4
Objective evaluation of clothing appearance

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4.1 Introduction

Subjective methods of evaluating clothing appearance, discussed in Chapter 2, tend to be inconsistent and inaccurate as the results are influenced by the personality, experience, background and state of mind of the assessors. For several decades, researchers have therefore attempted to develop objective methods for evaluating clothing appearance. In this chapter, the different objective methods for assessing fabric wrinkling, pilling, seam pucker and overall garment appearance are reviewed.

4.2 Objective evaluation of fabric wrinkling

Objective evaluation of fabric wrinkling has long been of interest to researchers in the textile and related industries. According to the way in which the wrinkled appearance is detected and measured, these systems can be classified into two main categories: contact and non-contact methods. Furthermore, the non-contact methods may be classified into two main types, namely laser scanning and image processing.

4.2.1 Contact methods for objective evaluation of fabric wrinkling

An early instrument, designed and used by Hebeler and Kolb[1] in the 1950s for tracing the surface of a wrinkled sample, is an example of the contact objective method. The instrument, named 'Wrinklometer', consisted of a movable platform, a variable-speed motor, a small counterbalanced probe linked to a shutter, a light source, a photovoltaic cell and a signal recorder. The contour of the wrinkled fabric was recorded on the recorder paper. There was a one-to-one correlation between each wrinkle in the fabric and a peak in the curve on the recorder paper. The area under the traced curve was proportional to the product of the mean wrinkle height and the length of the trace on the fabric, which was converted into the mean

Figure 4.1 SAWTRI Wrinklemeter.

wrinkle height of the fabric. The instrument also had an electronic integrator which simplified the calculations of mean wrinkle height. To demonstrate its reproducibility and ranges of applicability, Kaswell[2] used the 'Wrinklometer' to measure the mean profile heights of some randomly wrinkled samples.

Shiloh[3] designed and built an instrument, called the Sivim Wrinklemeter, to be followed by the SAWTRI Wrinklemeter (Fig. 4.1), to measure the contours of fabric surfaces automatically. The instrument consisted of two major parts:

1. A tracing system, which includes an electro-mechanical device which translates contour variations into voltage; the tracing element has a frictionless-core suspension so that the fabric is traced under conditions of minimum constant pressure and wrinkle deformations are largely avoided.
2. An analogue computer with an operational amplifier, integrators, differentiators, multipliers, squares and control circuits.

The analogue computer processes the input voltage according to the required equations to give a value of wrinkle height $H(\theta)$, wrinkle slope$T(\theta)$, the density of zero points $N_0(\theta)$ and the density of extreme points $N_1(\theta)$ in real time.

The wrinkled surface of the fabric is regarded as a random rigid surface. Its mathematical representation is $z = f(x, y)$.

For a particular cross-section of the fabric at a given direction, θ to the axes, the following wrinkle parameters have been suggested:[3,4]

1. The wrinkle height

$$H(\theta) = \sqrt{\overline{f(x)^2}} \tag{4.1}$$

where $\overline{f(x)^2}$ is the mean square height of the section curve from its regression line.

2. The wrinkle slope

$$T(\theta) = \sqrt{\overline{f'(x)^2}} \quad (4.2)$$

where $\overline{f'(x)^2}$ is the mean square of the first derivative of the above-mentioned curve.

3. The density of zero points

$$N_0(\theta) = \frac{1}{\pi} \cdot \frac{T(\theta)}{H(\theta)} \quad (4.3)$$

the cross-sectional line being assumed to be a random curve.

4. The density of extreme points

$$N_1(\theta) = \frac{1}{\pi} \cdot \frac{K(\theta)}{T(\theta)} \quad (4.4)$$

a random curve again being assumed. Here $K(\theta) = \sqrt{\overline{f''(x)^2}}$, where $\sqrt{\overline{f''(x)^2}}$ is the mean square of the second derivative of the curve.

These parameters were considered necessary for adequately representing the severity of wrinkling quantitatively.

It was suggested the wrinkle parameters be measured within the following ranges:

1. Wrinkle heights should be greater than 0.2 mm and smaller than 10 mm.
2. Wrinkle wavelengths should be longer than 0.5 mm and shorter than 50 mm (or wrinkle densities not exceeding 2 per mm and not less than 0.02 per mm).

The Sivim Wrinklemeter was capable of measuring wrinkle parameters of fabrics quickly and non-destructively.

Contact instruments, such as the 'Wrinklometer', 'Sivim Wrinklemeter' and SAWTRI Wrinklemeter, use a stylus or other similar device which comes into contact with the fabric surface and which to a certain degree can disturb the fabric wrinkle and, depending on the type and size of the 'stylus', can miss certain wrinkle signals, which could result in an error in the assessment of fabric wrinkles. Along with the emergence of the laser and the development of new opto-electronic devices, such as the CCD camera, non-contact methods have been developed to evaluate fabric wrinkling objectively.

4.2.2 Laser scanning system

Laser has been defined as light amplification by stimulated emission of radiation. A simple definition for a laser would be 'a light-emitting body with feedback for amplifying the emitted light'.[5] Since its first demonstration in

1962, the laser has become a fascinating technology, and one which has attracted enormous interest across a wide range of industries. Thus, a large variety of lasers has been developed by scientists. With the gradual improvement in laser design and promising laser materials and processing research results in the early 1980s, the laser was no longer treated as laboratory research equipment or a scientific curiosity. Laser technology has been widely applied in the textile and clothing industries too.

Ramgulam *et al.*[6] used a laser sensor to measure the distance between itself and the object, using a laser triangulation technique. A beam of light, 25-micron in diameter, was projected from a laser diode onto the object, and part of the light was reflected back onto a photosensitive detector, which then signalled the position of the image from it. As the reflected light strikes the detector at different locations depending on its distance from the surface under examination, the location of the reflected light can be converted into the distance. The sensor used was capable of measuring the distance (and hence the height of the object) with a resolution of 10 microns. The fabric sample was placed and fixed on a dialed stage which was mounted on an X-Y table. The X-Y table was equipped with stepping motors and the whole system, except for the dialled stage, was interfaced with a microprocessor. The stage, and hence the bias angle of the sample with respect to either an X or Y movement, could be rotated and fixed manually.

Amirbayat and Alagha[7] used Ramgulam *et al.*'s[6] laser scanning system to measure heights at different points of the replica plates within a base of 100 × 100 mm at intervals of 1 mm which produced 10 000 readings for each replica. With the obtained heights, Amirbayat and Alagha[7] calculated the following geometrical parameters by applying simple numerical algorithms:

- Mean length of the paths over the wrinkled surface along X and Y directions, L_1, L_2;
- Surface area, A;
- Volume under the surface, V;
- Mean principal curvature, K_1, K_2;
- Mean maximum twist, T.

The results showed that mean twist, T, which has the dimension of the inverse of length, was a main factor in evaluating the severity of fabric wrinkles. The following equation was derived to relate the grade of wrinkle recovery (WR) to the mean twist T:

$$\mathrm{WR} = 0.73 + 7.73e^{-T\sqrt{A/10}} \tag{4.5}$$

The most important advantage of laser triangulation, in addition to the accuracy and the fact that it is non-contact, is its ability to measure the height of any surface regardless of the colour and pattern, which affects image analysis methods employing an ordinary light source.

The three-dimensional scanning device developed by Park and Kang[8] to measure wrinkle shape consisted of a laser scanner, an A/D converter and a personal computer. The laser was composed of a laser sensor to detect the magnitude of a wrinkle, a system to control the movement of the laser sensor and an amplifier to amplify the sensor signal. The laser sensor had a reference distance of 50±1 mm and could measure within the range of ±5 mm at the reference position with a resolution of 10 μm.

