

A MECHATRONIC APPROACH FOR AUTOMATIC INSPECTION OF DEFORMABLE WEBS

Umer Farooq[†], Prof. Tim King[‡], Prof. P H Gaskell[§], Dr. N Kapur[±]

University of Leeds, School of Mechanical Engineering, Leeds, LS2 9JT,
United Kingdom.

email: [†] texuf@leeds.ac.uk, [‡] t.king@leeds.ac.uk
[§] p.h.gaskell@leeds.ac.uk, [±] nik@efm.leeds.ac.uk

Abstract

The ever-increasing cost of labour in the textile industries coupled with rapid advances in technology has resulted in the automation of most sections in the present textile manufacturing industry. The recent addition to the automation drive, mostly in the last decade, has been substantial research in applying machine vision tools to replace humans for tasks such as inspection, textile characterisation and apparel manufacturing. This paper investigates a novel approach for automatic inspection of deformable textile webs, particularly lace fabrics, in real time. The authors have worked on an incremental approach using a multi Digital Signal Processor (DSP) system to achieve the required task at a reasonably high speed with minimum false alarms. A direct comparison of the live image with a perfect prototype in real time is found to be the most adaptable solution to the problem.

1 Introduction

Lace, used in ladies' garments, decorative textiles, curtains etc., is a high value fabric and is mass produced in wide rolls. In order to achieve high productivity, apparel lace is knitted in lengths of 100 m or more, with a pattern running the full length of the web and repeating at intervals across its width. The manufacture of Raschel* lace is a capital and labour intensive process which consists of several operations including; warping, knitting, dyeing, stentering, checking, scalloping, inspection and spooling [King, 1995].

Yazdi and King [Yazdi, 1998] categorized the lace faults into two broad classes, namely: (i) geometric defects; (ii) random and isolated defects. Geometric defects encompass variation in scale, stretch, skew and combinations of all these. These distortions are the direct result of various forces acting on the lace during different manufacturing processes. Random and isolated defects, like holes, missed stitches, cut purls etc are the result of wrong calibration and/or malfunctioning of different machines in the production line. Figure 1 shows some of the lace defects.

Automatic inspection of lace is particularly challenging because of the very nature of the knitted lace fabric – characterized by its high stretchability, low weight per unit area, low dimensional stability and unlimited design possibilities.

* A specialized type of warp knitting machine extensively used in lace production.

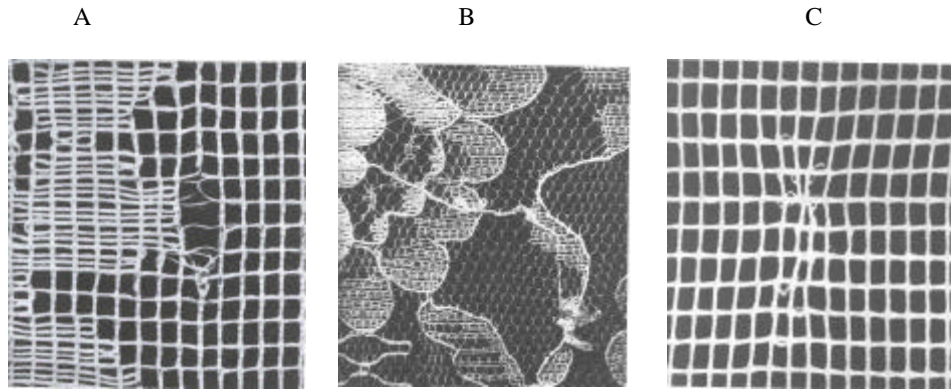


Figure 1. (A) Breakdown of the fabric structure – a hole, (B) incorrect laying of pattern thread, (C) split filaments distorting the ground structure [Wheatley, 1972].

The many design possibilities and the open structure of the lace make it almost impossible to apply global techniques of image processing, such as thresholding, Fourier transform based spectrum analysis, edge detection etc. on their own to trace the defects. Therefore techniques applied for automatic fault detection in woven fabrics, where the fabric texture is mostly uniform except in Jacquard fabrics, [Jasper, 1995], [Xu,1996], [Goswami, 2000], [Conci, 2000], are ruled out. The only effective method to handle virtually any design, as perceived by early researchers, seems to be a direct comparison with a perfect reference image. However, the repeats in lace fabric are never identical. This is due to the openness of the structure of lace fabric making small distortions unavoidable, moreover, the fabric comprises fine and complex yarn structures, which are easily deformed and have a high degree of ‘natural variability’. A sensitive, direct comparison method, such as the one employed with automated inspection of printed circuit boards, will therefore be prone to unacceptable false alarms. The situation is further aggravated because we are aiming for a high speed final inspection station and at this stage the lace fabric is not under constant stretch conditions as in on-line inspection on the knitting machine. A proper ‘conditioning’ of the image to be inspected, in real time, is therefore essential before any attempts are made to compare it with the reference image. These requirements demand a huge amount of image data to be processed in real-time.

