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On-line Optical Measurement and Monitoring of Yarn Density in Woven Fabrics

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1. ABSTRACT

This paper describes a vision-based system that monitors the yarn density of woven fabrics on-line. The system is described in terms of its two principal modules, namely, the image acquisition and the image analysis subsystems. The image acquisition subsystem is implemented with standard components on a low-cost personal computer platform. These components consist of a line-scan camera, a DSP-based image acquisition and processing card, and a host personal computer. The image acquisition process is controlled by a software module that runs on the DSP board and accumulates a 2-D image suitable for the density measurement algorithm. The image analysis subsystem, which also runs on the DSP board, implements a novel, yet straightforward, algorithm that utilizes the discrete Fourier transform for monitoring the yarn density of the fabrics from the acquired images. In this algorithm, the Fourier spectrum of the images is covered by contiguous, concentric annular regions that have a prespecified width. The spectrum values within each annular region are summed, normalized, and subsequently used to produce a 1-D signature. Simple statistics of the obtained signatures are the basis for characterizing the fabric in terms of its yarn density. The described system is tested on seven fabrics with common properties but varying yarn densities and has shown to be accurate within 2 yarns per inch in either direction. It is also shown that the obtained accuracy, which is primarily a function of the image resolution, can be greatly improved.

Keywords: woven fabrics, web inspection, image processing, on-line vision systems, periodic structures

2. INTRODUCTION

On-line measurement of fabric quality is highly desirable for the textile industry in lowering costs and improving the quality of the finished fabric. The automation of the inspection of woven fabric has been the subject of considerable research. Most work in this area has involved optical measurements, particularly imaging techniques using line-scan CCD image sensors.[1,2] Real-time systems have been developed that emphasize the image acquisition hardware and the high-performance computing requirements for discrete defect detection and classification.[3,4] Examples of successful methodologies for image analysis include those based on the material densitometrical profile[5] and on textural models[6] for defect detection, as well as knowledge-based techniques for defect classification.[7] While the characterization of woven fabrics in terms of their periodic structure has received some attention,[8] to our knowledge, the issue of yarn density measurement and monitoring has not been directly addressed.

Yarn density of woven fabrics is an important product feature that impacts the quality and the value of loom-made textiles. It can be defined in terms of two quantities: (1) the pick density and (2) the warp density. The first quantity denotes the number of yarns per unit length in the pick direction (perpendicular to machine direction),

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while the second signifies the same quantity in the warp direction (machine direction). At different points in the process of fabric manufacturing and because of a number of different but known causes (e.g., changing tension in the take-up activity or the process of sanforization), the pick and warp densities can undergo subtle, as well as drastic, variations. To ensure that these variations are within an allowable tolerance and to create the opportunity for automatic process control, accurate on-line measurement and monitoring of yarn density is the necessary first step.

This paper describes a vision-based monitoring system that accomplishes the above task on-line. The system is described in terms of its two principal modules, namely, the image acquisition and the image analysis subsystems. The image acquisition subsystem, described in Section 3.1, is implemented with standard components on a low-cost personal computer platform. The main function of this subsystem is to acquire high-resolution, vibration-free images of the fabric that are suitable for processing by the ensuing image analysis subsystem. This subsystem implements a novel algorithm (Section 3.2) that utilizes the discrete Fourier transform to generate a 1-D signature representing each fabric. Simple statistics of the obtained signatures are the basis for characterizing the fabric in terms of its yarn density. The obtained results from testing the proposed monitoring system on seven fabrics with common properties but varying yarn densities are reported in Section 4.

3. VISION-BASED MONITORING SYSTEM

The proposed yarn density monitoring system is described below in terms of its two major modules. First, the image acquisition subsystem, whose main function is to acquire high-resolution, vibration-free images of the fabric, is outlined. Then the image analysis module is delineated in terms of an algorithm that efficiently estimates the yarn density of the fabrics from the Fourier spectrum of their images.