With the developed instrument, Kim[9] scanned wrinkled fabric specimens generated according to AATCC 128. There were 64 $\times$ 64 points of sampling data, with an interval of 1.5 mm in the X and Y directions in an area at the centre of the specimen. Neural networks were used to construct a generalised delta rule[10] to quantify wrinkle evaluation. A Windows program was developed to control the operation, perform calculations and display the degree of wrinkles. The study revealed a linear relationship between objectively and subjectively evaluated wrinkle severity, the correlation coefficient being 0.95. Nevertheless, the correlation coefficients for dark coloured or checked patterned fabrics were less than those for bright single colour fabrics.

Kang and Lee[11] proposed measuring the severity of the fabric surface wrinkles using fractal dimensions. The surface contours of wrinkled fabrics or puckered seams were first scanned using a laser scanning system, and the fractal dimensions of the surface were then counted using a box-counting method.[12] Fractal dimensions in the X and Y directions have proved to be closely related to the severity of wrinkles or puckers.[11]

In all laser scanning systems, the surface profile of a fabric specimen is scanned using a laser probe to measure surface height variation.[6–9,11] Such devices have excellent resolution in the order of microns. Nevertheless, because a laser makes one measurement at a time, a mechanical stage has to be used to move the sample in the X and Y directions to obtain a surface map and, as a result, the scanning process tends to be too slow to be suitable for industrial applications.

In order to improve the scanning speed of laser scanning systems, Xu *et al.*[13] developed a system, in which a laser stripe line was projected onto the fabric specimen to obtain a line of data simultaneously. A motorised stage was used to rotate the sample, a video camera to grab images at certain rotational angles of the stage and a computer to process the acquired data.

To make the instrument suitable for a broad range of fabric types, in terms of colour and designs, Xu *et al.*[13] took into account three practical issues during the development:

1. The necessity to obtain measurements insensitive to the orientation of the fabric wrinkles, such as wrinkles which follow one main direction or are randomly oriented. Cameras or laser scanning mechanisms may produce different surface data when the orientation of the wrinkles is dominant in

one direction or when a fabric is placed at different angles relative to the light source.

2. The need to obtain measurements unaffected by the colour of a fabric, its construction, pattern or any printed design.
3. 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, non-pressed appearance.

Xu *et al.*[13] used three geometric factors to characterise wrinkle appearance: wrinkle roughness, wrinkle sharpness and wrinkle density.

1. *Wrinkle roughness* is a measure of the size of the wrinkles, with no consideration of their shape, and is characterised by four different quantitative measures.
   - *Arithmetic average roughness*:

$$R_a = \frac{1}{n}\sum |Z_i - m| \tag{4.6}$$

   - *Root mean square roughness*:

$$R_q = \sqrt{\frac{1}{n}\sum (Z_i - m)^2} \tag{4.7}$$

   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 which fits in the middle of the profile. Both these measures compute the average height of the wrinkles from the mean line.
   - *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, 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.
2. *Wrinkle sharpness k* represents the shape of the wrinkle, describing the top point of the wrinkle which forms a definite peak. The ratio of the height to the width of the wrinkle is used to quantify sharpness.
3. *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. The selection of bandwidth is important to avoid tiny peaks and valleys which may correspond to noise signals.

In addition to being quantitative and automated, Xu *et al.'s*[13] instrument was not influenced by whether the fabrics were uni-directionally wrinkled or not, owing to the rotation of the sample during the test. It was also not influenced by colour differences in the fabric, due to the use of a laser stripe in scanning. It was capable of distinguishing between replicas SA-3.5 and SA-3.

4.2.3 Image processing systems

Xu and Reed[14] proposed a computer image system and testing procedure for automated grading of fabric wrinkling. The system consisted of a Dell 486/M compatible computer, an HP colour scanner and the self-developed software. The main benefit of using the colour scanner was that an identical environment of image capturing, such as illumination conditions and background, can be easily maintained for separate tests. Two wrinkling descriptors, surface area and shaded area, were derived from the measured image intensities. They were used to measure two perspectives, wrinkle depth and wrinkle size. *Wrinkle ratio* was defined as the ratio of the surface area to the image square area of the image. Obviously, the larger the wrinkle ratio, the more wrinkled the fabric appears to be. *Shade ratio* was defined as the ratio of the shaded area to the image size. A large shade ratio suggests a highly wrinkled appearance.

Seven fabrics, varying in fibre content and other structural characteristics, were tested for wrinkling by subjective evaluation and image analysis. The results showed that the grades assigned by the subjective AATCC method were not linearly, but exponentially related to the above objective parameters (i.e. the wrinkle ratio and the shade ratio) obtained from image analysis. The computer predicted grades, using two exponential equations, were close to the visual grades.

Mori and Komiyama[15] used a grey scale image analysis method to evaluate the visual features of wrinkles in plain fabrics made from cotton, linen, rayon, wool, silk and polyester. Colour images of each wrinkled sample were scanned into the computer, using a colour scanner (Epson GT-9500). When scanning a wrinkled sample, the cover of the scanner was supported by a separator, which creates a space large enough for the sample to be placed in the scanner without any pressure on the wrinkled surface. The obtained colour image contains RGB colour coordinates for all pixels. From the RGB value of a pixel, the grey level at that point can be calculated by the following equation:

$$L = 0.177R + 0.813G + 0.011B \tag{4.8}$$

where L is the grey level of a pixel, the RGB value of which is (R,G,B). A colour image was converted into a grey level image using this equation.

Four parameters characterising the visual features, based on a matrix $M(d,\theta)$, were used in their research. The co-occurrence matrix $M(d,\theta)$ consists of probability $P_\delta(i,j)$, $(i = 1, 2, \cdots, n)$, in which the pixel of the grey level i appears separated a distance $\delta = (d,\theta)$ from the pixel of grey level j, where the parameters d and θ are the distance and positional angle between a certain grey-level pair. The four parameters and fractal dimension D were defined as follows:

- Angular second moment (*ASM*)

$$ASM = \sum_{i=0}^{n=1} \sum_{j=0}^{n-1} \{P_\theta(i,j)\}^2, i = 1, 2, \cdots, n-1; j = 1, 2, \cdots, n-1 \tag{4.9}$$

- Contrast (*CON*)

$$CON = \sum_{k=0}^{n-1} k^2 P_{x-y}(k), |i-j| = k, k = 1, 2, \cdots, n-1 \tag{4.10}$$

where

$$P_x(i) = \sum_{i=0}^{n-1} P_\delta(i,j)$$

$$P_y(j) = \sum_{j=0}^{n-1} P_\delta(i,j)$$

$$P_{x-y}(k) = \sum_{i=0}^{n-1} \sum_{j=0}^{n-1} P_\delta(i,j)$$

- Correlation (*COR*)

$$COR = \left\{ \sum_{i=0}^{n-1} \sum_{j=0}^{n-1} i \cdot j \cdot P_\delta(i,j) - \mu_x \cdot \mu_y \right\} / \sigma_x \sigma_y \tag{4.11}$$

where

$$\mu_x = \sum_{i=0}^{n-1} i \cdot P_x(i), \mu_y = \sum_{j=0}^{n-1} j \cdot P_y(j)$$

$$\sigma_x^2 = \sum_{i=0}^{n-1} (i - \mu_x)^2 \cdot P(i), \sigma_y^2 = \sum_{j=0}^{n-1} (j - \mu_y)^2 \cdot P_y(j)$$

- Entropy (*ENT*)

$$ENT = \sum_{i=o}^{n-1} \sum_{j=0}^{n-1} P_\delta(i,j) \cdot \log \{P_\delta(i,j)\} \tag{4.12}$$

- Fractal dimension *D*

$$D = \frac{\log c - \log(N(r))}{\log(r)} \tag{4.13}$$

where c is a positive constant, r is the side length of the cube and $N(r)$ is the number of cubes which cover the image.