Work on automating the inspection of Lace, using machine vision, began as early as 1988 when Norton Wayne et al. [Norton-Wayne, 1991, 1995] started working on a project supported by British Lace Federation. They came up with a solution, using direct comparison of the live image with a perfect prototype and their idea has been developed by Shelton Vision Ltd. However their system does not take the normal lace distortions into account and is therefore only suitable for finding defects on the lace knitting machine where the lace is under controlled tension and advances slowly (3mm per second) giving more processing time. Yazdi and King [Yazdi, 1998] later worked on automating the final inspection stage of lace manufacturing, which demands higher processing speed and process flexibility in terms of different distortions in the lace. They managed to show a system detecting obvious faults, but the speed was low – an inspection rate of only 50 mm per second was reported.

2 Our Approach

We are working on an incremental approach using a multi DSP system to achieve the required task at a reasonably high speed and with a minimum of false alarms. The image is acquired by a monochrome line-scan CCD camera whilst the lace is transported over a back lit stage. The live image is compared with a reference image of a single pattern repeat, stored in memory. A 2-D cross-correlation technique is first used to determine the starting position. Once the start point has been determined and the live image is in synchronisation with the reference image, each line in the live image is matched to the corresponding line in the reference image by a more computationally efficient tracking technique. During this matching the system determines if the live image lines are skewing, drifting apart (longitudinal scale errors) or stretching (lateral scale errors). The system performs necessary corrections to compensate for any such distortions continuously in real-time using a combination of hardware and software approaches, thus presenting a 'conditioned' live image for the actual fault detection.

The 'conditioned' live image lines are then subtracted from their corresponding reference image lines. The resulting image contains the random or isolated faults along with noise or a 'ghost image', which is inevitable due to the fact that individual threads in lace are not always in the same place, as well as because of any residual skew or stretch which might remain from the 'conditioning' process. Hence it is necessary to apply further processing to the subtracted image in order to isolate the actual faults. Once a fault is detected the system will record its position and physically tag it if required. The sequence of synthesized images in Figure 2 show the principle involved.

2.1 Image Acquisition

Image acquisition and illumination of the subject is one of the most important elements in any machine vision system. A monochrome line scan camera has been selected for this work. Monochrome, because most of the lace produced is monochromatic and the faults to be investigated are based on the structure of the lace rather than its colour. The localised dyeing faults in garment lace are not as critical as for normal woven or knitted fabrics, mainly because of the narrow width of the lace and its open structure, which make it difficult for the eye to detect these faults. A line scan camera was the obvious choice considering its speed, high resolution and other benefits described elsewhere [Finney, 2001].

Both back lit and front lit illuminations are suitable for the application. Back lighting has been selected with a view that the system will be looking at the lace structure and not its 'true surface'. Back lighting is also suitable for binary images which are intended to be used in this work in order to minimise the amount of data processing. Back lighting requires a transparent stage for mounting the lace. For experimental ease a cylinder made up of transparent plastic is used for this purpose. Later on a glass plate over which the lace can continuously move forward will replace it.

2.2 Architecture of the Experimental Rig

As the aim is high inspection speeds in the region of one metre per second, powerful signal processing hardware is needed. If a line resolution of five lines per mm is assumed and a line scan camera with a 2048 pixel sensor is employed then a pixel clock rate in excess of 10MHz (5000 lines per meter x 2048) would be needed. Clearly, processing at such a rate is a difficult task and needs either a very high specification single processor or parallel processing techniques. To start with, the project is being implemented in a parallel processing environment.

