A system for characterizing small fibers

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Abstract: A System for three-dimensional gauging of small fibers has been developed for process monitoring. The basic hardware consists of a pair of 2048 linear cameras orthogonally positioned, an IBM PC-compatible Pentium computer with frame grabber, a stepper motor and associated hardware for translating the fiber, a bright-field light source and special optics. The fiber is moved vertically past the two cameras as they scan. The computer acquires each scan line, processes it and then issues control signals to the stepper motor. Several different image processing operations are used to minimize the effects of illumination nonuniformity since fibers will sometimes have low contrast due to their small size. There are two sources of illumination variations, spatial and temporal which are processed independently. Image analysis is performed to provide three-dimensional fiber shape characteristics.

Key words: Gauging fiber CCD

1. INTRODUCTION

Physical characteristics of small fibers such as shape and thickness often need to be monitored during production to maintain desired properties. The development of a 3-dimensional PC-based vision system for such measurements is described in this paper. The hardware consists of two digital line-scan cameras, a Z-translation stage and stepper motor, special light source and optics, and a PC-compatible computer. A fiber is scanned by translating it past the two cameras mounted in an orthogonal configuration.

Fibers are translucent with widths on the order of 5 mils. Thinner fibers have relatively low contrast which necessitates careful image processing to detect them. Spatial variations due to light source and camera nonuniformities are more predominant than thin fibers. In addition, a readily available unregulated light source was used which had periodic temporal illumination variations caused by 60 Hz ripple in addition to variations caused by voltage fluctuations and aging.

In the next section, a description of the fiber measurement hardware is provided. This is followed by a discussion of the techniques that were used to process and analyze the image data. In the last section, system performance and results are presented.

2. HARDWARE

Measurement system hardware consisted of two cameras, an illumination source, custom optics, a PC-compatible computer and monitor, frame grabber, Z stage with stepper motor and fiber fixture, and power supplies as illustrated in Fig. 1. All of these components, except for the computer and monitor, were mounted on a 36” by 36 “ metal plate for stability and a Plexiglas enclosure was provided around the Z stage to minimize fiber movement due to air currents.

2.1 Optics and Lighting

Because of the nature of the inspection the optical system had to achieve a high resolution along with a fairly large depth of field. Additionally, the perspective error normally associated with a converging or diverging imaging system had to be avoided. Since the application required accurate three-dimensional gauging of the fiber sample, A custom telecentric imaging\illumination system was developed. Object pixel size is approximately .35 mil for a lateral field of view of .7 inches. The object field depth was also at least .7 inches as judged by the criterion of a 10% loss in signal contrast from an actual fiber. Illumination was provided by a high intensity fiber light source with a pair of fiber optic bundles and diffusers for the two cameras.

2.2 Image Acquisition Hardware

A pair of Dalsa 2048-element linear cameras and a Bitflow Raptor frame grabber were used to acquire fiber images. Since the frame grabber only had a single digital input, some type of multiplexing circuitry was needed to handle data from both cameras. The basic scheme used was to connect the output data lines of both cameras to the digital input and tristate one camera while acquiring data from the other camera. Signals from the printer port were used for camera selection. Logic was provided to prevent both cameras from being enabled simultaneously and provide dead times between deselecting one camera and selecting the other.
2.3 Stepper Motor and fixturing hardware

Other printer port output bits were used to control the Z-stage stepper motor and stepper motor direction. Software generated pulses from the printer port drive the stepper motor and move the fiber up or down as required. Two printer port status bits monitor the “home up” and “home down” limit switches for homing and limiting travel. A special fixture to hold the fiber was mounted to the Z stage so that the fiber was mounted vertically. Since the camera scanned horizontally, the entire fiber could be imaged by moving the fiber vertically while image data are read from the camera. The Plexiglas housing which minimizes fiber movements caused by air currents encloses the Z stage and diffusers.

3. IMAGE PROCESSING AND ANALYSIS

As stated in the introduction, the contrast of the fiber relative to the background may be much less than illumination variations. There are a number of sources for these variations which cause spatial and temporal variations. There are three potential sources of spatial variations: light sources; optics; and sensor pixel-to-pixel nonuniformities. It was observed that one of the light sources was noticeably brighter on one side but the other source was more uniform. Some effort was made to identify the cause of the nonuniformity but there was nothing obviously wrong to cause such a problem. As for possible variations associated with the optics, there were no indications of optically induced nonuniformities. However, the two cameras did exhibit noticeable pixel-to-pixel variations which also tended to obscure low-contrast fibers.