The Kalman filter algorithm was implemented in the procedure for training a neural network to evaluate the grade of wrinkled fabrics, using the above five parameters (*ASM, CON, COR, ENT* and *D*) as input and the mean sensory value presenting the grade of wrinkled fabrics as output. The calculated values obtained by the trained neural model for the unknown data indicated very good agreement with the sensory values, especially for cotton, linen and rayon fabrics. For evaluating the grade of wrinkled fabrics, the method using the colour scanner provided better accuracy than that using the digital camera. But in this research, the colour of the samples of the wrinkled fabrics used was only close to white. Their method was strongly influenced by colour and pattern of the fabric.

Dobb and Russell[16] also reported on an objective and quantitative method for measuring fabric wrinkles which was based on image analysis. The principle was based on the measurement of differential intensities across the wrinkled specimen under constant illumination. To facilitate intensity measurements, a Leica-Cambridge Quantimet 570 image analyser, coupled to a video camera, was used for recording the fabric images. Dobb and Russel[16] commented that, in order to make meaningful measurements of fabric wrinkles, the following points should be taken into consideration:

- Lighting conditions should be adjusted to prevent either completely black (grey level 0) or peak-white (grey level 255) regions occurring in the video image.
- Fabrics can only be meaningfully compared if the illumination conditions are kept constant.
- The steepness factor (i.e. the difference in light intensity between neighbouring pixels) is an arbitrary value depending on the lighting conditions.
- Only plain fabrics can be evaluated using this method; patterned fabrics will give rise to anomalous steepness factors.

Na and Pourdeyhimi[17] described a system of grading fabric wrinkle recovery through the application of digital image processing techniques. The image capture system consisted of a Sony CCD camera, a True Vision Targa 64 Plus 32-bit capture card and an IBM 80486 microcomputer. Degrees of fabric wrinkling, in accordance with AATCC replicate standards, were analysed in terms of texture and profile. From the data obtained, Na and Pourdeyhimi derived a number of geometric parameters to characterise wrinkle appearance, including wrinkle density, profile, sharpness, randomness, overall appearance, surface area, normalised relief and fractal dimension. The results showed that wrinkling could be analysed and quantified successfully and accurately using these parameters. The method was simple and could apply to the analysis of wrinkling in plain fabrics. For woven fabrics with large patterns or prints, additional steps were required for differentiating wrinkles from the patterns or prints.

Kang *et al.*[18] deployed a projecting grid technique for objectively evaluating fabric wrinkling. A parallel light source in a dark room illuminated the wrinkled surface through the aligned grid panel, creating uniform grid lines and a CCD camera was used to capture the deformation of grid lines. From the deformation ratios of the grid lines projected onto the wrinkled surface, the technique reconstructed the 3D shape of the wrinkles and quantified the degree of wrinkling using a number of derived parameters, including the roughness ratio, surface area ratio, wrinkle density and power spectrum density of the Fast Fourier Transform.

- *Roughness ratio*. Roughness ratio (W_R) was defined as:

$$W_R = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \Delta Z_i^2} \tag{4.14}$$

  where ΔZ_i is the difference of the ith height of an X direction in an X-Y plane coordinate from the mean height $(\bar{Z}), |Z_i - \bar{Z}|$, and n is the total number of data points in the X direction. In general, the larger the roughness ratio, the more wrinkled the fabric appears to be.
- *Surface area ratio*. Surface area depends mainly on the shape of the specimen. The more complex the surface shape, the larger the surface area of wrinkled space appears to be. The normalised surface area was obtained as follows. Three points were selected from the vertex of a rectangular facet on the 3D shape to make two vectors. The cross-product of the two vectors represents a triangular area. The total surface area was obtained by summing individual triangular areas. The summation results were divided into normalised areas by the orthogonal projection area of the surface area.
- *Wrinkle density*. Wrinkle density was defined as the number of wrinkles per unit area, assuming uniform wrinkle distribution, a turning point representing a wrinkle in the fabric. In this research, they counted the number of turning points instead of counting the number of wrinkles per unit area, by scanning the 3D projected grid lines horizontally.

The work demonstrated that there was good correlation between the four parameters and the wrinkle recovery grade of a wrinkled surface. This method could predict the fabric wrinkle grades without the influence of fabric colours and patterns but has limitations for sharply contrasting coloured fabrics.

Matsudaira *et al.*[19] described a method to evaluate objectively the appearance of fabric wrinkling replicas by image processing. The image processing system consisted of a light source, which allowed the incident lighting angle to be adjusted so as to adjust the light power intensity, a camera, a digitisation capture board and a computer. At first, the image captured from the fabric wrinkling replicate was filtered using a 7 × 7 weighting and smoothing filter to remove the noise produced from illumination reflection, camera imperfections, surface texture and fabric structure. Then the parameters were defined and the FFT was applied based on the grey level.

- Standard deviation of grey level (G_{sd}). G_{sd} is defined as:

$$G_{sd} = \sqrt{\frac{\sum_i \sum_j (Z(i,j) - \bar{Z})^2}{m \times n}} \tag{4.15}$$

  where $Z(i,j)$ is the grey level of point $A(i,j)$, $\bar{Z}$ is the mean of data points and m, n are the pixels in the X and Y directions, respectively.
- Ratio of surface area R_A. R_A is defined as Kang *et al.*'s[18] surface area ratio.
- Ratio of X direction length and Y direction length of surface profiles (R_{Lx} and R_{Ly}). R_{Lx} and R_{Ly} were defined as follows:

$$R_{Lx} = \frac{\sum_i \sum_j L_{A'B'}}{n(x_m - x_1)} \tag{4.16}$$

$$R_{Ly} = \frac{\sum_i \sum_j L_{A'C'}}{m(y_n - y_1)} \tag{4.17}$$

  where A', B' and A', C' are adjacent pixels on the image, respectively. $L_{A'B'}$ and $L_{A'C'}$ are the lengths of the lines A', B' and A', C' on the fabric surface, respectively.

The results showed that all the parameters of the fabric wrinkle grades fell into good logarithm functions, which meant that this method can objectively evaluate fabric wrinkling. The results of the FFT analyses showed that the spectra of surface profiles could quantify the wrinkle grades.

Recently, Hu and Xin[20] proposed a new method for measuring fabric wrinkling based on integrating photometric stereo and image analysis techniques. Their 3D wrinkling measurement system consisted of a colour digital camera, a lighting box, a frame grabber and a personal computer. Parallel lighting was controlled in four directions in their special lighting box, and they designed special equipment to generate calibrated parallel light sources from common fluorescent tubes. The dedicated image analysis software calculated two parameters, P and Q, for measuring wrinkling in the X and Y directions, respectively. $P+Q$ was used to describe the wrinkling of the whole fabric surface. Their work showed that the effective feature, $P+Q$, can give a good measure of the degree of wrinkling. Here

$$P = \frac{1}{N}\sum_{1}^{N} |p(i)| \tag{4.18}$$

and

$$Q = \frac{1}{N}\sum_{1}^{N} |q(i)| \tag{4.19}$$

where, $p(i)$ and $q(i)$ are the first partial derivatives of z with respect to X and Y of the surface element i, and N is the number of surface elements (pixels) of each image.

Yang and Huang[21] proposed an approach to reconstruct the fabric 3D surface shape from multiple illuminated images of the pattern, based on a photometric stereo method. They then measured the degree of wrinkling of an AATCC standard wrinkle pattern using four index values to indicate the variation of the surface height value.

The basic system of a photometric stereo method consists of multiple light sources, a CCD digital camera and other control systems. This photometric stereo method transfers the multiple grey level signals obtained from the multiple light sources into the height signal at any point on the 3D surface, producing the reconstruction of the 3D surface shape.[21] The research[21] applied four feature indices to measure the degree of wrinkling of the pattern. They were coarseness,[22] fractal dimension,[11] surface area[17] and average offset.[23] The results showed that there was a good linear correlation between the index value and the subjective grade, which meant that the photometric stereo method can possibly be used to reconstruct the 3D wrinkled surface shape of a fabric, and the index value to indicate the degree of wrinkling of the fabric.

