Textile laser-optical system for inspecting fabric structure and form

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ABSTRACT

The American textile industry has lost an estimated 400,000 jobs to offshore competitors since 1980. It is predicted they will lose an additional 600,000 jobs by the year 2002. These losses and their resulting economic threat to the U.S. textile industry can be attributed to the low operating costs of their offshore competition. In order to stem these rising losses, the American textile industry entered into an agreement with the U.S. Department of Energy (DOE) in a program called the American Textile Partnership (AMTEX™).

Since the minimum U.S. labor rate is well above that of its offshore competitors, one of the competitive factors the U.S. industry hopes to gain is a higher quality fabric. To facilitate this, a Computer-Aided Fabric Evaluation (CAFE) System has been developed at Oak Ridge National Laboratory (ORNL) and Lockheed Martin Energy Systems, Inc. (LMES).

The system is based on a class 3-a laser and a set of cylindrical lenses allowing for 1-D imaging of single yarns thrown in the fill direction. It has been designed to be located close to the point of fabric formation providing data and information on structure, patterns, and material defects of the fabric as it is being formed.

Keywords: Laser-optics, U.S. textile industry, textile inspection, 1-D image fabric reconstruction, automated defect detection, pick measurement device, real-time defect classification

1. INTRODUCTION

The need for inspecting all textile materials is derived from the fact that the end user must be kept from receiving goods that might be structurally or optically flawed. Typically, the inspection process relies strictly on the human eye and hand and is done after the fabric formation process. This presents several inherent problems. One is the expense of manual inspection, which is essentially a nonvalue-added activity. Two, human inspectors make mistakes, occasionally allowing off-quality products to pass through the system. Three, human inspectors fatigue over time allowing a higher percentage of off-quality products to pass through. Lastly, with present inspection methods (off-line) there is the potential for thousands of yards of off-quality products to be made before the problem is recognized. Therefore, there is a need to automate and improve the textile industry's inspection process to provide 100% reliable inspection. This inspection includes detection and classification of fabric anomalies, automatic defect marking (both mechanically and electronically), feed-forward quality information to the end supplier, feedback data to the manufacturing process, and optimized cutting schemes for increased fabric yield.

The CAFE Automated Pick Measurement Device (PMD) system integrates directly into the loom close to the point of fabric formation for the purpose of inspecting fabric and generating a defect map when an anomaly is found. It is developed around a modular, open hardware and software architecture to provide the best migration path for future growth. This approach will provide the best cost schedule for deploying the system. The system is sensitive to the existing textile manufacturing infrastructure allowing the baseline system to be used in many textile and/or finishing plants. A scale of economy has been applied to the build of the system as it has gone through the development cycle to ensure an appropriate return on investment. This has been accomplished through the development of an economic model.

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2. SYSTEM OVERVIEW

In the weaving of fabric, one of the critical specifications is the number of filling yarns per inch (pick density). Cost to supply fabric increases significantly as the pick density increases. This critical parameter is often measured manually to assure that the specified pick density is being achieved. It is necessary to allow some margin of error so that significant quantities of "out of spec" cloth are not produced. This margin of error must be balanced against the risk of having to sell the cloth as a second if it does not meet the pick density specification.

The on-line pick density allows a loom to be adjusted either manually or automatically to maintain closer pick density tolerances and thus, save considerable money. Since pick density changes from the formation of the fabric to the take-up roll, the system has been designed to allow placement either off-line (take-up roll) or on-line. Figure 1 shows the system mounted on an operational loom in one of the plants where operational tests were conducted. As seen, the system is mounted on the vertical plane of the loom between the point of fabric formation and before lay-up on the take-up roll. A fabric length determination obtained by the PMD allows the use of the device as a replacement for length encoders. The device has no moving wheel to slip and provides excellent accuracy (±0.1% over a roll of cloth).