3.1 Image acquisition subsystem

The task of on-line (or in this case, on-loom), real-time image acquisition that produces high-quality, high-resolution images of fabrics can present three major difficulties, namely,

1. the isolation of the mounting components from the considerable vibration produced during loom operation,

2. the decoupling of the true forward motion of the fabric from its irregular movement shortly after its construction, and

3. the placement of the monitoring system components so that they do not interfere with loom operation or with operator access.

Moreover, these challenges are combined with the requirement that an inspection device must meet a cost requirement in order to justify its use on an individual loom. Each of the above problems has been addressed in the development of the proposed image acquisition subsystem.

The proposed subsystem is implemented with standard components on a low-cost personal computer. These components, shown in block diagram form in Fig. 1, consist of (1) a line-scan camera that is synchronized to the moving fabric by means of an incremental encoder, (2) a source of illumination for backlighting the fabric, (3) a TMS320C40, DSP-based image acquisition and processing card, and (4) a host personal computer. These components are used to acquire high-resolution, vibration-free images of the fabric under construction and to store them on the on-board memory of the acquisition card. A custom interface between the camera and the encoder extracts the true forward movement of the fabric from the highly oscillatory motion and enables an accurate image line trig-

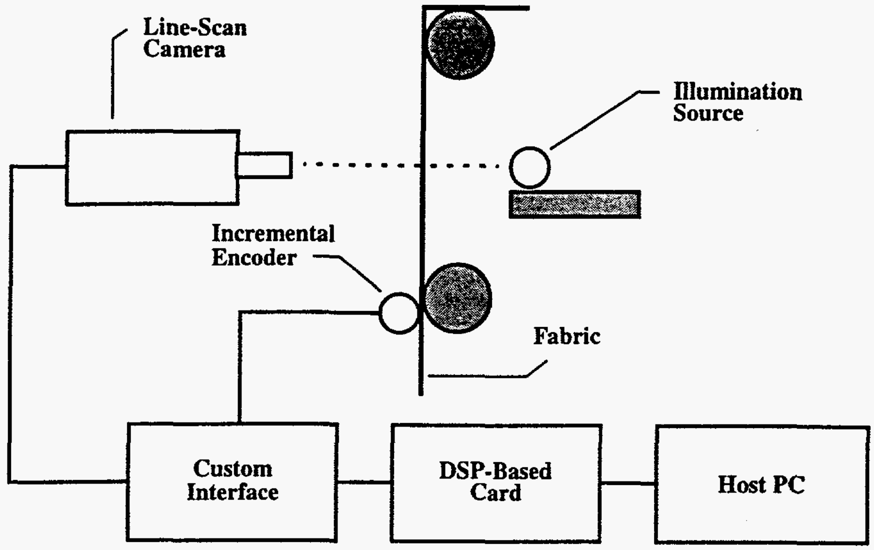


Fig. 1. The major components of the vision-based monitoring system.

gering for the line-scan camera. Software running on the DSP board controls the image acquisition process and accumulates a 2-D image that is subsequently used by the yarn density analysis subsystem.