Generally speaking, image processing methods are much faster in capturing the profiles of the wrinkled surface than the laser scanning method, but may be less accurate. They also tend to have difficulties in evaluating checked fabrics as the grey-value intensity cannot reveal the height of every position on the fabric surface since it is bound to change with the colour of the fabric, intensity and location of the light source, and even with the camera lens settings, contrast and brightness.

4.3 Objective evaluation of fabric pilling

Pilling of fabrics is a well-known phenomenon, and can seriously compromise a fabric's acceptability. Pilling is a fabric surface effect caused by wear and tear which considerably spoils the original appearance of the fabric. It begins with the migration of fibres to the outside yarn surface causing fuzz to emerge on the fabric surface. Due to friction, this fuzz becomes entangled, thus forming pills which remain attached to the fabric by long fibres.

Considerable research has been undertaken on the objective evaluation of fabric pilling. The research can be divided into two categories according to the method of acquiring the surface data from the fabric specimen. One is the laser scanning method,[24–26] and the other is the image processing method.[27–32]

Ramgulam and co-workers[24,25] applied the laser triangulation technique (see Fig. 4.4) to evaluate fabric pilling objectively.[24,25] Their system involved the following steps:

1. Measurement of height at different locations on the sample, using laser triangulation.
2. Elimination of the noise and excessive detail in the image by averaging the height measurements at any point.
3. Use of image segmentation, each sample surface being segmented into two separate zones, namely pills and background, according to height.
4. Counting the number of pills.
5. Measuring the total projected area and height of the pills.
6. Using information from 4 and 5 as point coordinates to relate it to the known pilling grade of a particular sample.

Based on the correlation analysis between the subjective grades and the objective parameters, they concluded that improved data analytical techniques were necessary in order to develop an effective objective evaluation method based on the triangulation technique.

Sirikasemlert and Tao[26] also adopted the laser triangulation technique to study fabric surface characteristics. The objective measurement system developed for fabric surface mapping, shown in Figs 4.2(a) and 4.2(b), consisted of a laser scanner from CyberScan Cobra, an X-Y position controller with a sample stage and a PC for controlling the laser scanner and collecting and processing the data. The experimentally determined surface profile was described as an array of independent profile height values as a function of the coordinates in the fabric plane (X, Y). The data were used to derive a number of surface texture parameters by statistical, fractal, Fourier and wavelet analyses. They derived eleven objective parameters for pilling: mean profile height, mean roughness CLA, mean roughness RMS, skewness, kurtosis, fractal dimension of pills, fractal dimension of pills and fuzz, wavelet energy, number of wavelet coefficients, ratio of the total area of pills and the number of pills and change in total power in the pill zone, which were defined as follows:

- *Mean roughness CLA*. Mean roughness central-line average (CLA) $\bar{R}_a$ was the average value of the integration of the heights deviating from the calibrated line:

$$\overline{R_a} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{L}\int^{L} zdx \tag{4.20}$$

where L is the scanned length and z is the profile height (X, Y).

(a)

(b)

Figure 4.2 (a) The measuring system using laser triangulation; (b) The laser scanner from CyberScan.

- *Mean roughness root-mean-square (RMS)* $\overline{R_q}$. This is given by:

$$\overline{R}_q = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\frac{1}{L}\int^{L} z^2 dx} \tag{4.21}$$

- *Skewness and kurtosis*. The probability density function $p(z)$ may offer useful information about surface texture in terms of its height-ordered moments.[33] The third moment, skewness (SK), a measure of distribution symmetry, is defined as:

$$SK = \frac{1}{\sigma^3}\int_{-\infty}^{\infty} z^3 p(z)dz \tag{4.22}$$

where σ is the standard deviation of $p(z)$.

The fourth moment, kurtosis (K), indicates Gaussian similarity, in simplified words, the peakedness of the distribution:

$$K = \frac{1}{\sigma^4}\int_{-\infty}^{\infty} z^4 p(z)dz \tag{4.23}$$

- *Fractal dimension of pills and fractal dimension of pills with fuzz*. Based on the binary image, by implementing a box-counting algorithm,[34] the fractal dimension D was defined as:

$$D = -\frac{\log(N(r))}{\log(r)} \tag{4.24}$$

where r is the side length of the squared box and $N(r)$ is the number of boxes which cover the image.

The fractal dimension of pills (D_p) and the fractal dimension of pills with fuzz (D_{pf}) were then determined based on the binary images of pills and pills with fuzz, respectively. The binary image of pills with fuzz was the image converted from an original image based on the selected threshold.
- *Change in total power in the pill zone*. The total power in the pill zone before and after wear (P_p) is described as:

$$P_p = \int_{\lambda_p \min}^{\lambda_p \max} (P_b - P_a)d\lambda \tag{4.25}$$

where P_b and P_a are the power spectrums before and after simulated wear, respectively. The wavelength λ can be expressed in terms of the position of a pixel by:

$$\lambda = \frac{1}{\sqrt{u^2 + v^2}}$$

where u and v are two frequency spectrum variables of the 2D Fourier transform.

- *Wavelet energy and number of wavelet coefficients*. From the image after thresholding, the wavelet energy of the pills (E_p) is calculated, based on the remaining wavelet coefficients (c_w), using the following equation:

$$E_p = \sum c_w^2(n) \tag{4.26}$$

The number of wavelet coefficients (Wn) is the number of pixels with a wavelet coefficient higher than the selected threshold, which these pixels represent as pills on the fabric surface.

In all these parameters, wavelet energy and the number of wavelet coefficients represent the best and the second best single parameter offering the highest and the second highest correlation coefficients with the subjective grade, respectively.

The laser scanning technique, however, is a much slower process than the camera-capturing technique, since it requires an X-Y stage to move the sample mechanically.[27] Digital image processing techniques have therefore been preferred for the objective evaluation of fabric pilling.

Konda *et al.*[28] developed a method of comparing images of pilled samples taken by a video camera with the corresponding images of standard photographs, thus determining a fabric pilling grade. Home video lights VZ-LS35 and an OLYMPUS TE-II were used as the light source for the standard photographs in JIS L1076 and the actual fabric samples, respectively. The images of the sample surface captured with a TV camera, NATIONAL VY7000, were displayed graphically and the feature values of pilling were calculated using a minicomputer. Konda *et al.*[28] discussed in detail the threshold values in the binary transformation. The threshold values were different for different categories of standard photographs, but nearly constant for different grades in the same category. The distribution curve of pill sizes, the total number and area of pills, and the mean area of pills could be calculated from the images of a pilling sample. The pilling grade of a given sample was determined by comparing its total number and area of pills with those of the standard photographs of different grades in the group. The judgement of pilling grade by two feature values, namely the total number and area of pills, was found better than that by any single feature value.

The method of determining fabric pilling grades, developed by Konda *et al.*,[28] was one of the early objective measurement techniques based on image processing. This method was good for grading the pilling of plain-coloured fabrics, but was unsuitable for patterned fabrics because the video camera cannot distinguish between the images produced from pills under the incident light and the dark regions of the fabric surface.