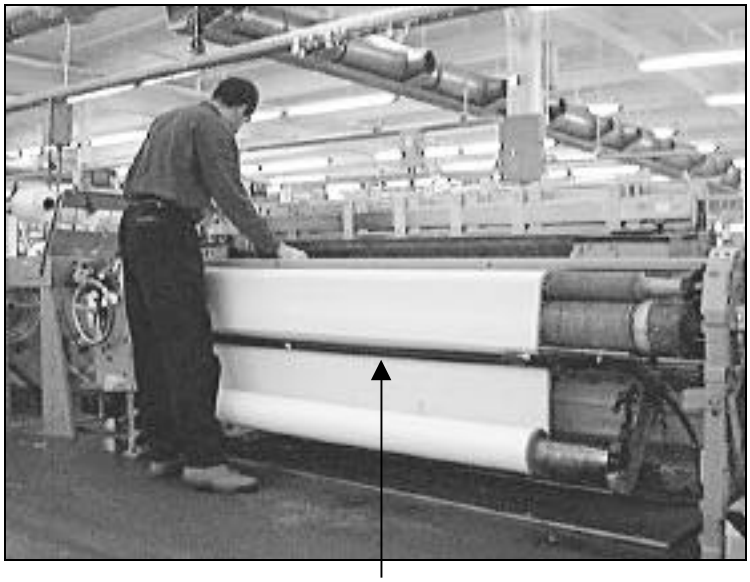

Figure 1. Automated PMD mounted on the vertical plane of an operational loom between the point of fabric formation and take-up roll.

The key to the cost effectiveness of this device is in its use of dedicated electronics rather than high-resolution video imaging with high-speed processing. Pick density, pick count, fabric length, and fabric velocity are all obtained by the PMD. An uncollimated class 3a, 5 mW laser diode is used to illuminate the fabric. An image of the cloth over the detector's window is focused onto a linear diode array by a pair of spherical lenses. A cylindrical lens just before the linear diode array is used to de-focus warp yarn so they do not cause interference. Spatial information provided by the array enables the determination of pick density. Pick count and pick rate are determined using output from a pair of pixels near the center of the array. Fabric position and velocity are calculated indirectly using the measured parameters above. A microcontroller provides the processing power to analyze incoming data and output a feature vector for use over a network. The microcontroller also supports a small local terminal for interfacing with operators locally. Figure 2 provides a schematic overview of the PMD's functional capabilities. Figure 3 shows the user's interface capability as configured for network use.

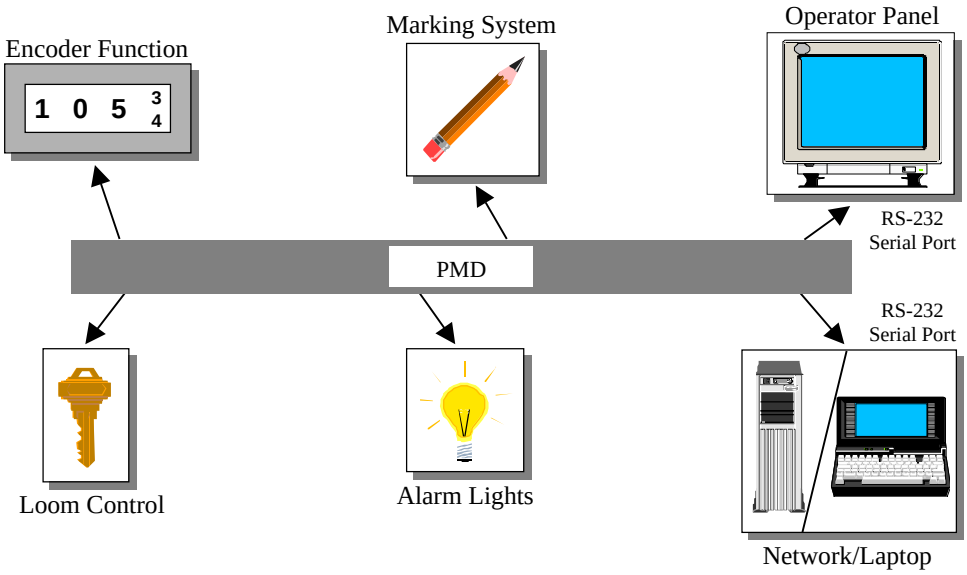

Figure 2. Schematic representation of PMD's functional capabilities that include alarms, input/output to a marking system, encoding function, loom control, networking, and user's interface.