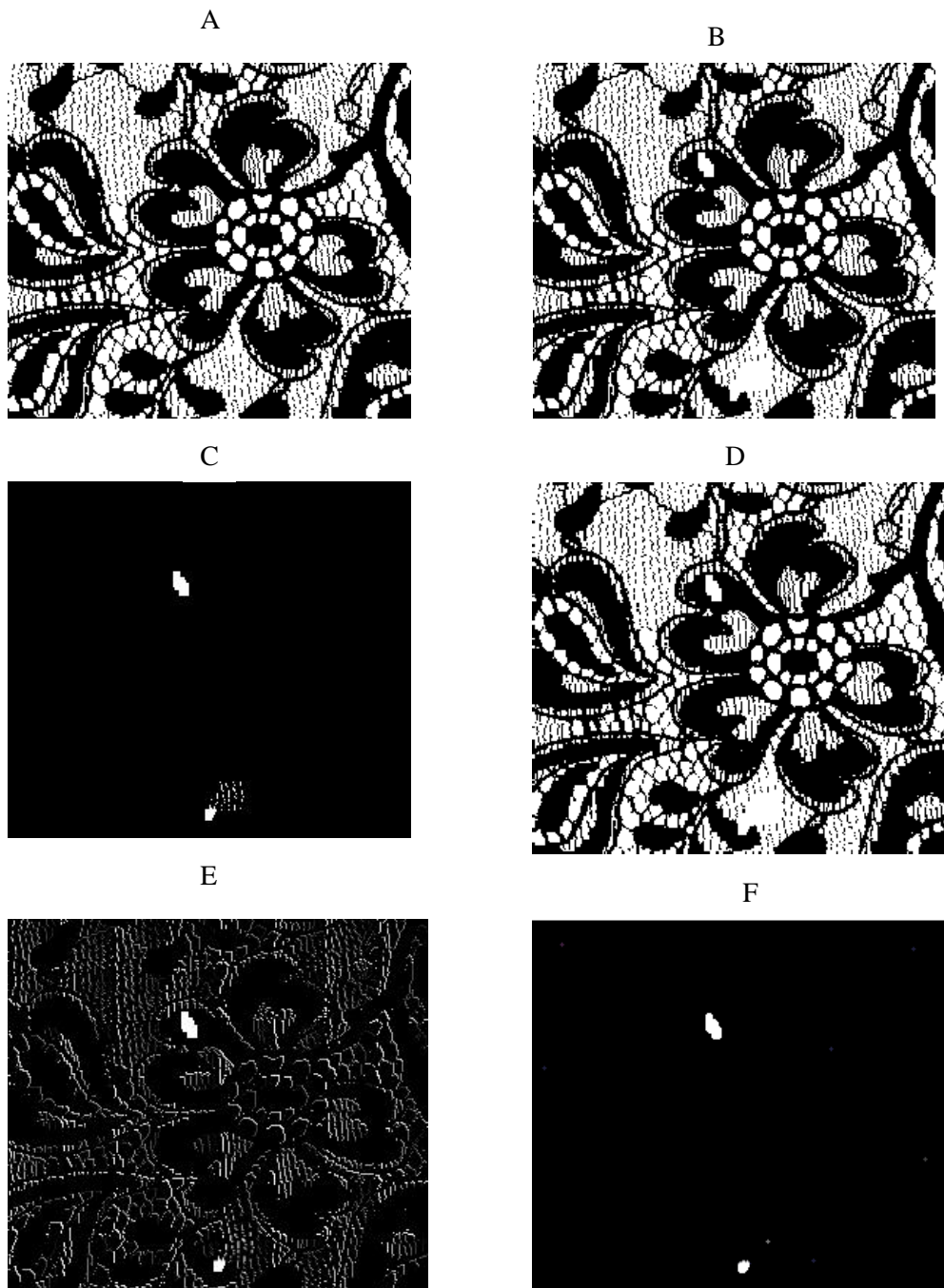


Figure 2. (A) The reference image, (B) Actual image with no distortion, perfectly aligned with the reference image, (C) the result of subtracting B from A, the faults are clearly visible, (D) Actual image stretched by 3% in both directions, (E) the result of subtracting D from A, the 'ghost image' or noise clearly seen along with potential faults, (F) Application of morphological erosion with a 'disk' of 1 pixel radius. The noise disappears leaving behind the actual locations of faults.

