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Evaluation of the Robustness of Objective Pilling Classification
Using the Two-Dimensional Discrete Wavelet Transform

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ABSTRACT

Previously, the authors proposed a new method of frequency domain analysis based on the two-dimensional discrete wavelet transform (2DDWT) to objectively measure the pilling intensity in sample fabric images. The method was further evaluated and the results obtained indicated that the method is robust to small horizontal and/or vertical translations of the image under analysis, is robust to significant variations in the brightness of the image under analysis, is sensitive to rotation of the image under analysis, and is sensitive to dilation of the image under analysis. The results obtained suggest that as long as precautions are taken to ensure fabric test sample imaging is performed under consistent conditions of weave/knit pattern alignment (rotation) and apparent inter-yarn pitch (dilation), then the method will yield repeatable results.

Fabric pilling is a serious problem for the apparel industry. Pills cause an unsightly appearance and can cause premature wear [10]. Resistance to pilling is
normally tested in the laboratory by processes that simulate accelerated wear, followed by a manual assessment of the degree of pilling by an expert based on a visual comparison of the sample to a set of test images [1]. A frequent complaint about the manual/visual evaluation method is the inconsistency and inaccuracy of the rating results [16]. In an attempt to bring more objectivity into the pilling rating process, a number of automated systems based on image analysis have been developed and described in the literature [1, 2, 4, 12, 15, 16]. All of these existing methods either employ expensive and complicated equipment, such as laser triangulation imaging [10, 12], and/or employ complex image processing algorithms that involve multiple stages [1, 15, 16].

In an earlier work [9], we described a methodology for the objective classification of fabric pilling based on the two dimensional discrete wavelet transform (2DDWT). When a fabric image is analyzed using the 2DDWT, at each wavelet analysis scale, there will be a distribution of detail coefficients (distribution of $cD_n^o$; where $n$ is the analysis scale and $o$ is the orientation – horizontal, vertical or diagonal). We proposed that for 2DDWT analysis of un-pilled fabric images, where the wavelet scale is close to the fabric inter-yarn pitch, the distribution of $cD_n^o$ will have a relatively small standard deviation ($SDcD_n^o$), and, as the amount of pilling increases, $SDcD_n^o$ will increase as the pills introduce variations into the image that disrupt the underlying pattern of the fabric structure. It was further proposed that it is possible to apply this image analysis method to a set of reference fabric pilling samples to develop a calibrated characteristic curve that relates pilling intensity to $SDcD_n^o$. 
The initial results obtained previously suggested that the method was feasible, and that the ability of the method to discriminate between levels of pilling intensity was dependent on the wavelet analysis scale being closely matched to the fabric inter-yarn pitch. We also presented a heuristic method for the optimal selection of an analysis wavelet and associated analysis scale. The results obtained suggested that the Haar wavelet was a reasonable basis for analysis due to its square wave structure approximating the weave/knit fabric structure. Here, we further evaluate the method to investigate its robustness to:

- horizontal and/or vertical translations of the image under analysis;
- variations in the brightness of the image under analysis;
- rotation of the image under analysis; and
- dilation of the image under analysis.

**Robustness to Horizontal and/or Vertical Translations**

To evaluate the robustness of the analysis method to horizontal and/or vertical translations the 1840 double jersey standard pilling test series from James H. Heal & Company Limited were used. The five test images were scanned at 600 dots per inch, rotated (where necessary) to have approximately the same orientation of fabric structure and cropped of edge markings. Figure 1 shows the images from this standard pilling test series for the supplier rated pilling intensities of 1 (maximum pilling), 3 and 5 (no pilling).
From each of the five ‘base’ images of the pilling test series, using the Microsoft Photo Editor program [8], a set of eight variations simulating small horizontal and/or vertical translations were created by cropping approximately 4 percent of the image from one or more sides. For example, using the pilling intensity 1 image and the labeling shown in Figure 1, image 1A was created by cropping 90 pixels from the top edge of the base image, image 1B was created by cropping 90 pixels from the right hand edge of the base image, and similarly for image 1C and image 1D. Additionally, image 1AB was created by cropping 90 pixels from the top edge and the right hand edge of the base image, image 1BC was created by cropping 90 pixels from the right hand edge and the bottom edge of the base image, and similarly for image 1CD and image 1DA. Viewed in succession, each set of eight images shows the base image undergoing a sequence of horizontal, vertical or diagonal translations. The fabric/pilling features in the sequence of eight images are similar, but not identical.