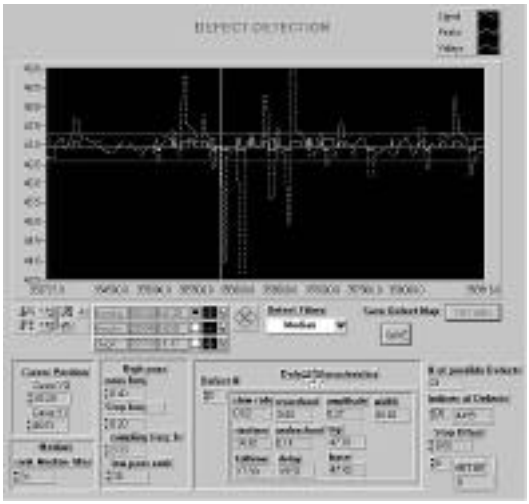

Figure 3. PMD's network configured user's interface for operator display of defects and process statistical information.

3. THEORY OF OPERATION

3.1. Optics

As mentioned above, this cost-effective method of obtaining pick density, pick count, fabric length, and fabric velocity uses a linear diode array to detect picks as they are imaged on the array face. A pair of spherical, achromatic lenses focuses the image on the detector. To prevent interference from warp yarns, a cylindrical lens is used to de-focus warp yarn.

3.2. Analog Front-end Electronics

The image on the array appears as a set of parallel lines, each representing one pick. A series of analog voltages are clocked out of the array, each of which is proportional to the light intensity on a specific array pixel. Figure 4 shows this series of analog voltage levels in a single scan of the array, called analog output (AO), as they are clocked out. In the case of front-lit fabric (fabric lit from the same side as the detector), each maximum represents a pick. As a side note, the PMD has been operated in both front-lit and back-lit modes.

Output from the linear diode array is processed by electronics housed in a 2.0 inch (outside diameter) black anodized tube. The series of analog voltage levels shown in Figure 4 are converted to a discrete binary pulse string, DO, using a couple of filters and a comparator. The first of the two filters is a fourth-order, smoothing filter used to remove transition spikes between voltage levels in AO. This filter also serves to minimize the effect of pixel-to-pixel variation errors in the array. The cut frequency of this filter is adjusted so that the amplitude of AO is not significantly decreased. A second filter, called a "bias" filter, has a lower cut frequency that provides additional filtering and phase shift to the smoothed signal. By comparing the outputs of these two filters, a discrete series of voltage levels is produced. The bias filter is adjusted to obtain enough phase lag and signal attenuation to reliably give a high pulse for each pick on the cloth.

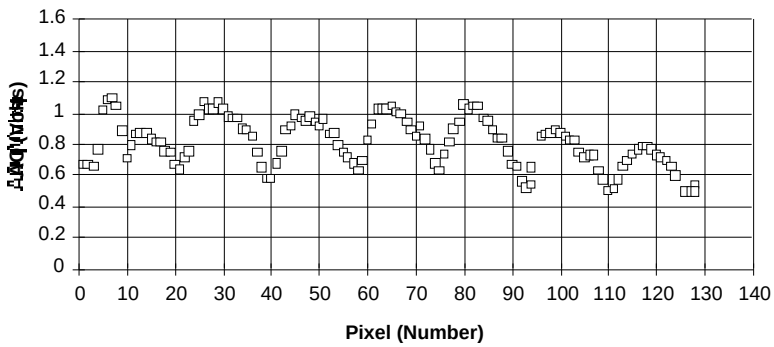

Figure 4. Serial AO voltage levels representing individual picks as seen by the array.