Xu[30] and Xu and Ting[35,36] developed an image-analysis system to evaluate fabric appearance. The system consisted mainly of a CCD camera, a colour scanner, an imaging board, a computer and the self-developed software. Two

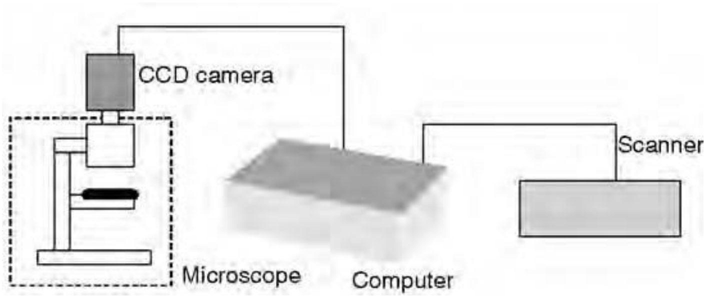


Figure 4.3 Schematic set-up of the image-analysis system.

different devices can be chosen as image-input devices. One is a JVC TK1070U CCD camera and the second is an HP Scanjet IIC scanner. The basic set-up of the system is shown in Fig. 4.3.

To accommodate differences in fabric colour, an auto-iris lens was used so that constant brightness could be maintained over dark and bright samples. A three-chip colour CCD camera was used to provide accurate colour information for removing the pattern in the imaging analysis. Since the pills observed in worn garments vary appreciably in size and appearance, the system was designed to be capable of capturing and analysing multi-frame images of the samples at various locations to generate reliable statistical data. To avoid human interference, a stage, driven by a DC motor, was designed to automatically transport the sample under the camera. The number of positions and the interval between two positions could be set from the computer interface. The stage moved from one end and stopped at each position to let the camera capture a still image.

Since the development of pills may be accompanied by other surface phenomena, such as a loss of cover, colour change, or the development of fuzz, the image of a tested fabric often contains a non-uniform background, varying contrast and other defects. It is necessary to correct or reduce the image defects to facilitate pill identification. For example, floating-yarn points in the image are a barrier to identifying pills, because such points often have similar sizes and intensities to the pills. FFT techniques were applied by Xu[30] to separate pills from floating-yarn points. Other methods of enhancing images for pill identification have also been suggested.[27,35,36]

Xu[30] characterised pills using three parameters: pill density, pill size and contrast between a pill and its surrounding area. In order to make the rating results generated by the pilling-evaluation system consistent with the visual standards, the ASTM photographic pilling standards were first analysed by using the system, and the rating equations were built on the basis of the measurements of the pill properties from these photographs. The experimental results showed that the density, size and contrast were the important properties of pills which describe the degree of pilling and were used as independent variables in the grading equations for pilling.

Xin and Hu[32] presented an objective evaluation method of pilling in knitted fabrics by image analysis techniques. They developed a special lighting box which illuminated fabric samples uniformly, simulating day-time lighting conditions. With the captured image, pilling was evaluated by template training, template matching, image segmentation, feature extraction and grade rating. The pill template was trained by using actual pill images and the two-dimensional Gaussian fit theory. In total, five parameters were extracted: pill number, mean area, total area of pills, contrast and density. Except for contrast, the other parameters have high correlations with the subjective grades, and four rating formulae were derived by means of these four parameters. This method was effective for fabrics of a uniform colour, but could not be used for printed fabrics of multiple colours, which not only contain shape information, but also colour space information.

Jensen and Carstensen[37] presented an automatic and objective method for reproducible image acquisition and evaluation of fuzz and pills in knitted fabrics. A new sensor technology was used for the measurements and acquired all the images of the samples by means of a Videometer camera system. This system was a highly precise device to measure colour, texture and shape using a calibrated 3CCD colour camera. The system was designed as a high-intensity, integrating sphere illuminator, which delivers well-defined and diffuse illumination in a closed environment. Images were captured as an average over ten frames to eliminate single-frame noise. In order to recognise more clearly fuzz and pills and remove the knitted stitch pattern, images were filtered first using the Fourier 'mask' which consisted of a circular centered area excluding smaller circular areas centered over the positions of the peaks characterising the knitted structure.

They defined a fuzz and pill feature (FP) as follows:

$$FP = \sum_{(u,v) \in M} |F(u,v)|^2 \tag{4.27}$$

where M was the mask region in the Fourier power spectrum and $F(u,v)$ was the frequency domain function of the image signal.

Results showed that the fuzz and pill evaluation method was consistent with results obtained from expert evaluations.

4.4 Objective evaluation of seam pucker

During the past five decades, considerable efforts have been directed towards developing objective methods for the evaluation of seam pucker. Techniques for the objective characterisation of seam pucker may be classified into two main categories, namely 'contact' and 'non-contact' methods. Most of the non-contact type instruments involve optical methods. The non-contact type testers have advantages over the contact type, as a device which contacts the fabric may disturb the fabric surface and provide an inaccurate assessment of geometric roughness. The non-contact type of test tends to have high accuracy, good resolution and high reproducibility.

4.4.1 Contact methods for the objective evaluation of seam pucker

Shiloh[38] used the Wrinklemeter, originally developed to detect and measure fabric wrinkling, to evaluate seam pucker by tracing the seam contour curve. The trace was made on two contour curves, parallel to the seam, at a distance of 2 mm from the sewing thread on both sides. The first trace provided height, the second trace provided the slope and the third trace, the curvature. From the curvature, density was easily calculated. Finally, the means of the measurements obtained from the two contours along the seam were calculated to represent the extent of puckering.

The samples were prepared on a set of seven cotton seam specimens, sewn with cotton threads. These were washed and then selected to represent a wide variation in puckered appearance. Shiloh[38] gave the results of the measurements, which included AATCC visual rating, ranking score, seam height, seam slope and 'puckering-severity index' (the product of height and slope, *HT*, was suggested as a 'puckering-severity index'). From these results, significant correlations were found between the puckering-severity index and both the scores and the AATCC visual ratings. The densities of zero points and extreme points were also calculated. These were found to be related to the stitch length used in preparing the seamed specimens.

Galuszynski[39,40] developed the SAWTRI puckermeter, which measured pucker by comparing the length of the puckered seam with that of the seam without puckers. The puckermeter enabled one to evaluate the contribution to seam pucker of such factors as differential shrinkage of seam components, fabric displacement during seam formation, sewing thread tension and inherent puckers. The degree of seam pucker was expressed in terms of a 'pucker index'.

4.4.2 Non-contact methods for the objective evaluation of seam pucker

Owing to the fact that direct contact between the sensor and the seam specimen can undermine the accuracy and reproducibility of the measurements, Belser *et al.*[41] designed a photo-electric device to quantitatively evaluate seam pucker by examining the magnitude of the seam pucker profile. They used the ratio of the length of the curve on the seam surface to the length of the straight centre-line as a measure of seam pucker. The total length of the curve from beginning to end was measured with a Stadimeter. The results obtained showed good agreement between visual assessments made in accordance with the AATCC standards, except for fabrics with complex patterns and colours. Bertoldi and Munden[42] used a similar apparatus to assess the shadow pattern created by light falling on the puckered surface. It assessed the darkness and shadow areas of the undulations in the case of an angular light beam. The ratio of the length of the recorded curve to the seam length was used as an index. Nevertheless, they did not compare their values with the grading according to the AATCC method.

Recently, the quantitative evaluation of seam pucker has been made by more advanced non-contact technologies, such as the Moiré measurement method, CCD camera, laser scanning technology and ultrasonic wave technology.

CCD camera

Stylios and co-workers[43–45] developed a so-called Pucker Vision System, comprising a CCD camera, to replace the human eye, and a software program simulating the human cognitive process. The system was designed to capture the images of two groups of seam stripes produced from the same fabric, one an unstitched seam and the other sewn with puckers. Using the mean reflection of the unstitched seams as a reference, the system assessed the configuration of the pucker by identifying the pucker wavelength and pucker amplitude to develop a pucker severity index. The consistency of the light source and the influence of the pattern and colour of the fabric were the major limitations of the system.

Forschungsinstitut für Textiltechnologie Chemniz GmbH Germany (FIFT)[46] also developed a system using a special camera. Seam pucker was evaluated by photogrammetric interpretation of photographs taken of the seams using this camera.