Figure 3 show the architecture of the experimental rig developed for this work. The lace is mounted on the transparent drum and illuminated from below. An angular optical encoder is provided to keep track of lace movement. The lace drum can be rotated at different speeds by means of a stepper motor. A DALSA CL-C3 2048 element line scan digital CCD camera is used to image the lace. Image capture and initial image processing is accomplished using a Coreco Oculus-F/64 board incorporating a TMS320C40 Digital Signal Processor. Further processing is then implemented on a Loughborough Sound Images (LSI) processor board with four TMS320C44 DSPs. A PC communicates with the DSPs through shared memory and provides the human interface necessary to operate and program the system. A separate monitor is connected to the Oculus F/64 to display the images acquired by the camera. Two multipurpose interface boards are also provided.

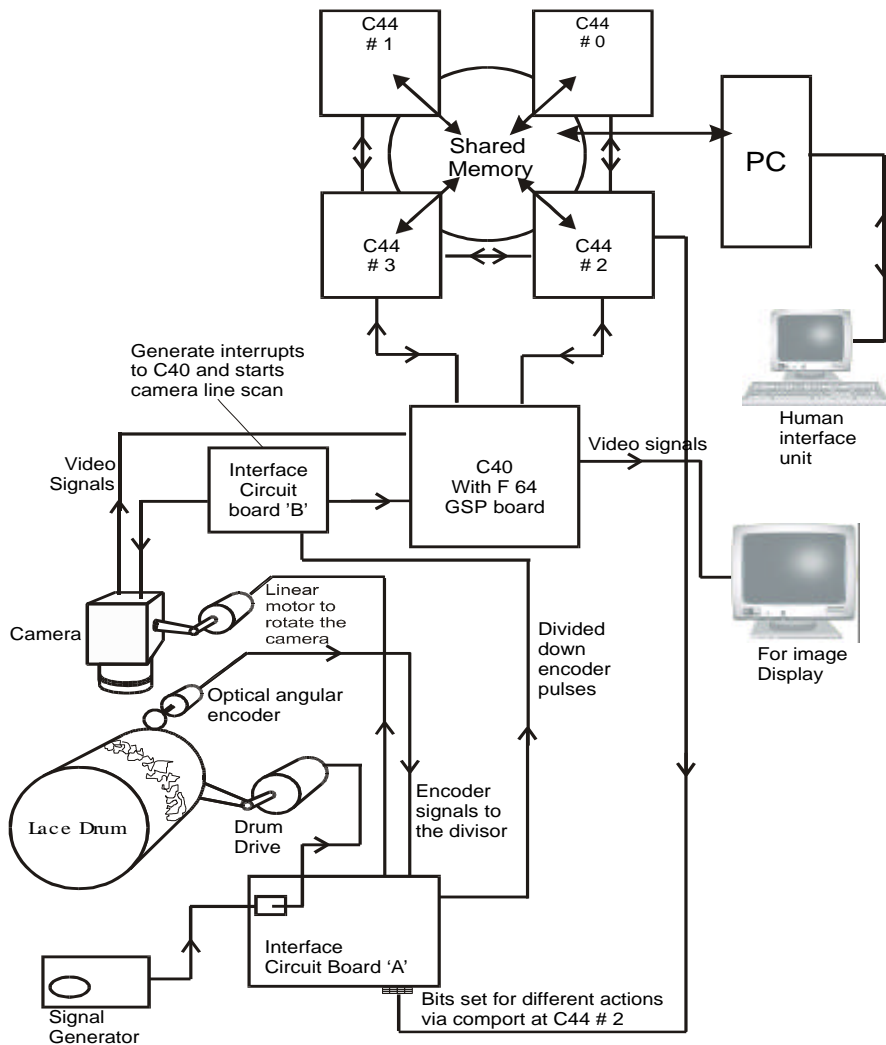


Figure 3. The Architecture of the Experimental Rig.

The Coreco Oculus-F/64 board can capture up to 30,000 lines per sec, which is more than adequate for our application. The board incorporates a TMS340C20 Graphic Signal Processor (GSP) for line acquisition and image display functions and a TMS320C40

DSP (C40 for short) for general data processing. Both processors can share the same frame buffer. The C40 incorporates six communication ports for interfacing to the outside world and / or other C40 family processors.

The multi-DSP LSI board is a general purpose digital signal processing platform containing four TMS320C44 processors (C44s) interconnected in ring topology. The C44 DSP is very similar to the C40 except that it has only four communication ports (comports for short). C40 and C44 devices are 32 bit floating point DSPs.