Converting the array's analog signal to a binary pulse string is the key to making an inexpensive detector. Expensive vision systems also have higher quality arrays and optics, adding cost. Additionally, expensive analog to digital converters and high-speed processing capability must be used to store and process analog information coming at rapid rates. The pick density detector rapidly processes the discrete information using digital logic at a fraction of the cost of vision systems. The next section describes how the system calculates pick density, pick count, fabric length, and fabric velocity from the discrete DO signal.

3.3. Pick Density Calculations

After determining the magnification constant M (which is identified in the Installation and Hardware Setup Manual) the pick density, ρ, can be calculated as follows:

$$\rho = \frac{n_{picks} \cdot 400 \cdot M}{n_{pixels}} \tag{1}$$

where n_{picks} is the number of whole picks used for the calculation, n_{pixels} is the number of pixels over which these picks fall, and 400 is the number of pixels per inch on the array. n_{picks} is determined as the number of whole picks imaged on the array between the 25th and the 128th pixels. The first 24 pixels are disregarded to allow the filters time to charge. The 129th clock cycle is for initialization of the array and does not represent a valid pixel element. Therefore, the portion of the array used in the calculation begins on the first negative going transition of DO after the 24th pixel and ends on the last negative going transition before the 129th pixel. n_{picks} and n_{pixels} are accumulated over 256 scans in counters before being transferred to the microcontroller for computation of the pick density. This allows time for the microcontroller to make the calculation without

slowing down scans of the array. Each scan of the array occurs every 688 µs. The microcontroller outputs values serially every 0.176 seconds.

Only a small portion of the cloth is imaged on the detector. Typically, this length is on the order of 0.10 inches. Because pick density changes significantly from one 0.10 inch section of cloth to another, it is necessary to filter the measurement to reduce noise. The detector uses a variable length boxcar filter to perform this filtering. To allow this filter to be adjustable, a selectable number of density measurements, RF, obtained every 0.176 seconds are averaged before filling one box of the filter. The effective length of fabric over which the pick density is averaged, L_{bc}, can be calculated as:

$$L_{bc} = (3.5s)(RF)(\nu_f), \tag{2}$$

where ν_f is the typical fabric velocity.

Determination of changes in density over a small length of cloth can be useful in determining defects in the cloth. Therefore, a delta density value, $\Delta\rho$, is reported which is the difference between consecutive density values obtained before the boxcar filter is applied. Density values used in this calculation are called instantaneous density values and have a time resolution of 0.176 seconds.

3.4. Pick Count and Fabric Calculations

Once the pick density is known, a length of cloth can be obtained by counting picks after a user specified point in time. Each pick is counted as it passes the center section of the array. The system adds picks as they pass in the forward direction and subtracts them if vibration or the weaving process causes the pick to temporarily back up.

To count picks, the state of the binary pick signal, DO, is stored in a latch when the 64th pixel is clocked out of the array. This location is the center of the array where the illumination of the cloth is best. Also, the state of DO as the 64 + nth pixel is clocked out of the array is stored in a latch. Outputs from these two latches are updated each time the linear diode array is scanned (688 µs). A constant, n, is chosen so that the two signals will be separated by 1/4 of a pick as the cloth is imaged on the array. This places the two signals in a quadrature relationship. The appropriate value of n can be calculated as:

$$n = \frac{100 \cdot M}{\rho_{typ}} \tag{3}$$

where ρ_{typ} is the typical pick density for the fabric being inspected. It is not critical that n be exact, however, this value should not be off more than ± 50%. Tolerance to errors in n is somewhat dependent on the type of cloth being inspected and therefore some investigation into its values is appropriate.

The quadrature signals from the pair of latches are input to a phase detector circuit. This circuit has an output that produces four short pulses for every pick that travels past the center area of the array and a second line to indicate the direction. The factor of four, which is introduced by the phase detector, comes from the fact that the detector produces a pulse when either of the quadrature signals switch state.

It is possible to have the forward direction of the cloth change in differing installations of the device. To accommodate this possibility, a command can be issued from the user's panel or via a network command to change the count direction. The current state of this variable is reported in the status word of each feature vector.