For each of the 40 images thus created, the standard deviation of the distribution of the horizontal details coefficients ($SDcD^h_i$) at various analysis scales,
based on analysis using the Haar wavelet, was computed using the Matlab Wavelet Toolbox [14]. For each of the five pilling intensities, the mean and standard deviation of $SDcD_n^h$ were computed for the set of eight translation images. Using the mean value for $SDcD_n^h$ in the heuristic method described previously [9], the optimum analysis scale was found to be scale 5. Assuming that the distribution of $SDcD_5^h$ from the translation set is approximately Gaussian, then we can compute a confidence interval based on a small sample for the mean value of $SDcD_5^h$ using the ‘one-sample t test’ [11]. Figure 2 presents the mean values and 90 percent confidence intervals of $SDcD_5^h$ for each of the five pilling intensity levels, based on the eight translation images created for each pilling intensity level.

![Figure 2](Image)

Figure 2. Mean values and 90 percent confidence intervals of $SDcD_5^h$ from translation image sets generated from 1840 double jersey series.
The results obtained suggest that the method is relatively robust to small translations of the image under analysis. This would be expected, as neither the orientation of the underlying pattern of the fabric structure nor the bulk of the pilling details are altered.

Robustness to Variations in Image Brightness

An important method of quantitatively and qualitatively analyzing the characteristics of an image is to produce a histogram that gives the frequency of occurrence of each possible pixel value [6]. For a 256 gray level image, the histogram x axis will span the values 0 to 255, and the y axis will give the frequency of occurrence of each x axis pixel value in the image. Images with a histogram distribution concentrated at lower pixel values will appear darker, while images with distribution concentrated at higher pixel values will appear lighter. One method of adjusting the gray level of an image is to add a constant value to each pixel, which alters the overall brightness of the image [5]. Adding a positive offset to all pixels will lighten the image and move its frequency histogram to the right; adding a negative offset will have the opposite effect. In a gray scale image, pixel values cannot be less than zero or exceed \( n - 1 \) (where \( n \) is the number of gray levels), hence at extreme levels of brightness adjustment, pixel values will accumulate at the edges of the histogram and the operation of altering the brightness of the image will produce non-linear effects on the frequency histogram [6].

To evaluate the robustness of the analysis method to variations in brightness, the level 1 pilling intensity (maximum) 1840 double jersey standard pilling test image from James H. Heal & Company Limited was used. The level 1 pilling image created
for the translation trials was cropped square and scaled to 512 by 512 pixels to speed processing and analysis operations. Using the Microsoft Photo Editor program [8], a series of images with varying brightness were created using the base image. When modifying image brightness the Photo Editor sets the current image brightness to a scale value of ‘50’, and permits adjustments in the range 0 to 100. Using the base image at brightness ‘50’, images were created with varying brightness in the range 20 to 90 in increments of 10. For each image, a pixel value frequency histogram was created with the Matlab mathematical analysis software package [13], with a data range of 0 to 255 and 64 bins each of size 4. Figure 3 shows a sub-set of these images for brightness levels of 30, 50, 70 and 90, along with their pixel value frequency histograms. It can be observed that the original brightness ‘50’ image had a mid-range histogram, and that the range of images created included brightness adjustments that both linearly translated the original image histogram, as well as some extreme cases that caused the image histogram to be compressed due to accumulation of pixel counts at extreme brightness values.

Brightness = 30
Figure 3. Test images with varying brightness and their associated pixel value frequency histograms – generated from 1840 double jersey series.
For each of the eight test images with varying brightness, $SDcD_n^b$ at analysis scales 1 to 6, based on analysis using the Haar wavelet, was computed using the Matlab mathematical analysis software package [13]. Figure 4 presents the values for $SDcD_n^b$ at analysis scales 1 to 6 for each of the brightness levels 20 to 90.

![Figure 4](image)

Figure 4. Values of $SDcD_n^b$ for varying levels of image brightness at analysis scales 1 to 6 – from 1840 double jersey series, pilling intensity 1 image.