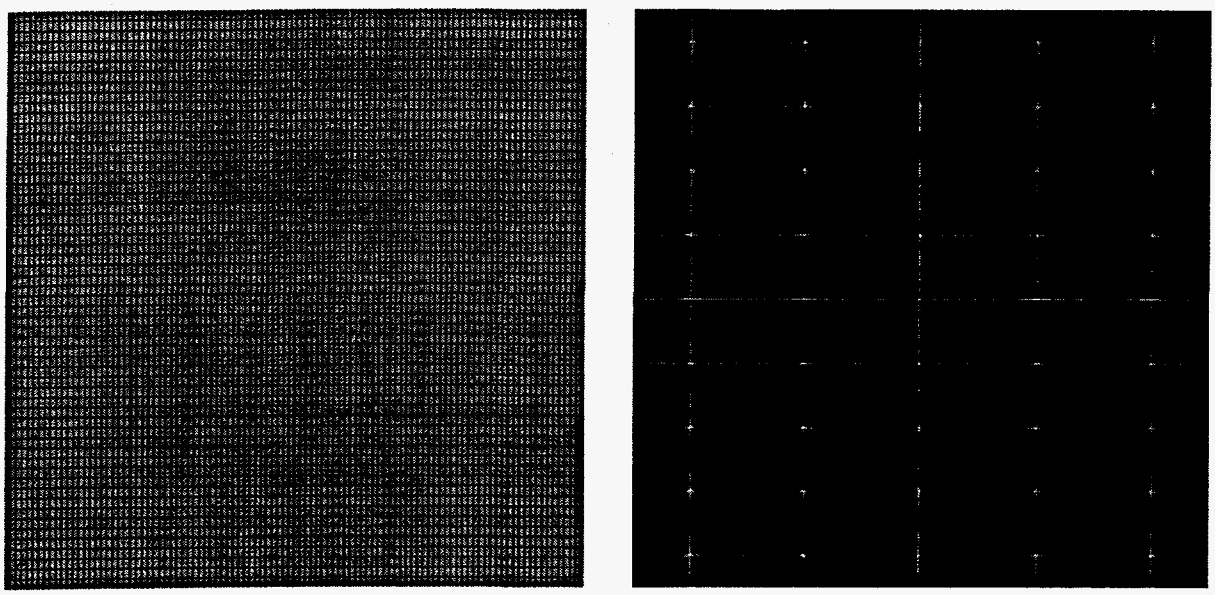
Vibration measurement and analysis were performed on a test loom at potential mounting locations to extract the magnitudes and frequencies of the physical displacements. This analysis indicated that the most significant frequencies of interest are above 50 Hz. As a result, a mounting fixture was designed to attenuate frequencies above this value. A study of the forward motion of the fabric, as characterized by the incremental encoder, demonstrated that the fabric motion after construction is irregular but cyclical. Although the average motion is in the forward direction, during a portion of the cycle, the fabric actually moves backwards. To keep track of only the forward motion of the fabric, an encoder interface circuit was designed and fabricated that monitors the encoder response and provides a digital output corresponding to the true forward motion. The line-scan camera that is synchronized to this output signal produces a line of data when the fabric has moved forward by an amount corresponding to the desired image resolution. Exposure time for the image acquisition is fixed at approximately 2 milliseconds per line, regardless of the loom speed. This time is sufficient to freeze the motion of the fabric during exposure so that variations in motion have little effect on the resulting image. Backlighting of the fabric has been found to produce higher contrast images of the fabric than frontlighting. In this application a fluorescent tube driven by a high-frequency ballast is used to obtain a constant, uniform backlit image.

Software, written in C for the TMS320C40 DSP board, initiates the start of an image frame. The image width and height in pixels along with such parameters as integration time, clock frequency, and synchronization signals are specified. While the encoder and interface circuit control the individual line-by-line timing, the DSP card determines when an entire frame is acquired. The acquired frame is subsequently passed on to the analysis module for yarn density monitoring. It should be noted that the resolution in the pick direction is set by the optics while the warp direction resolution is determined by the encoder clock divider circuitry. To generate images with square pixels, the resolutions in the pick and the warp directions must be equal.

3.2 Image analysis subsystem

The primary analysis tool used in this application is the discrete Fourier transform or, more specifically, the Fast Fourier transform.[9] There are two basic reasons for this choice. First, because of the nature of the construction of woven fabrics on looms, they exhibit distinct periodic structures, which are optimally characterizable by the Fourier transform. Second, it is seldom, perhaps never, necessary to monitor the yarn density over 100% of the web; hence, off-the-shelf, low-end hardware modules (as described in the previous section) can be effectively utilized to implement the Fourier transform in a just-in-time mode of operation.