A read line generated by the field programmable gate array (FPGA) lets the microcontroller know when to initiate a new read cycle of the current on-line counters. The microcontroller responds by telling the FPGA which counter data to present on an eight-bit data bus via a control line.

The FPGA counters collect 256 scans of the array before requiring a read by the microcontroller. This scheme allows the microcontroller time to make necessary calculations on the data without limiting the speed at which the array is scanned. Since the array is scanned every 688 µs, the counter is read every 0.176 seconds. Having a high array scan rate is important if the effects of vibration on the measurement are to be eliminated.

Once the microcontroller has collected the pick count, c_{picks}, the cloth length, l_{fabric}, is calculated as:

$$l_{fabric} = \frac{c_{picks}}{\rho}. \tag{4}$$

The fabric velocity, v_{fabric}, is also determined using the output from the pick counters. Values of c_{picks} from the pick counter is accumulated by the microcontroller for a length of time designated as, t_{gate}. This time is currently fixed at two minutes in software. If the count summed over the gated interval is designated as c_{gate}, the pick velocity can be determined as:

$$v_{fabric} = \frac{c_{gate}}{t_{gate} \cdot \rho} \tag{5}$$

where ρ is the output of the boxcar filter when c_{gate} is obtained. Because the velocity measurement does not have a boxcar filter, the velocity values are updated on the measured time interval (t_{gate}).

It should be noted again that since c_{picks} is a factor of four too large, fabric length and fabric velocity are also a factor of four too large. These values are scaled appropriately before outputting data.

3.5. Laser Power Control

To maintain good signal amplitude, a circuit is provided to keep the laser diode at near maximum power without saturating the AO. A peak detector circuit captures and holds the maximum voltage of any pixel during a scan. A circuit is provided which gradually allows this maximum pixel measurement to bleed off for capture of future maxima. The setpoint on this loop can be adjusted using a command entered through the user's panel or via a network command.

3.6. Interlock Systems

The prototype pick density measurement device uses a class 3a (5 mW, 670 nm) laser diode without collimation for the light source. This source diverges at 8° and 30° on the two cross sectional axis of its beam. Beam divergence provides a first level of protection since one would have to be close to the source to sustain eye damage.

A safety system is also provided to prevent operations when the fabric is removed from the device. The fabric diffuses the beam as an additional level of protection. The interlock system has two subsystems. The first subsystem requires that the maximum pixel intensity described in the previous section be greater than a preset setpoint. In the event that a bright light is shining in the window that is great enough to keep the interlock from tripping, a second safety subsystem is provided. This subsystem requires that picks be detected by the discrete circuitry. If picks are not observed, the second subsystem will cut the laser power off within 1.8 ms.

3.7. Network Interface Port

The microcontroller unit (MCU) commands and responses are transmitted through the network interface port that is RS232 compatible. The MCU supports synchronous and asynchronous transmission modes. Synchronous data transmission is performed in response to a host command. Synchronous transmissions are sent immediately following a valid command. Asynchronous transmissions are performed at times established by the current configuration. Asynchronous transmissions will only occur when the MCU is in the "on-line" mode.

The MCU firmware structure is an event loop that processes messages from a queue. To handle asynchronous events and exceptions, three interrupt service routines are provided. The Serial Communications Interface interrupt is used to manage the host interface port. The Interrupt Request routine services the external READ exception. The Real Time Clock interrupt is used to handle periodic time-based tasks.

4. PMD PERFORMANCE EVALUATION

Laboratory and operational tests were conducted over a two-year period to verify the PMD's ability to meet the functional and operational requirements established for the system. These requirements, along with a cost profile, are identified in the PMD Functional Description and Requirements Document (FD/RD), the CAFE Architecture Document, and the CAFE Economic Model. The protocols for all laboratory and field tests were developed around the specifications outlined in these documents with the FD/RD serving as the guiding principle for all activities.