3.1 Image Processing

The illumination sources also exhibited pronounced temporal variations, as mentioned previously. Because illumination was provided by an incandescent source, even a small change in voltage would cause a relatively large change in light level. With the 60 Hz. voltage source used, a very pronounced ripple was observed in the light output. This occurred because the temperature of the lamp filament decreased during zero crossings of the source voltage. Ripple is not normally a problem with standard video cameras because their field rates are very close to 60 Hz. Illumination appears to be constant under such conditions. In this application, however, a line scan camera was used and a faster scan rate was needed to reduce acquisition time. The result was large line-to-line differences as illustrated in Fig. 2. Thus it was necessary to provide compensation for both types of variations. The following approach can be used to accomplish this objective.
First, consider a simple model for the effective illumination reaching the sensor can be expressed as a function of both time and spatial position

\[ I_{[j,n]} = I_0_{[j,n]} s_{[j,n]} \] (1)

where \( I_{[j,n]} \) is the effective radiation for the \( j \)th time sample impinging on the \( n \)th camera pixel, \( I_0_{[j,n]} \) is the background illumination and \( s_{[j,n]} \) is the \( n \)th scene pixel for time sample \( j \). Short-term temporal illumination variations can be assumed to be independent of spatial variations because temporal variations are almost exclusively a function of applied voltage. For this reason, \( I_{[j,n]} \) can be decomposed into the product

\[ I_{[j,n]} = I_t_{[j]} I_s_{[n]} \] (2)

where \( I_t_{[j]} \) is the relative illumination level for the \( j \)th sample and \( I_s_{[n]} \) is the value of the illumination for the \( n \)th pixel at a designated time sample, such as \( j = 0 \). Under the same assumptions as (2), the voltage output of the sensor, \( v_{[j,n]} \), becomes

\[ v_{[j,n]} = I_t_{[j]} b_{[n]} s_{[j,n]} \] (3)

where \( b_{[n]} \) is the voltage output for the \( n \)th pixel. Note that \( b_{[n]} \) is a function of both the light impinging on the corresponding pixel and the efficiency with which the light is converted into a voltage. Even if \( I_s_{[n]} \) and \( s_{[j,n]} \) are completely uniform over the camera array, \( b_{[n]} \) can vary substantially depending on camera pixel response uniformity.

By taking the log of \( v_{[j,n]} \) the output \( d_{[j,n]} \) is obtained as

\[ d_{[j,n]} = \log(v_{[j,n]}) = \log(I_t_{[j]} b_{[n]} s_{[j,n]}) \]

\[ = \log(I_t_{[j]}) + \log(b_{[n]} s_{[j,n]}) \] (4)

Note that the temporal illumination component is now linearly separable from scene information represented by \( s_{[j,n]} \).

Assume that some reference region \( R \) exists in the image that is temporally invariant except for variations due to \( I_t_{[j]} \). The light reaching the camera from this region will vary directly as a function of the illumination. Let \( a_{[j]} \) be the average value of the \( N \) density-image pixels in this region for the \( j \)th sample,

\[ a_{[j]} = \frac{1}{N} \sum_{n \in R} (\log(I_t_{[j]}) + \log(b_{[n]} s_{[j,n]})) \] (5)
\[
\frac{1}{N} \left( \sum_{n \in R} \log(I_t[j]) + \sum_{n \in R} \log(b[n]s[j,n]) \right)
\]  \hspace{1cm} (6)

Note that \(\log(I_t[j])\) is constant for all pixels in region \(R\) since it only varies as a function of the sample number. Similarly, a constant \(k_R\) can be defined as

\[
k_R = \frac{1}{N} \sum_{n \in R} \log(b[n]s[j,n])
\]  \hspace{1cm} (7)

since region \(R\) is temporally invariant by definition except for \(I_t[j]\). The average of region \(R\) becomes

\[
a[j] = \log(I_t[j]) + k_R
\]  \hspace{1cm} (8)

This value can be used to generate a normalized version of the \(j\)th image, \(d_n[j,n]\)

\[
d_n[j,n] = \log(I_t[j]) + \log(b[n]s[j,n]) - a[j]
\]  

\[
= \log(I_t[j]) + \log(b[n]s[j,n]) - \log(I_t[j]) - k_R
\]  

\[
= \log(b[n]s[j,n]) - k_R
\]  \hspace{1cm} (9)

Notice that the amount of processing required is relatively small. The region \(R\) need only be large enough to minimize errors due to camera signal noise. The image normalization operation only requires that a constant value be added to each pixel which is a simple operation. Using this approach on the acquired fiber image illustrated in Fig. 2, the illumination corrected image shown in Fig. 3 is obtained.

Figure 4. Fiber image completely normalized for illumination and sensor variations.
Prior to scanning the fiber, a background scan was obtained and normalized using (9). When this image is subtracted from the image in Fig. 3, the completely normalized image of Fig. 4 is obtained. The background of this image is very uniform with very small range of gray-scale values. The threshold for images processed in this manner is fixed as a percentage of the background light level.