The discrete Fourier transform of an ideal periodic structure consists mainly of high-energy, highly localized peaks (impulses), some of which correspond to the fundamental frequency of the periodic pattern while others represent the higher order harmonics (Fig. 2). Therefore, the integrity of an ideal periodic structure can be monitored



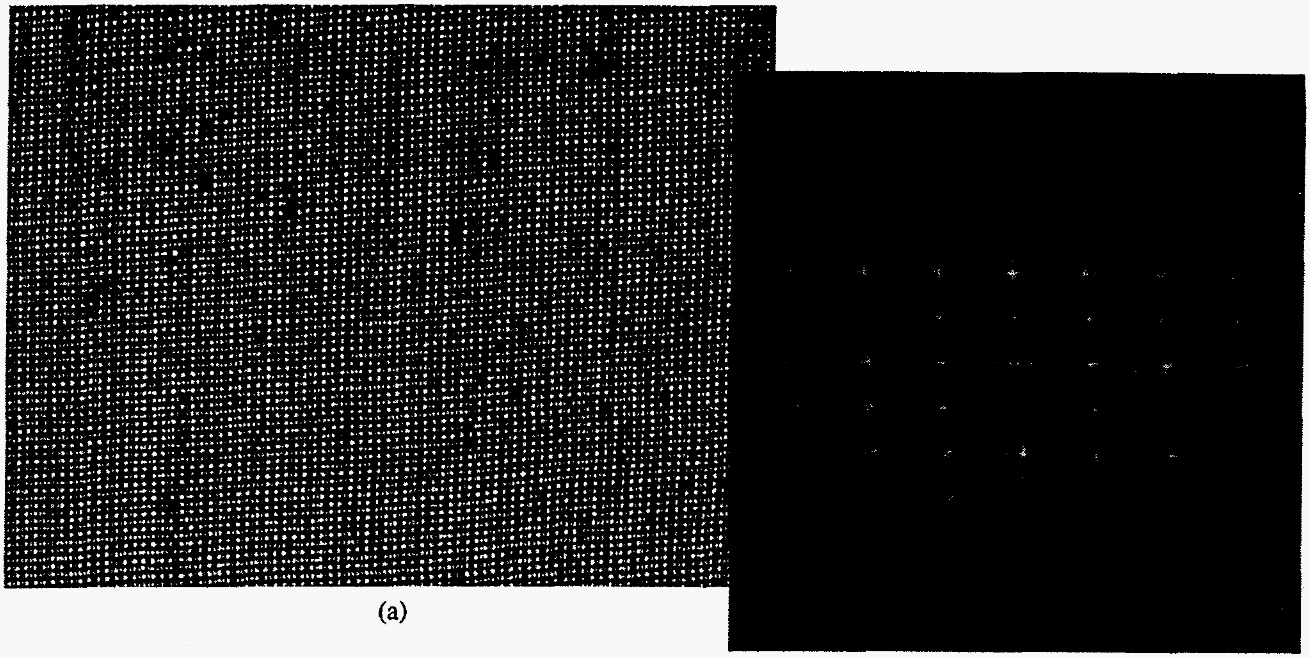
(a) (b)

Fig. 2. An ideal periodic structure in (a) and its Fourier spectrum in (b).

by observing only a few samples (local maxima) in the 2-D frequency space. This, however, is not the case for woven fabrics since they exhibit a somewhat different behavior in the frequency domain. Although their dominant periodic structures do give rise to peaks in the frequency domain (see Fig. 3), often these peaks are loosely localized and embedded in a noisy background (Fig. 4). Furthermore, the location of the maxima of these peaks may change from one image of the fabric to the next. There are a number of factors that contribute to these phenomena, for example,

