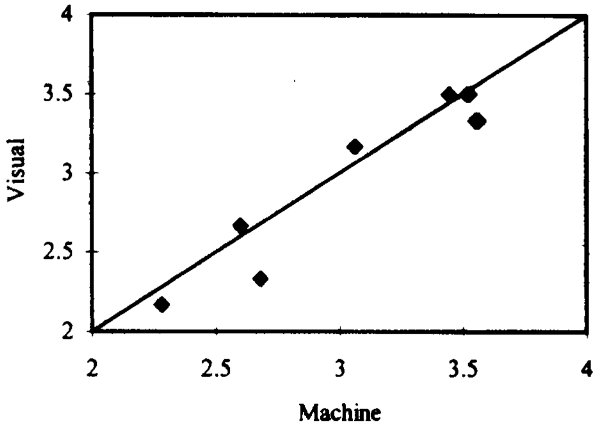

FIGURE 11. Correlation between machine and visual SA ratings.

Another possible cause for differences in the two sets of ratings could have been the placement of fabric specimens on the rotating stage. If a specimen were carelessly placed on the stage, waves or folds could have been mistakenly interpreted as wrinkles by the instrument. On the other hand, if an operator brushed the specimen to eliminate these waves, wrinkles could have been compressed, creating a smoother appearance than was true. This problem is less serious in the visual inspection by an observer, because the fabric sample is hung vertically and the observer is instructed to identify and discount the aberrations. We noticed that gentle brushing before taking instrumental measurements produced ratings more compatible with those obtained from visual inspection.

Conclusions

This paper presents a method for characterizing fabric smoothness (wrinkling) that possesses several de-

TABLE II. SA ratings by visual and machine inspections.

Specimen	O1	O2	O3	SA_v	SA_{Ra}	SA_{Rq}	SA_{Rz}	SA_{tp}	SA_{PVc}	SA_k	SA_m
1	3.5	3.0	3.5	3.33	–	–	–	–	3.50	3.50	3.50
2	3.0	3.0	3.5	3.17	–	–	–	–	3.01	3.00	3.00
3	3.5	3.0	3.5	3.33	–	–	–	–	3.50	3.50	3.50
4	3.5	3.5	3.5	3.50	–	–	–	–	3.38	3.50	3.44
5	3.5	3.5	3.5	3.50	–	–	–	–	3.50	3.50	3.50
6	3.5	3.5	3.5	3.50	–	–	–	–	3.46	3.04	3.25
7	2.5	2.0	2.5	2.33	2.80	2.81	2.72	2.37	–	–	2.68
8	2.0	2.0	2.5	2.17	2.60	2.62	2.70	2.49	–	–	2.60
9	2.5	2.5	3.0	2.67	2.33	2.31	2.29	2.20	–	–	2.28

sirable features. It is quantitative and automated, and it provides an objective way to evaluate fabric smoothness appearance. Due to the rotation of the sample, the system is insensitive to fabrics that are uni-directionally wrinkled. Since it uses a laser stripe for scanning, it is insensitive to color differences on the fabric. Its speed makes it suitable for industrial use. It is able to distinguish between replicas SA-3.5 and SA-3. It relies on six different parameters to characterize wrinkles, thus making it a robust and reliable system.

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