It can be seen that the $SDcD_n^b$ values obtained were constant over a wide range of brightness; the results obtained for images with brightness of 40, 50, 60 and 70 were identical to within 0.02 percent at all analysis levels. Variations in $SDcD_n^b$ with image brightness only became apparent where the adjustment to the image...
brightness caused the original brightness histogram to become compressed into extreme pixel values due to the large brightness offset employed. Variations in image brightness that cause only a translation of the brightness histogram have virtually no effect on the value of $S D c D_n^h$ obtained; it is only when the change in brightness is large enough to cause the actual image brightness distribution to be non-linearly modified that $S D c D_n^h$ is changed.

This result was confirmed by constructing a ‘mosaic’ image of successive horizontal segments from the 40, 50, 60 and 70 brightness images, each segment being a 25 percent section of the total image. This process was repeated for successive vertical segments from these images. These two horizontal and vertical mosaic images were then analyzed using the same method as the other brightness images, and both values obtained for $S D c D_n^h$ were identical, to within the same small tolerance, to those obtained for the individual brightness images. So, even when significant variations in brightness occur across a single image, as long as the brightness histogram does not become compressed at extreme light or dark values, then the method produces robust results.

The results obtained suggest that the method is relatively robust to variations in the brightness of the image under analysis. This would be expected as changes in image brightness level affect the entire image in the form of an offset of the image pixel data, which is a low spatial frequency effect that principally impacts on the wavelet approximation coefficients (which represent lower spatial frequency components in the image) and not the detail coefficients (which represent higher spatial frequency components in the image) employed in the analysis method. The sensitivity of wavelet analysis approximation coefficients to image brightness variations (such as from camera flash) is noted in the literature [7]. In the trials
presented above, the values of the wavelet approximation coefficients at all analysis scales were observed to vary in direct proportion to the brightness of the test images. Extreme variations in brightness that distort the original image pixel frequency histogram destroy some frequency information in the image and hence impact on the higher spatial frequency aspects of the image that are captured by wavelet detail coefficient analysis.

Robustness to Image Rotation

To evaluate the robustness of the analysis method to variations in image rotation, the level 1 pilling intensity (maximum) 1840 double jersey standard pilling test image from James H. Heal & Company Limited was used. The level 1 pilling image created for the translation trials was used as the basis for creating a series of images with small rotations. Using the Corel Photo House program [3], the base image was rotated about the center of the image through the range minus nine degrees to plus nine degrees in one degree steps, and at each step a new image was created by cropping a 512 by 512 pixel square from the center of the rotated image. This ensured that the series of rotated images produced had a common center of rotation. Figure 5 presents a subset of these images for rotations of –9, 0 and +9 degrees. The change in rotation of the images can be discerned by observing the rotation of aligned pills and other prominent image features.
Using the heuristic method described previously [9], based on analysis using the Haar wavelet, it was found that the optimum analysis scale for the set of five pilling standard images from which the base level 1 pilling image used here was drawn was scale 4, though scales 3 and 5 also produced viable analysis characteristics. For each of the 19 images thus created, $SDcD_n^h$ at scales 3, 4 and 5, based on analysis using the Haar wavelet, was computed using the Matlab Wavelet Toolbox [14]. Figure 6 presents the values for $SDcD_n^h$ at analysis scales 3, 4 and 5 for each of the 19 rotation angles.
Figure 6. Values of \(SDcD^h_n\) for image rotation –9 to +9 degrees at analysis scales 3 to 5 – from 1840 double jersey series, pilling intensity 1 image.

It can be seen that the \(SDcD^h_n\) values obtained show significant variation from the base image in the range of rotation for all analysis scales. The maximum deviations from the base (0 degree) value of \(SDcD^h_n\) were +5.8 percent for analysis at scale 3, +14.9 percent for analysis at scale 4 and -7.9 percent for analysis at scale 5. These deviations would impact on the ability of the method to reliably identify the pilling intensity of a sample test image.

The results obtained suggest that the method is sensitive to rotation of the image under test, and that consistent alignment of sample images being analyzed would be a prerequisite for achieving successful results. This would be expected as image rotation changes the alignment of the fabric weave/knit, and hence the effective fabric inter-yarn pitch in any given direction, and so would impact on the degree of
match between the image data and the analysis wavelet, yielding variations in the
wavelet details coefficients and $SDcD_n^h$. Image rotation may also change the pilling
features in the area of the image under analysis, and hence cause further variations in
$SDcD_n^h$.