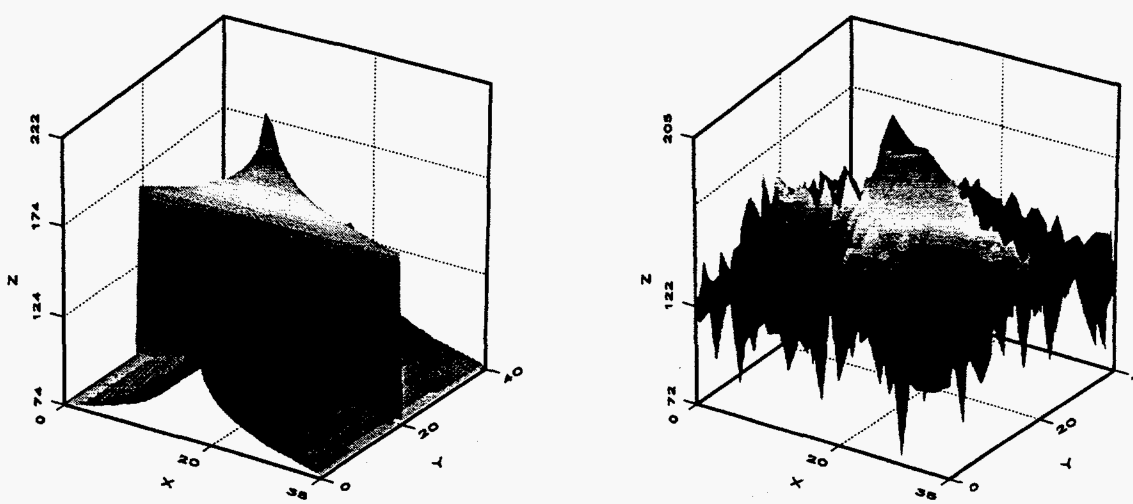
- Events such as surface tufts give rise to a stochastic, textured component in the images of fabrics that coexist with the periodic structure. This plus the presence of local distortions in the fabric [see Fig. 3(a)] directly contribute to the noisy background in low frequencies.
- Noisy background in high frequencies can be attributed in part to perturbations in the sensing process, such as illumination fluctuations and high-frequency mechanical vibrations.
- Deviation of fabric images from perfect periodic structures (as described above), as well as the very operation of discrete Fourier transform on these images, cause a smearing (blurring) effect in the frequency domain, which, in turn, generates loosely localized peaks.

Because of these effects, the local maxima in the 2-D frequency plane are not only difficult to locate automatically, but they may not even correspond to the exact frequencies of the periodic structure.



(a) (b)

Fig. 3. An image of a woven fabric in (a) and its Fourier spectrum in (b).



(a) (b)

Fig. 4. (a) The 3-D representation of a portion of the image in Fig. 2(b) depicting a high-energy, localized peak. (b) The 3-D representation of a portion of the image in Fig. 3(b) depicting a smeared peak with background noise.

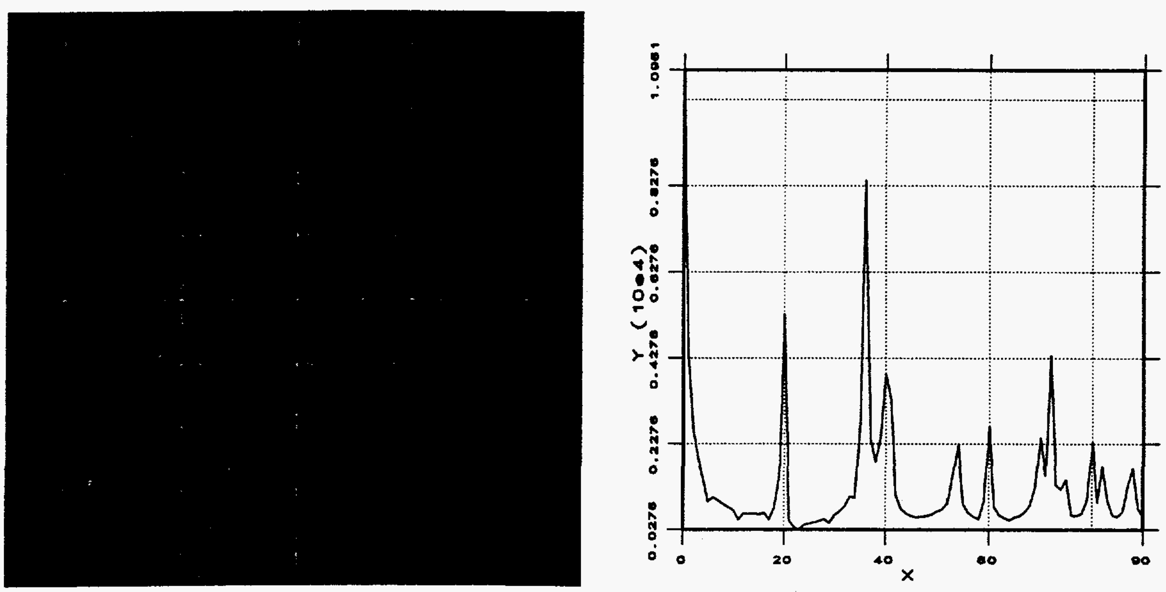
To overcome a number of the aforementioned difficulties, the proposed approach in this work utilizes a conglomeration of points in the 2-D frequency plane, rather than only the local maxima, to characterize the periodic structure of the fabrics. To establish a set of loci for these points, concentric rings, with constant widths, that include various amounts of the image Fourier spectrum are computed [Fig. 5(a)]. The spectrum values within each ring are summed, normalized, and subsequently used to generate a 1-D signature of the underlying Fourier response [Fig. 5(b)]. To guarantee that every point below the Nyquist frequency is included within a ring once and only once, the consecutive rings are computed such that they are perfectly contiguous and nonoverlapping. The latter condition ensures that the responses from the individual rings are decoupled. The local statistics of the generated 1-D signatures, specifically, two most dominant local maxima (not including the one at the origin), are used to monitor the pick and the warp densities of the woven fabric [see Fig. 5(b)]. This approach enjoys a number of desirable properties, such as the following:

- Because of the integration of a conglomeration of points within each ring, the proposed approach is less sensitive to the background noise and to the perturbations in the locations of the peaks' maxima. The width of the rings accommodates for the smearing effect described above but at the cost of lesser accuracy.

- Because of the properties of the Fourier spectrum and the manner in which the 1-D signature is generated, the proposed approach is invariant to camera translation and fabric rotation. More interestingly, because the Fourier transform is not localized, monitoring of yarn density in the presence of small fabric distortions and defects is quite possible.

- Analysis of the 1-D signature is computationally less expensive and technically less challenging than that of the 2-D spectrum.

For an accurate monitoring of yarn density, the proposed approach relies on the image acquisition subsystem, as described in the previous section, to capture high-quality and high-resolution images of the fabric. This means that



(a) (b)

Fig. 5. (a) Two of the rings used to characterize the spectrum of the image in Fig 2(a), and (b) the corresponding 1-D signature. Note that the two most dominant peaks (not including the one at x = 0), which correspond to the inner and the outer rings in (a), respectively, indicate the fundamental spatial frequencies (in x and y directions) of the ideal pattern.

the images acquired for analysis must have high contrast and, for the most part, be free of artifacts due to mechanical vibrations and aliasing. To avoid erroneous results due to aliasing, the fabric is required to be sampled, in both the pick and warp directions, with the spatial sampling frequency that satisfies the sampling theorem.

4. EXPERIMENTAL RESULTS

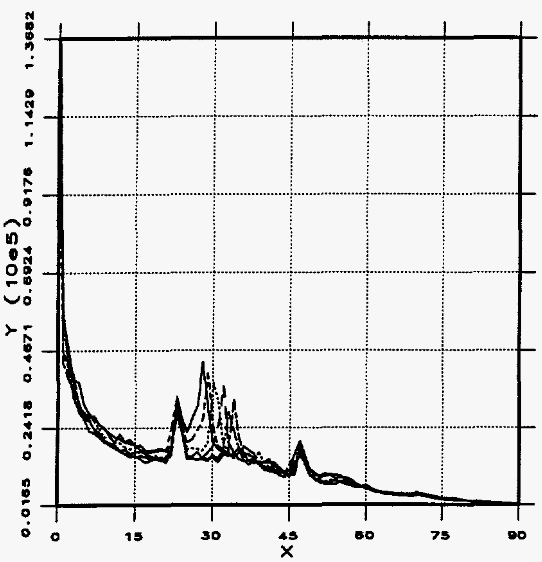
To conduct a proof-of-concept experimentation, seven types of woven fabrics were examined. All fabrics had identical characteristics, that is, same fiber type, yarn count, weave type, etc., but differed in their pick or warp densities. Six of the seven fabrics had the same warp density (78 yarns per inch) but varying pick densities (44, 46, 48, 50, 52, and 54 yarns per inch). The seventh fabric was constructed with a pick density of 52 and a warp density of 73 yarns per inch.