The importance of the FD/RD is due to the performance measures and characteristics defined within it. These metrics are applied to those process parameters that are either directly measured or inferred and are defined in terms of measurement, operations, and accuracy. The parameters are listed below.

Pick Count: Cumulative total of the number of picks or filling yarns contained within the fabric (picks).

Pick Density: Quantification of the average number of picks or filling yarns per inch of cloth (picks/inch).

Delta Density: Calculation of the instantaneous variation in pick density measurements (+/- picks/inch).

Fabric Velocity: Calculation of the rate of fabric production (yards/min).

Defect Inference: Defects caused by variances in individual yarn structure and/or changes in fabric structure.

Table 1 identifies the metrics associated with the operations of the system.

Table 1. Performance measures for the PMD.

Parameter	Accuracy/Performance
Pick Count	+/- 0.15% of total
Pick Density	+/- 0.10 picks/inch
Speed Range	$200_{min}/1500_{max}$ picks/min

The complete series of PMD tests were conducted at ORNL/LMES laboratories, in the field at industry partners' facilities, and at the ORNL Web Test Bed, a facility dedicated specifically to image processing research. These tests began with the researchers deploying the unit on a project loom and concluded with the field tests conducted solely by facilities personnel. The device was tested on air jet, water jet, and rapier-type looms in operational settings.

4.1. System parameter performance measures

Figures 5 and 6 show results from tests conducted at one of the facilities where the extended operational field tests were held.

4.1.1. Pick density

Figure 5 is a plot of density error and cumulative density error over a 40-day period. The test protocol was to have the plant operator set a single calibration on the unit and run for 40 days with minimum operator intervention, except for physical adjustments of the device during loom setup. As seen, over the 40-day period the PMD was within the error budget allocated in the FD/RD (</= 0.10 picks/inch). The cumulative error exceeded the measures of performance (MOP) set by the FD/RD. From an operational perspective, this does not present a problem since during that 40-day period several fabric rolls were made and removed from the loom.

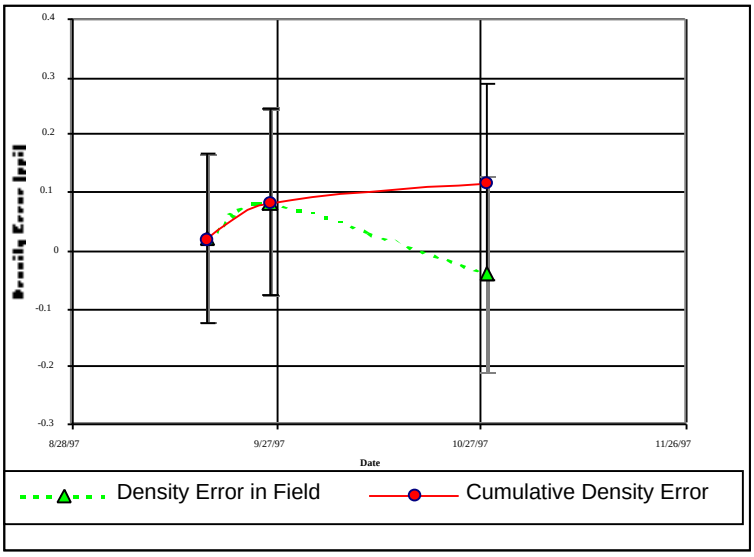

Figure 5. Pick density test conducted over a 40-day period. Results show that the PMD met the FD/RD requirement of <0.10 picks/inch error.

4.1.2. Pick count

Figure 6 shows the results from a two-day total pick count test conducted at the same facility where the pick density test was held. The graph is a plot of Pick Count Error (Percent and Total) vs. Loom Pick Count. Pick Count Error is the difference between the PMD's count and the pick counter on the loom. As seen over the two-day test, the PMD had an error of 354 picks out of 870000 picks—an error of 0.04% well within the MOP set by the FD/RD (0.2%).