3.2 Feature Extraction and Fiber Characterization

After the image is thresholded, a fast thinning algorithm is used to reduce the fiber to a single pixel width as shown in Fig. 5. Here the boundary is distorted by the presence of a dust particle. In addition, the thinning algorithm introduced some edge noise. Morphology or some heuristic rules can be used to prune the line segments generated by the dust particle.

Next, the coordinates of the thinned fiber are extracted and curve fitting techniques are used to extract features of interest such as curvature and changes in curvature over the length of the fiber.

After thinning of side view images the three-dimensional coordinates of the fiber are extracted. The three-dimensional fiber description is used to compute characteristics of the fiber represented by radius of curvature and torsion. These characteristics will be used to relate fiber quality to fiber production process parameters.

Let 3D curve \( r \) be given by the parametric equation:

\[
\mathbf{r}(t) = \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix}^T.
\]  

(10)

Assume that the parametric curve \( r(t) \) is of class \( C^3 \). Let \( s(t) \) denote the length of curve \( r \) counting from an arbitrary point on \( r \). The curvature \( \frac{1}{\rho} \) of the curve \( r \) is the norm of the second derivative of \( r \) with respect to \( s \):

\[
\frac{1}{\rho} = \left| \frac{d^2 \mathbf{r}}{ds^2} \right| = \sqrt{\left( \frac{d^2 x}{ds^2} \right)^2 + \left( \frac{d^2 y}{ds^2} \right)^2 + \left( \frac{d^2 z}{ds^2} \right)^2}
\]

(11)

The radius of curvature \( \rho \) of the curve \( r \) is the inverse of the curvature. The torsion \( \frac{1}{\tau} \) of the curve \( r \) can be calculated from the following formula:

\[
\frac{1}{\tau} = \rho^2 \left| \begin{array}{ccc}
\frac{dx}{ds} & \frac{dy}{ds} & \frac{dz}{ds} \\
\frac{d^2 x}{ds^2} & \frac{d^2 y}{ds^2} & \frac{d^2 z}{ds^2} \\
\frac{d^3 x}{ds^3} & \frac{d^3 y}{ds^3} & \frac{d^3 z}{ds^3}
\end{array} \right|
\]

(12)

For a practical implementation of formulas (10) — (12) two difficulties need to be addressed: 1) data are given in a discrete form, 2) data are corrupted by noise. The major concern is implementation of derivatives since they are very sensitive to digitization error and measurement noise. Data can be smoothed by approximating each of the coordinates, \( x(t) \), \( y(t) \) and \( z(t) \), with best fit polynomials. The approximation is performed locally and separately for each of the ordinates in which

Figure 5. Thresholded and thinned fiber.
polynomials are fitted using a least-square fit. The least-square fit would be laborious and time consuming if actually
performed at every data point. However, assuming that data are equally spaced (using interpolation whenever necessary),
and since the process of least-square fitting involves only a linear matrix inversion, it can be shown that the coefficients of a
fitted polynomial are themselves linear in the values of the data. This means that all the coefficients can be calculated in
advance, and then used to do the fits on the real data by taking linear combinations. This is the essence of the Savitzky-
Golay filtering method. The precalculated polynomial coefficients are used to construct a digital filter, called a Savitzky-
Golay filter. The impulse response of the Savitzky-Golay filter is convoluted with discrete x, y and z coordinates of the
measurement data to obtain smoother data. The discrete convolution is performed using fast Fourier transform. The
Savitzky-Golay filter is also used to calculate higher-order derivatives directly from the measurement data. Fig. 6 is a plot of
radius of curvature and Fig. 7 is a plot of torsion. No filtering was used for either plot. Figs. 8 and 9 are plots of the same
fiber characteristics using the Savitzky-Golay filter (polynomial approximation). Note that different scales are used between
the plots of the original in Figs. 6 and 7 and plots of the filtered data in Figs. 8 and 9.

![Figure 6. Radius of curvature vs. fiber length](image6.png)

![Figure 7. Torsion vs. fiber length.](image7.png)

![Figure 8. Radius of curvature data after filtering](image8.png)

![Figure 9. Torsion data after filtering](image9.png)
RESULTS AND CONCLUSIONS

By filtering the data, much useful information about the fiber can be obtained. A high-quality reconstruction of the fiber from filtered data is illustrated in Fig. 10. The performance of the system has met the requirements of the application and work is in progress to relate fiber characteristics with process parameters. The capabilities of the system are much better than any other available technique for measuring fiber characteristics in terms of speed and accuracy.

![Reconstructed fiber](image.png)

Figure 10. Reconstructed fiber.

REFERENCES