The analysis algorithm, as outlined in the previous section, was applied to the images of the above test fabrics. According to the sampling theorem, to avoid aliasing, the sampling frequency must be greater than two times the pick or the warp densities, whichever is larger. However, to have the ability to *resolve* individual yarns in both the machine and cross directions (a requirement in our case), the sampling frequency should be up to four times greater. For this experiment, the resolutions in the pick and the warp directions were both set to 220 pixels per inch; that is, for resolving individual yarns, the sampling theorem is satisfied in one direction but not the other. The spectrum of each of the acquired images was covered by contiguous, concentric rings with constant width equal to $4\sqrt{2}$. The spectrum points included in each ring were then used to construct the 1-D signature characterizing each of the fabrics.

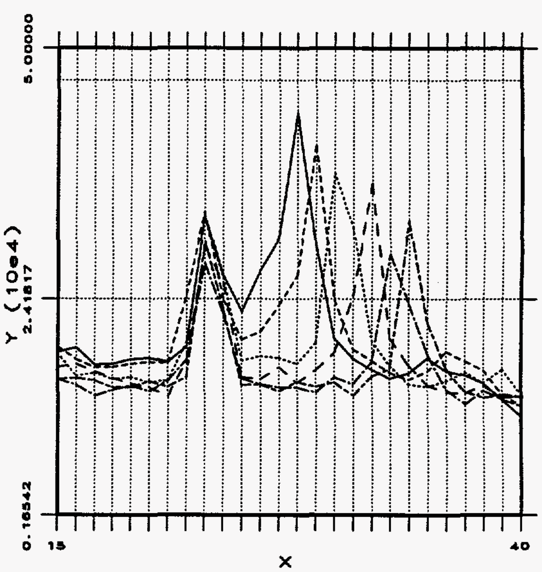
The signatures for the six fabrics with different pick densities, but equal warp density, are shown in the plot of Fig. 6(a). To demonstrate the accuracy of the produced signatures, plots of Figs. 6(b) and 6(c) are zoomed in around the significant peaks of the original signatures. Two events are of interest in the first of these two plots: (1) the first peak, where all six curves reach a local maxima, is believed to exist because of the undersampling of the warp yarns (given that $220 < 4 \times 78$) and (2) the remaining six peaks with their clear separation demonstrate the accuracy of this particular setup of the proposed vision system to monitor the fabric's yarn density with an accuracy of two picks per inch. Obviously, more than any other factor, this accuracy is a function of the resolution of the acquired images, as well as the selected width of the rings. The portion of the signature shown in Fig. 6(c) clearly demonstrates that all six fabrics do indeed have the same warp density. The plots of Fig. 7 demonstrate the accuracy of the proposed system in monitoring the yarn density of woven fabrics with different warp densities.