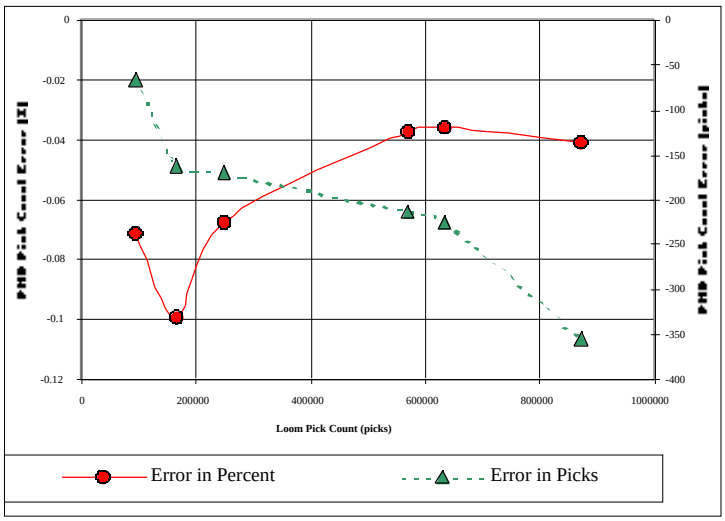

Figure 6. Pick density total pick count test – Pick Count Error (Percent and Total Picks) vs. Loom Count. Only 354 picks total error out of 870000 picks thrown.

4.2. Defect Detection Performance Measures

The PMD has the capability to detect fabric defects in one of two ways. It can either infer the defects from the measured/calculated pick density value or extract it directly from the 1-D image captured by the linear diode array. Figure 7 shows a block diagram of this relationship with Figures 8 and 9 showing defect detection being accomplished through the pick density variable or the 1-D image, respectively. From a process standpoint, the 1-D image defect detection and classification scheme is far superior to the pick density measurement in that it will have the greatest sensitivity to yarn/fabric variation while not being impacted by process setup. Additional benefits derived from the ability to image the cloth is that patterns can be quantified and then used as a template to check for consistency in the fabric form and that filament diameter variations (>30%) can also be seen.

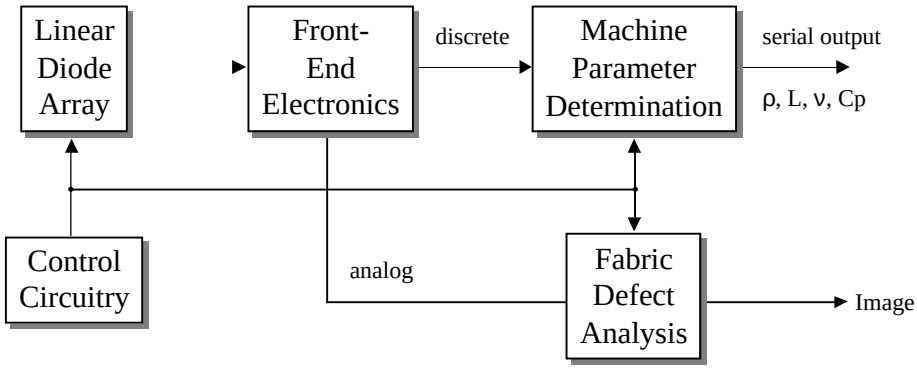

Figure 7. Pick density sensor and related analysis function block diagram showing defect detection capability streams – pick density variable (machine parameter determination) and 1-D image (fabric defect analysis).