3 Working of the Rig – Key Algorithms and their Results

Accurate image registering with a line scan camera requires precise control of the movement of the lace under the sensor. This is achieved by rotating the lace drum at a desired speed controlled by a signal generator. The optical angular encoder generates a specific number of pulses for a certain drum movement. The encoder pulses are used to control the clock pulse of the camera and also to generate external interrupts to the DSP C40 to register each new image line. These external interrupts for each line help in keeping track of the memory location of the line in the Video RAM of the Coreco Oculus-F64 board.

The Coreco Oculus F/64 board's GSP and C40 DSP play an important role, not only in capturing and displaying the lace image but also in doing some initial image processing and coordinating with both C44#2 and C44#3 processors for subsequent processing.

The first step, towards inspection, is to create a reference image from a prototype 'perfect' lace sample presented under the camera. A reference image should be of exact repeat length and, ideally, the start and finish of the reference image should match perfectly to allow it to be repeated to form a 'seamless' virtual endless reference. This is not without difficulties because of the locally variable nature of lace and so, at present, some manual adjustment of the reference image is required to achieve a good match between start and finish. Once created, the reference image is stored in memory for future use.

4.1 Finding the Start Position

The inspection process starts with finding the current position of lace under the camera with respect to the reference image. A wide range of algorithms could be applied for this task, but for simplicity a basic two dimensional template matching approach using binarised images has been used. In order to minimize the time involved and to make the system work more efficiently the lace images are processed in two halves i.e. the right hand side of the image is always processed by the C44#2 and the left hand side by C44#3. The *Find Start Position* algorithm has a single pixel resolution and uses minimized search field and early termination techniques to speed up the process. The algorithm not only provides the position of the best matched starting line but also gives the best horizontal alignment of the search window in the reference image. This value is used later in the *Tracking* routine to estimate the initial lateral tracking positions. The algorithm is found to be very effective and reliable. Average time to find the start position is about 20 sec for a 1024 pixel wide pattern with 550 lines per repeat

4.2 Tracking Algorithm

After the start position has been located and the processors know which line the camera is about to scan with respect to the reference image, the tracking algorithm 'registers' each successive line scanned with the corresponding line in the reference image,

continuously and in real-time. The tracking algorithm scans a portion of the current 'live' line, and finds its best match from among three candidate 'corresponding lines' from the reference image. The three candidate lines are (a) the next logical line in the reference image, (b) the line before it (i.e. the 'corresponding line' for the previous 'live line') and (c) the line after. The determination of the 'corresponding line' helps to compensate for any longitudinal deformation in the live image. For instance, if the 'corresponding line' is the next logical line in the reference image, the 'reference image pointer' will 'STEP' one line for the next scan; if the 'corresponding line' is the line before the logical one, the 'reference image pointer' will 'STAY' as it is for the next scan and, finally, if the 'corresponding line' is the one after the logical line, the pointer will 'SKIP' one line for the next scan, hence effectively shrinking the live image if it is too big and vice versa (Figure 4).

To avoid excessive and rapid changes in the reference image pointer the selection of *stay*, *step* or *skip*, was 'compensated' by using the following rule:

- Consecutive *stay* or *skip* will be replaced by a step.

We term this process the Stay-Step-Skip (or SSS) routine.