Robustness to Image Dilation

To evaluate the robustness of the analysis method to image dilation, the level 1
pilling intensity (maximum) 1840 double jersey standard pilling test image from
James H. Heal & Company Limited was used. The level 1 pilling image was scanned
at very high resolution (2400 dots per inch) to permit a number of images at lower
resolutions to be created while retaining image fidelity. The scanned image was
approximately 10,000 pixels square. From this, a ‘base’ image with a width of 400
pixels was created, maintaining the aspect ratio of the scanned image, using the
Matlab mathematical analysis software package [13]. Using the same method, a
series of comparison images were also created with the same aspect ratio, but with
widths varying from 388 pixels to 412 pixels in steps of 2 pixels, representing a
variation range in linear image dimensions, from the 400 pixel wide image, of –3
percent to +3 percent in 0.5 percent steps. All images were then cropped, about the
center, to the same dimensions as the 388 pixel wide image, creating a series of
images with varying linear dilation, but the same size field of view. Figure 7 presents
a subset of these images for width variations of -3 percent, 0 percent and +3 percent
(compared to the original 400 pixel wide image). These images simulate a range of
apparent image dilation that might occur due to variations in magnification and/or
distance between the test sample and the imaging system.
Figure 7. Test images with varying apparent dilation, -3 percent to +3 percent variation in image width – from 1840 double jersey series, pilling intensity 1 image.

For each of the 13 images thus created, $SDcD^h_n$ at scales 3, 4 and 5, based on analysis using the Haar wavelet, was computed using the Matlab Wavelet Toolbox [14]. Figure 8 presents the values for $SDcD^h_n$ at analysis scales 3, 4 and 5 for each of the 13 values of image dilation.
Figure 8. Values of $SDcD_n^h$ for image width dilation $-3$ to $+3$ percent at analysis scales $3$ to $5$ – from 1840 double jersey series, pilling intensity $1$ image.

It can be seen that the $SDcD_n^h$ values obtained show significant variation from the base image in the range of dilation for all analysis scales. The maximum deviations from the base (original 400 pixel wide image) value of $SDcD_n^h$ were $-3.4$ percent for analysis at scale $3$, $-6.5$ percent for analysis at scale $4$ and $+10.9$ percent for analysis at scale $5$. These deviations would impact on the ability of the method to reliably identify the pilling intensity of a sample test image.

The results obtained suggest that the method is sensitive to dilation of the image under test, and that consistent magnification and distance to imaging system of sample images being analyzed would be a prerequisite for achieving successful results. This would be expected as image dilation changes the apparent fabric inter-yarn pitch, and so would impact on the degree of match between the image data and the analysis wavelet, yielding variations in the wavelet details coefficients and $SDcD_n^h$. Image dilation may also change the pilling features in the area of the image under analysis, and hence cause further variations in $SDcD_n^h$.

**Conclusions**

A previously described new method of frequency domain analysis based on the two-dimensional discrete wavelet transform (2DDWT) to objectively rate the pilling intensity in sample images was further evaluated. The results obtained indicate that the method is robust to small horizontal and/or vertical translations of the
image under analysis, is robust to significant variations in the brightness of the image under analysis, is sensitive to rotation of the image under analysis, and is sensitive to dilation of the image under analysis. Small translations of the image do not vary the apparent inter-yarn pitch or significantly change the bulk of the pilling features. Whereas both rotation and dilation of the image do vary the apparent inter-yarn pitch, and may significantly change the pilling features in the image area under analysis. Variations in image brightness that do not distort the image brightness histogram in a non-linear manner have no effect on the analysis method. The compression of the image brightness histogram that occurs at extreme levels of light or dark brightness variation destroys some spatial frequency information in the image and hence impacts on wavelet detail coefficient analysis. The results obtained suggest that as long as precautions are taken to ensure fabric test sample imaging is performed under consistent conditions of weave/knit pattern alignment (rotation) and apparent inter-yarn pitch (dilation), then the method will yield repeatable results.

Acknowledgement

The standard pilling test series images in Figures 1, 3, 5 and 7 are the copyright property of James H. Heal & Company Limited and reproduced with their permission.

Literature Cited