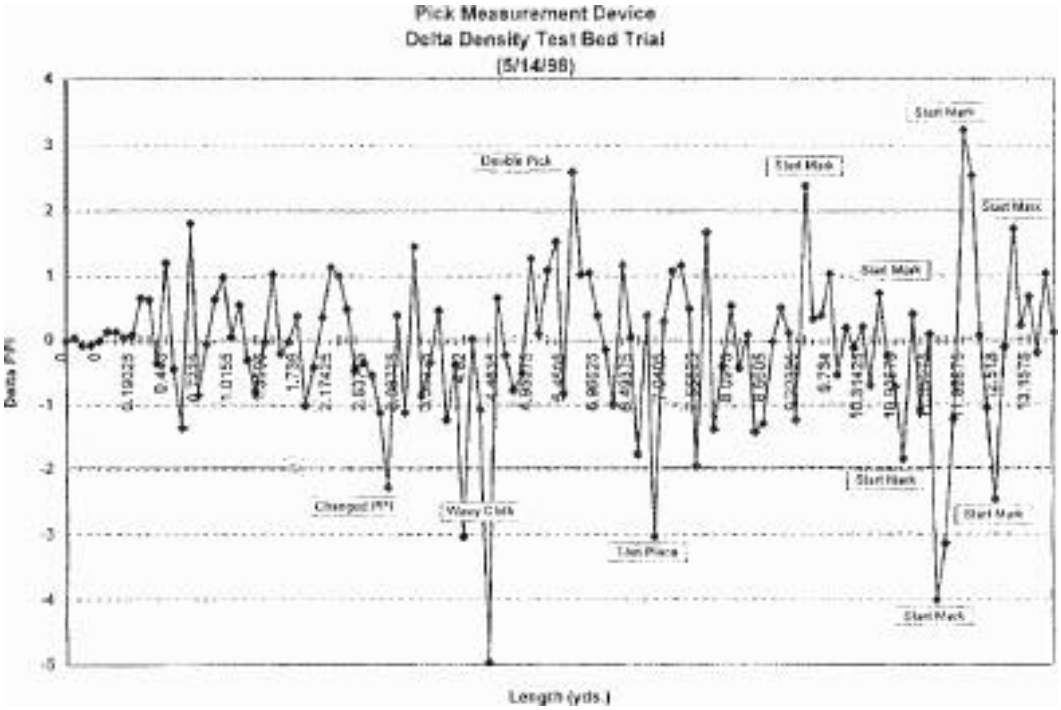

Figure 8. PMD Delta Density test bed trial highlighting the device's capability to see fabric defects based on the pick density profiles. Defects shown include double pick, wavy cloth, thin place, start mark, and changed pick (different structure).

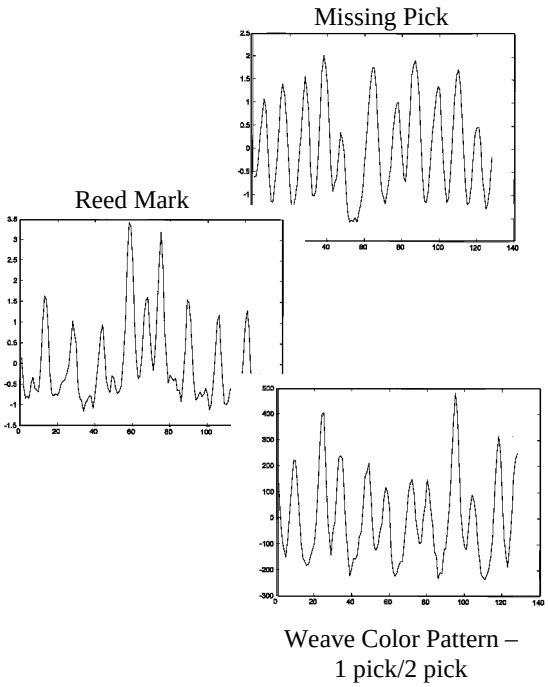

Figure 9. 1-D images extracted from linear diode showing vertically running fabric structure and ability to image defects such as missing picks and reed marks and the ability to image patterns in fabric such as a 1 pick/2picks, etc.

5. CONCLUSION

The Automated PMD has met or exceeded all functional requirements established by the CAFE industry partners. It has been tested extensively over a two-year period with little or no intervention from the laboratory developers. During this time the system has suffered no degradation due to environmental influences or operator misuse.

Tests on the system have included total pick counts, pick density measurements, fabric velocity, encoder counts, and defect detection capabilities. During the tests, a virtual presence was established using phone lines and networking links. The system has a projected cost between $1,200 and $2,200.