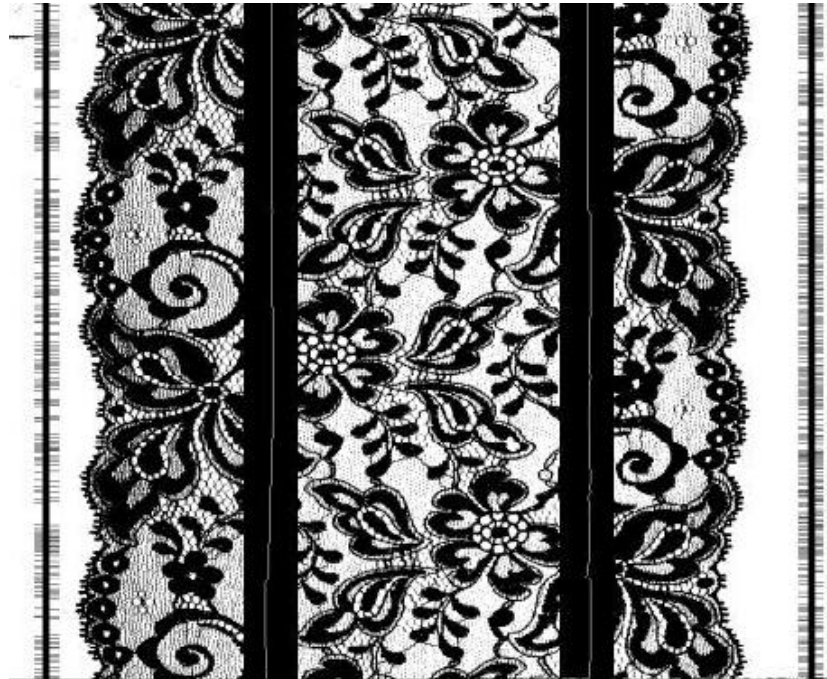


Figure 4. Actual display of the screen showing the two tracked paths for left and right hand sides of the image, processed by different DSPs. The 'ladders' on either side show the results of the SSS routine, with the central black spine representing a STEP a spike on the left hand side of the spine representing a STAY and a spike on its left a SKIP.

The tracking algorithm also gives the best matched horizontal position. The best matched horizontal positions of the Right and Left hand sides can provide information about lateral stretch as well as lateral shift, which can be used to correct the live image before actual comparison. To avoid unpredictable and rapid shifts in the tracking path the horizontal position is damped by taking into account the 'history' before computing the horizontal position. Currently we are taking into account the previous lines results to

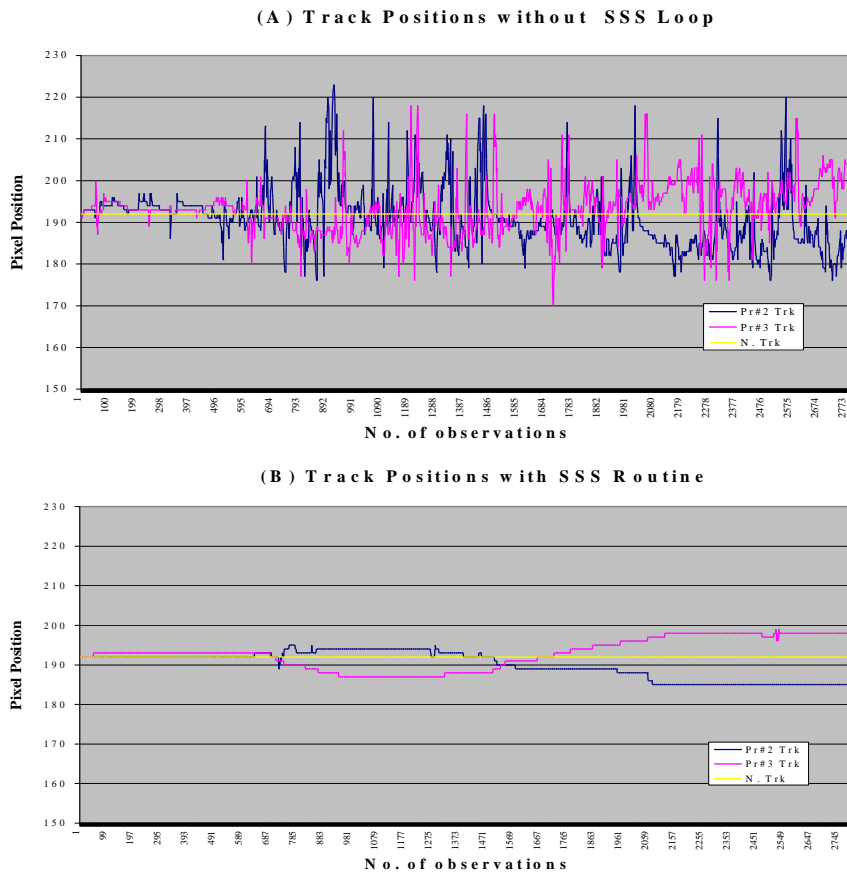


Figure 5. (A) The track positions without lateral compensation, (B) track position along the same path with lateral compensation.