Richard[47] developed a computer-based seam pucker measurement system (SPMS) for quantifying seam surface irregularities using digital image analysis. A video camera was used to capture seams in the immediate vicinity of the seam formation area. The measurement of the pucker index on a scale of 1 to 5 was very rapid and the results were incorporated into a fabric sewability report, together with the measurement of the dynamic force of the sewing process.[47, 48]

Ultrasonic wave technology

Ultrasonic wave technology was used by Shigeru and Atsuo[46] as a non-contact method for measuring seam pucker with high precision. It collects information about the surface shape of seam pucker through an ultrasonic image scanner. The ultrasonic waves are narrow beams and the intensity of reflection was related to the slope of the surface. The seam pucker surface was measured by the ultrasonic wave reflection and the intensity of reflection. Seam pucker was related to various waves of the surface of the seam. In ultrasonic wave technology, data values relate to the slant angle (slope) of the surface. The data were used for the variables of surface shape and also improved the performance of discrimination under optimum conditions in terms of the length or pitch of the measurement. They found that the measurements were not affected by surface colour.

Laser scanning

Shigeru and Atsuo[46] applied laser scanning technology for the objective evaluation of seam pucker. The laser technology system consisted of a laser displacement meter, a moving stage with two axes, magnetic displacement meters, controllers and a computer. The laser scanner detected the reflection from the puckered surface by a light-detecting semi-conductor. With the output of the height of the reflecting point, which is calculated by the principle of triangulation, the data on the lines, with respect to the wave and power spectra of each line, were calculated by means of Fast Fourier Transform (FFT).

Logarithmic power spectra were used to emphasise the wave power at a small frequency because the wave power at a high frequency is very small compared with the power wave at a low frequency and the high frequency wave is important for evaluation. The frequency band of the power spectra was divided into three band segments and all lines were divided into three groups. The nine areas were defined by a division of frequency and position. With these nine values and the division of five grades, the relationship was analysed with discriminate analysis. It was difficult to discriminate slight pucker values with the data from objective measurements.

Park and co-workers[49,50] and Park[51] also used laser technology to capture seam pucker and evaluate it using artificial intelligence. A displacement meter, consisting of a laser diode, can accurately measure the surface profile of the seam regardless of changes in colour or surface condition. The data obtained along the seam line were transformed into power spectra at a frequency domain using FFT. The power spectra created the specified patterns for neural networks, which evaluated the seam pucker by simulating the AATCC rating of well-trained human experts. They found that the prediction and optimisation of seam pucker were possible using the approach developed in their research with material properties and processing parameters.

Kawabata[52] and Kawabata *et al.*[23] used the laser scanning method to measure seam pucker and analysed the sensory evaluation of seam pucker using the Weber-Fechner law. In their work, the geometrical shape of pucker was measured by a scanning laser beam to obtain a height profile. The height signal passed through a low-pass filter with a cut off frequency of 1 Hz (1 Hz is equivalent to 4 cm of the wavelength at a scanning velocity of 4 cm/s) to eliminate the influence of a longer wave on the pucker evaluation. From the height signal, they calculated a surface roughness parameter and found that sensory evaluation of seam pucker follows the Weber-Fechner law, which states that a sensory value is proportional to the logarithm of the magnitude of the quality of the physical stimulation. Based on the above theory, they developed an equation for the objective prediction of seam pucker. It was a very important contribution, discovering an almost linear relationship between the subjective pucker grade and physical quantity.

Figure 4.4 The 3D Model Maker laser scanner.

In 1997, Fan and co-workers[22, 53–57] developed an objective method for the evaluation of seams on a 3D garment surface through the application of laser scanning technology. For this experiment, a commercial 3D laser scanning system, which consisted of a laser scanning head, robot arm, computer and some special software for data acquisition, was used to scan garment seams. The 3D laser scanning system, called 3D Model Maker, is shown in Fig. 4.4.

2D Digital filters were used to obtain pucker profiles by removing the high-frequency components in the seam profiles, which might be contributed by the individual threads of the fabric or noise, as well as the lower frequency components, which might be contributed by the garment surface. They considered the following four geometrical parameters calculated from the pucker profile:

- The average displacement from the mean magnitude (R_a)

$$R_a = \frac{1}{N}\sum_{i=1}^{N}\left(|z(i) - \overline{z(i)}|\right). \tag{4.28}$$

  where $z(i)$ is the height of the ith measurement, and N is the number of measurement points.
- The variance, given by:

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}\left(z(i) - \overline{z(i)}\right)^2 \tag{4.29}$$

- The skewness of the distribution of the heights of the pucker profile, given by:

$$S = \frac{1}{N}\sum_{i=1}^{N}\left(z(i) - \overline{z(i)}\right)^3/\sigma^3 \tag{4.30}$$

- The pointedness (kurtosis) of the distribution of the height of the pucker profile given by:

$$K = \frac{1}{N}\sum_{i=1}^{N}\left(z(i) - \overline{z(i)}\right)^4/\sigma^4 \tag{4.31}$$

It was found that the logarithm of the average displacement from the mean magnitude (log R_a) and logarithm of variance (log σ^2) were linearly related to the severity of seam pucker. The addition of the logarithm of skewness (S) and pointedness (K) of the height distribution hardly improved the correlation. Log R_a and log σ^2 were therefore recommended as objective measures of seam pucker.

In their research, Fan and Liu used ten men's shirts, made from two different fabrics of similar weight and density, one a white polyester/cotton and the other a red-and-white cotton check, as samples. They discussed the relationship between the logarithm of variance (log σ^2) and the subjective grade of seam pucker close to four parts on the sample garment, which were yoke seam, pocket seam, placket seam and armhole seam. The relationships are shown in Figs 4.5(a), 4.5(b), 4.5(c), and 4.5(d), respectively.

Based on this investigation,[53] the following conclusions were drawn:

1. The 3D laser scanning system is effective for capturing the garment surface with sufficient accuracy and reproducibility for the objective evaluation of garment appearance.
2. The reported 2D band-pass digital filter is effective for extracting the pucker profiles from the scanned garment surfaces by removing the 'high frequency' components from the fabric surface texture and the 'low frequency' components representing the garment silhouette and drape.
3. The subjectively assessed pucker grades of garment seams are linearly related to log (σ^2), which can be calculated from the pucker profiles.
4. The pucker grades of garment seams can be objectively evaluated through the measurement of log (σ^2). The objective evaluation is more accurate and reproducible than the subjective assessment.
5. The objective evaluation method is not affected by the colour and pattern of the fabric, from which the garment is made.

Although the objective method had been proven through this investigation, further work was still considered necessary. The system consisted of expensive hardware and software. It might still be too expensive for routine industrial application, although it was practically feasible when only a small number of samples were required for testing. Future efforts were needed to reduce the cost of the system and make it more robust for industrial use.