5. CONCLUDING REMARKS

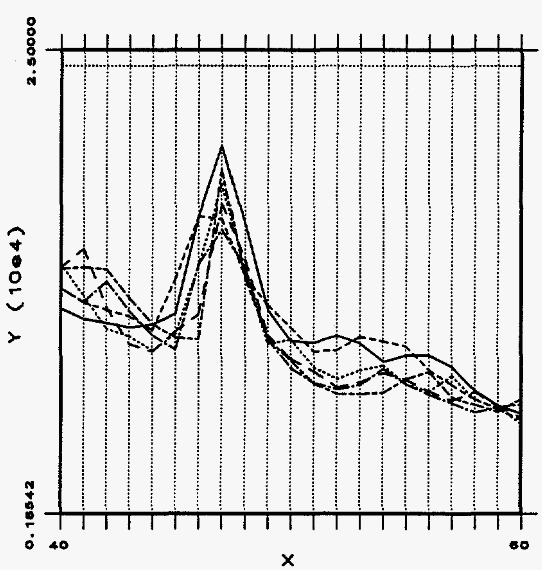
In this paper, we have described a vision-based system that monitors the yarn density of woven fabrics on-line. The proposed system, described in terms of its image acquisition and image analysis subsystems, is demonstrated to accomplish this task efficiently and cost effectively. The image acquisition subsystem, which consists of four major components, was tested on a loom and is shown to possess the ability to acquire high-resolution, vibration-free images of the fabric under construction. The image analysis subsystem consists of an efficient algorithm that was tested on seven fabrics with common properties but varying yarn densities and has shown to be accurate within 2 yarns per inch in either direction. The conditions under which a better accuracy may be achieved have also been discussed.



(a)



(b)



(c)

Fig. 6. (a) The 1-D signatures of six fabrics with the same warp density but different pick densities. (b) The zoomed portion of the plot in (a) from x = 15 to x = 40 that carries the pick frequencies of the fabrics (see text for explanation). (c) The zoomed portion of the plot in (a) from x = 40 to x = 60 that includes the warp frequency of the fabrics.

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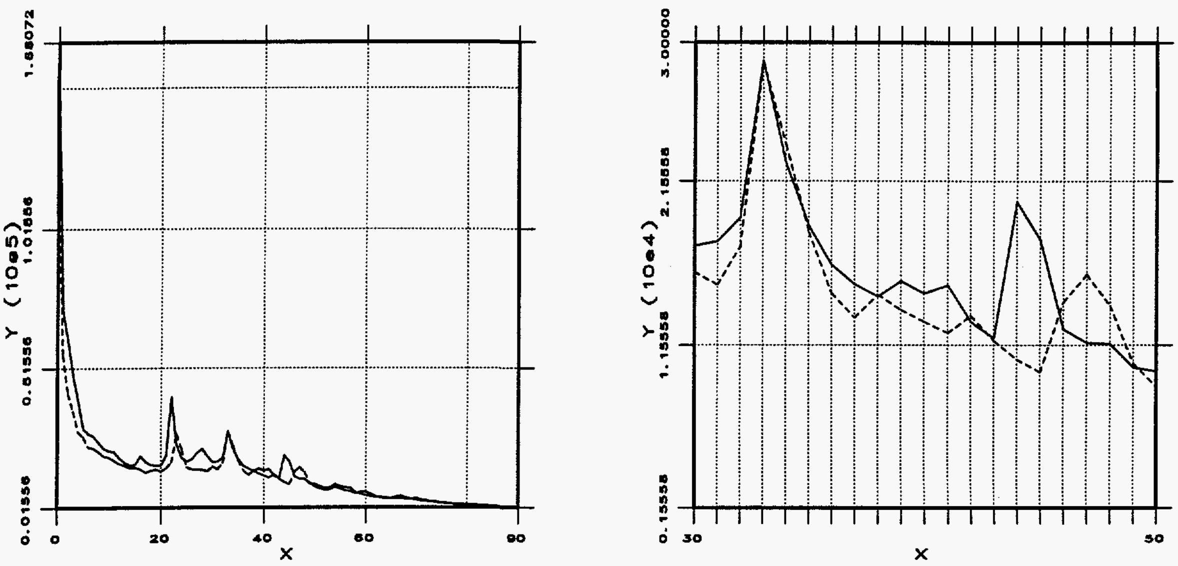

(a) (b)

Fig. 7. (a) The 1-D signatures of two fabrics with the same pick density but different warp densities. Note that the two main peaks between x = 15 and x = 30 are due to the undersampling of the warp yarns. (b) The zoomed portion of the plot in (a) from x = 30 to x = 50 that indicates an equal pick density but distinct warp densities for the two fabrics.

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