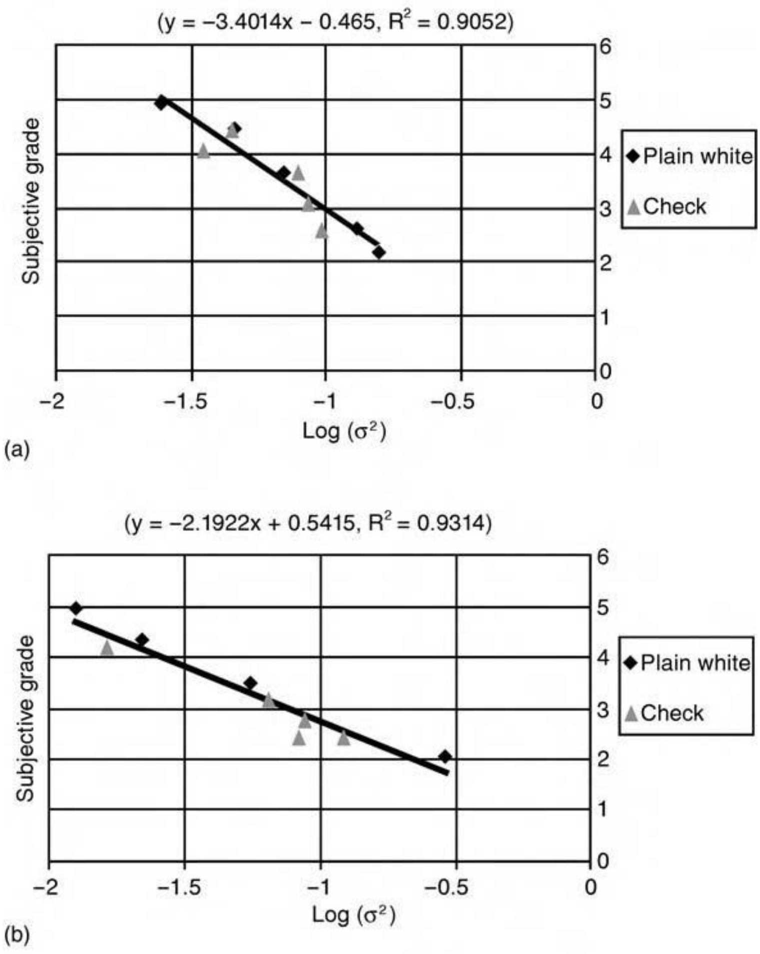
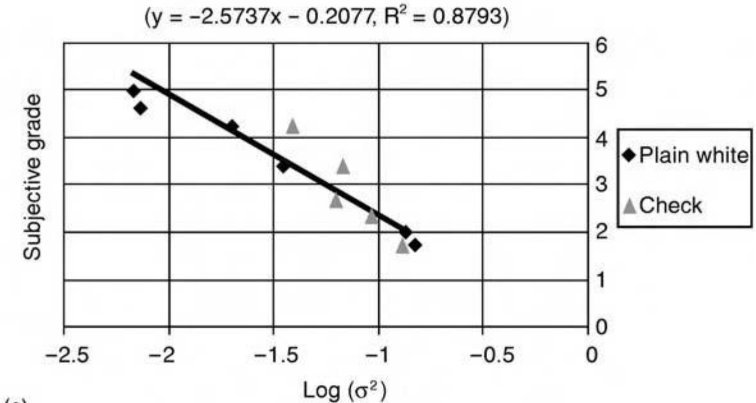


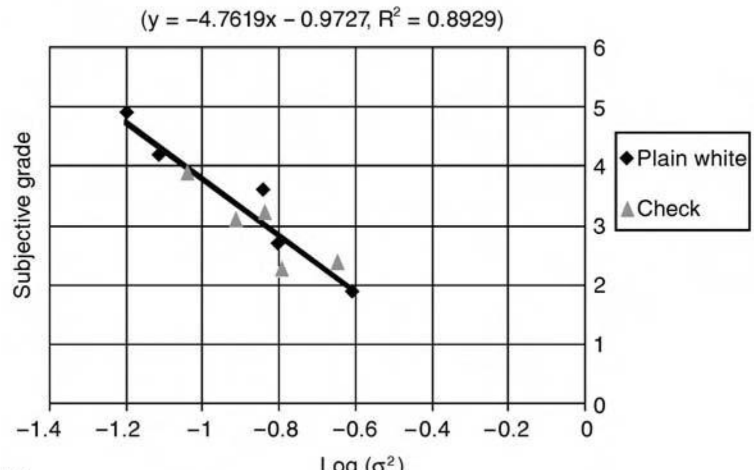
Figure 4.5 (a) Subjective Grade vs Log(σ^2) for Yoke seam; (b) Subjective Grade vs Log(σ^2) for Pocket seam; (c) Subjective Grade vs Log(σ^2) for Placket seam; (d) Subjective Grade vs Log(σ^2) for Armhole seam.

4.5 Objective evaluation of overall garment appearance

Attempts are being made to capture the 3D garment surface profile using a 3D laser scanner, such as Cyberware and a 3D Model Maker, and to analyse garment appearance profiles using image processing techniques. Figure 4.6 shows an image of a shirt captured by a Cyberware laser scanner. The following procedure was used to analyse the image:



(c)



(d)

Figure 4.5 Continued.

(1) Selection of a particular portion of 3D garment appearance for analysis
Using a specialty software, Surfacer Version 3.0, run in a UNIX platform, a portion of area was selected.

(2) Segmentation of a particular portion
Using the segmentation technique, curves which are separated by the same distance along the X-Y axis of a particular portion were determined with the same direction as for the scanning of the garment surface.

(3) Digital filtering
2D Digital filtering techniques were applied to remove the high frequency components, due to fabric surface texture, and the low frequency components,

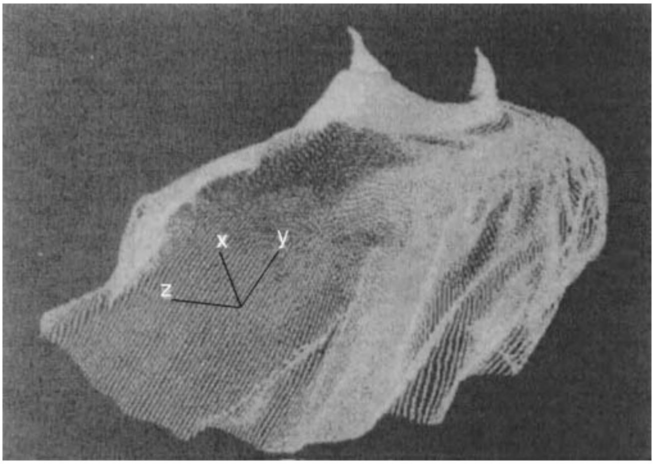


Figure 4.6 Objective evaluation of overall garment appearance.

due to the garment silhouette and drape, so as to obtain surface profiles representing the roughness, and wrinkling or puckering of the surface.

(4) Evaluating surface roughness
The degree of the roughness, wrinkling or puckering of the garment surface was measured using the physical parameters as was done with garment seams.

Current work on the objective evaluation of overall garment appearance still has considerable limitations in the following areas:

1. A large 3D laser scanner is required to scan the garment surface, which is too expensive for use in apparel production.
2. The time required to scan the entire garment surface is too long to be feasible for on-line application.
3. The accuracy of scanned data could be a problem, particularly in areas of large curvature.
4. Three independent software packages are used for data analysis. Further work is required to integrate these software packages.

4.6 References

1. Hebeler H H and Kolb H J, 'The measurement of fabric wrinkling', *Text Res J*, 1950 **20**(9) 650.
2. Kaswell E R, 'Evaluation of the celanese wrinkle tester', *American Dyestuff Rep,* 1959 **48**(7) 56.
3. Shiloh M, 'The effect of fabric structure on wrinkling, studies in modern fabrics', *Text Inst,* 1970 **61** 14.
4. Shiloh M and Grill A, 'The evaluation of wrinkles in textile fabrics', *Text Res J*, 1966 **36**(10) 924.

5. Muncheryan, and Hand M, *Laser Technology*, Indianapolis: H. W. Sams, 1979.
6. Ramgulam R B, Amirbayat J and Porat I, 'Measurement of fabric roughness by a noncontact method', *J Text Inst,* 1993 **84**(1) 99–106.
7. Amirbayat J and Alagha M J, 'Objective assessment of wrinkle recovery by means of laser triangulation', *J Text Inst,* 1996 **87**(2) 349–355.
8. Park C K and Kang T J, 'Objective rating of seam pucker using neural networks', *Text Res J*, 1997 **67**(7) 494–502.
9. Kim E H, 'Objective evaluation of wrinkle recovery', *Text Res J,* 1999 **69**(11) 860–865.
10. Freeman J A and Skapura D M, *Neural Networks Algorithms, Applications and Programming Techniques*, New York, Addison-Wesley, 1992.
11. Kang T J and Lee J Y, 'Objective evaluation of fabric wrinkles and seam puckers using fractal geometry', *Text Res J*, 2000 **70**(6) 469–475.
12. Peitgen H O, Jurgen H and Saupe D, *Fractals for the classroom, part one, introduction to fractals and chaos*, New York, Springer-Verlag, 1992.
13. Xu B, Cuminato D F and Keyes N M, 'Evaluating fabric smoothness appearance with a laser profilometer', *Text Res J*, 1998 **68**(2) 901–906.
14. Xu B and Reed J A, 'Instrumental evaluation of fabric wrinkle recovery', *J Text Inst,* 1995 **86**(1) 129–135.
15. Mori T, and Komiyama J, 'Evaluating wrinkled fabrics with image analysis and neural networks', *Text Res J*, 2002 **72**(5) 417.
16. Dobb M G and Russell S J, 'A system for the quantitative comparison of wrinkling in plain fabrics', *J Text Inst,* 1995 **86**(3), 495–497.
17. Na Y G and Pourdeyhimi B H, 'Assessing wrinkling using image analysis and replicate standards', *Text Res J*, 1995 **65**(3) 149–157.
18. 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', *Text Res J*, 1999 **69**(4) 261–268.
19. Matsudarai M, Han J, and Yang M, 'Objective evaluation method for appearance of fabric wrinkling replica by image processing system', *J Text Eng,* 2002 **48**(1) 11.
20. Hu J L and Xin B J, 'Measuring and modeling 3-D wrinkles in fabrics', *Text Res J*, 2002 **72**(10) 863.
21. Yang X B, and Huang X B, 'Evaluating fabric wrinkle degree with a photometric stereo method', *Text Res J*, 2003 **73**(5) 451.
22. Fan J, Lu D, MacAlpine M and Hui P, 'Objective evaluation of pucker in 3-dimensional garment seams', *Text Res J,* 1999 **69**(7) 467–472.
23. Kawabata S, Mori M and Niwa M, 'An experiment on human sensory measurement and its objective measurement of seam pucker level', *Int Cloth Sci Technol*, 1997 **9**(2-3) 203–206.
24. Ramgulam R B, Amirbayat J and Porat I, 'The Objective Assessment of Fabric Pilling, Part I: Methodology', *J Text Inst,* 1993 **84**(2) 221–226.
25. Ramgulam R B and Alagha M J, 'The objective assessment of fabric pilling, part II: experimental work', *J Text Inst,* 1994 **85**(3) 397.
26. Sirikasemlert A and Tao X, 'Objective evaluation of textural changes in knitted fabrics by laser triangulation', *Text Res J*, 2000 **70**(12) 1076–1087.
27. Xu B G, 'An overview of applications of image analysis to objectively evaluate fabric appearance', *Text Chem Colourage*, 1996 **28**(5) 18–23.
28. Konda A, Xin L C, Takadera M, Okoshi Y and Toriumi K, 'Evaluation of pilling by computer image analysis', *J Text Mach Soc Japan*, 1990 **36**(3) 96–107.

29. Hector C A, Millan M S, Torres Y and Navarro R, 'Automatic method based on image analysis for pilling evaluation in fabrics', *Optic Eng*, 1998 **37**(11), 2937.
30. Xu B, 'Instrument evaluation of fabric pilling', *J Text Inst,* 1997 **88** Part 1(4) 488.
31. Wang B, and Associates, 'Development of an image analysis algorithm for assessing pilling', *TAPPI Nonwovens Conf*, 1999 305.
32. Xin B J and Hu J L, 'Objective evaluation of fabric pilling using image analysis techniques', *Text Res J*, 2002 **72**(12) 1057–1064.
33. Thomas T R, *Rough Surface*, New York, Longman, 1982.
34. Mori T, Endou Y and Nakayama A, 'Fractal analysis and aesthetic evaluation of geometrically overlapping patterns', *Text Res J*, 1996 **66**(9) 581–586.
35. Xu B and Ting Y L, 'Fiber-image analysis, part I: fiber-image enhancement', *J Text Inst*, 1996 **87**(2) Part 1 274.
36. Xu, B. and Ting, Y.L., 'Fiber-image analysis, Part II: Measurement of general geometric properties of fibers', *J Text Inst,* 1996 **87** Part 1 284.
37. Jensen K L, and Carstensen J M, 'Fuzz and pills evaluated on knitted textiles by image analysis', *Text Res J*, 2002 **72**(1) 34.
38. Shiloh M, 'The evaluation of seam-puckering', *J Text Inst,* 1971 **62**(3) 176.
39. Galuszynski S, *Seam Pucker*, SAWTRI Special Publication, May, 1986.
40. Galuszynski S, 'Objective measurement of seam pucker', *Proc Symp New Technol Text*, South African Wool and Textile Research Institute, Port-Elizabeth, July, 1986 100–113.
41. Belser R B, Kwon C T and Conrad J M, 'Instrument for grading seam pucker', *Text Res J*, 1968 **38**(3) 315.
42. Bertoldi A M and Munden D L, 'The effects of sewing variables on fabric pucker', *Cloth Res J*, 1974 **2**(1) 68.
43. Stylios G and Parsons Moore R, 'Seam pucker prediction using neural computing', *Int Cloth Sci Technol*, 1993 **5**(5) 24.
44. Stylios G and Sotomi J O, 'Investigation of seam pucker in lightweight synthetic fabric as an aesthetic property part II: model implementation using computer ''vision'' ', *J Text Inst*, 1993 **84**(4) 601.
45. Stylios G and Sotomi J O, 'Investigation of seam pucker in lightweight synthetic fabric as an aesthetic property, part I: a cognitive measurement of seam pucker', *J Text Inst*, 1993 **84**(4) 593.
46. Shigeru I and Atsuo S, 'Objective evaluation of seam pucker', *Int Cloth Sci Technol*, 1992 **4**(5) 24.
47. Richard C, 'Pucker as fabric-thread machine mechanical instability phenomenon', *J Fed AsianProf Text Assoc*, 1996 **3**(2) 69.
48. Richard C, 'Sewability in the dynamic environment of the sewing process', *J Fed Asian Prof Text Assoc,* 1995 **3**(1) 83.
49. Park C K, Lee D H and Kang T J 'A new evaluation of seam pucker and its application', *Int J Cloth Sci Tech*, 1997 **9**(3) 252.
50. Park C K and Kang T J, 'Objective rating of seam pucker using neural networks', *Text Res J*, 1997 **67**(7) 494–502.
51. Park C K, 'Objective evaluation of seam pucker using artificial intelligence', *J.S.N. Int*, Sept., 1997 43.
52. Kawabata S, 'Fibre science to apparel engineering', *Text Asia*, Nov., 1998 51–56.
53. Fan J and Liu F, 'Objective evaluation of garment seams using 3-D laser scanning technology', *Text Res J*, 2000 **70**(11) 1025–1030.

54. Fan, J., 'Assessing the quality of garment appearance', *ATA Journal*, 76 (Jun./July, 1998).
55. Fan J, MacAlpine J M K and Lu D, 'The use of a 2-D digital filter in the objective evaluation of seam pucker as 3-D surface', *J Text Inst*, 1999 **90** Part 1 (3) 445.
56. Fan J, Hui C L P, Lu D and MacAlpine J M K, *Latest Development of Objective Evaluation of Garment Appearance*, Hong Kong Polytechnic University, 1998.
57. Fan J, Hui C L P and Lu D, 'Towards the objective evaluation of garment appearance', *Int Cloth Sci Technol*, 1999 **11**(2/3) 151.