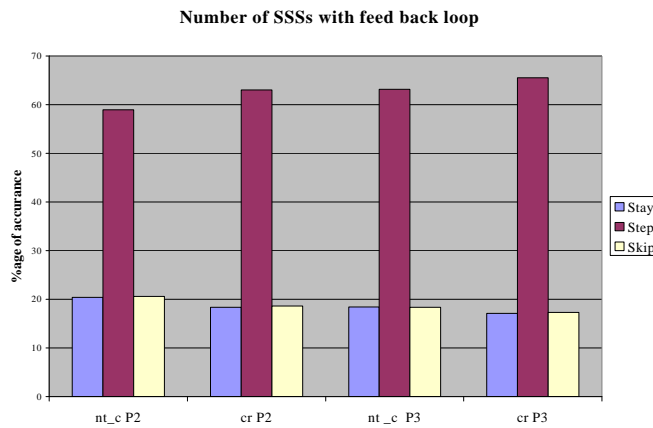


Figure 6. Distribution of Stay, Step and Skip for Left hand (P3) and Right hand (P2) processors. ('nt.c P2' indicates 'not compensated' distribution of SSS for Processor 2, while 'cr. P2' means 'compensated' distribution of SSS for Processor 2.)

determine the new horizontal position, in a manner similar to an Infinite Impulse Response (IIR) filter, by using the following algorithm.

$$\text{Horizontal Position} = \text{History_coeff}(\text{Previous H.Position}) + \text{Current_coeff}(\text{Current H.Position})$$

$$\text{Previous H. Position} = \text{Horizontal Position}$$

Where *History_coeff* and *Current_coeff* range from 0 to 1, and always sum to 1.

Figure 5 shows the effectiveness of the SSS routine by comparing the position of the track paths with and without the SSS routine implemented.

Figure 6 shows the distribution of STAY, STEP and SKIP over a 'track length' of 2800 lines. A perfectly balanced distribution i.e. predominantly STEP and equal numbers of STAYS and SKIPS suggests that the lace on the drum is in equilibrium and, as expected, is not stretched or shrunk compared with the reference image, which in this case was also taken from the lace on the drum. However the presence of STAYS and SKIPS also suggests that local variations are inherent in lace and very important to account for in the present problem as indicated by the massive improvement in the track paths shown in figure 5.

4.3 Image Subtraction

Once the live image lines are in synchronization with the reference image, the two can be subtracted and the result displayed through the VRAM of Oculus F/64 on the monitor. Since we are dealing with binary images a simple XOR function is used to generate a subtracted image. Figure 7 compares the result of subtraction in real time with

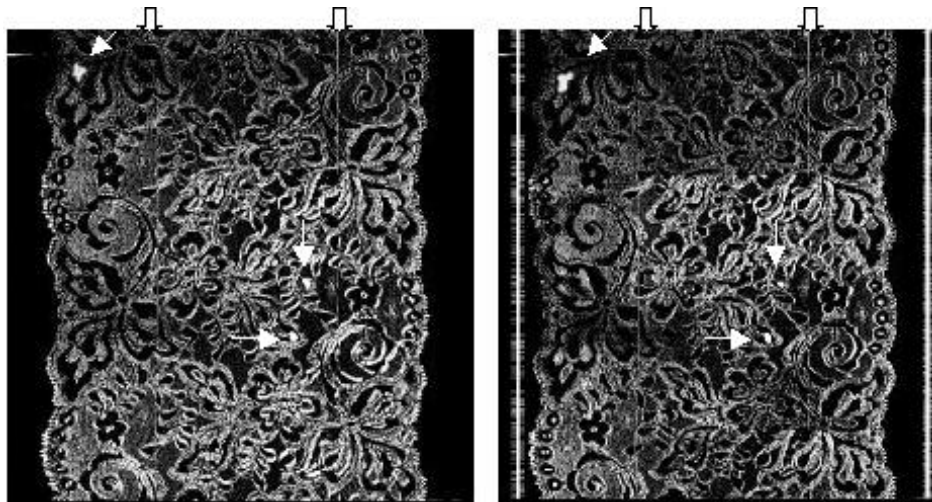


Figure 7. Image subtraction in real time (a) without SSS routine and (b) with SSS routine. Arrows indicating the potential faults. The black arrows at the top indicate the tracking path positions, plotted to these output images for information as a thin line of white pixels.

and without the SSS routine. The comparison clearly shows the importance of the SSS routine during the subtraction, but also suggests that a mere correction in the vertical direction is not enough for final fault detection – a lot of noise is still present in the subtracted images which needs to be removed.

To achieve a superior error detection capability, we are employing two approaches, which will be used in combination, to reduce the 'noise' left after subtraction:

- (a) Morphological filtering – erosion of the subtracted image.
- (b) A feed back approach for rapid and efficient geometric correction of the live image to match the reference.

4.4 Morphological Filtering

The subtracted images in Figure 7 are filled with noise, which hinders the detection of actual faults. We are applying simple morphological filtering, e.g. morphological erosion

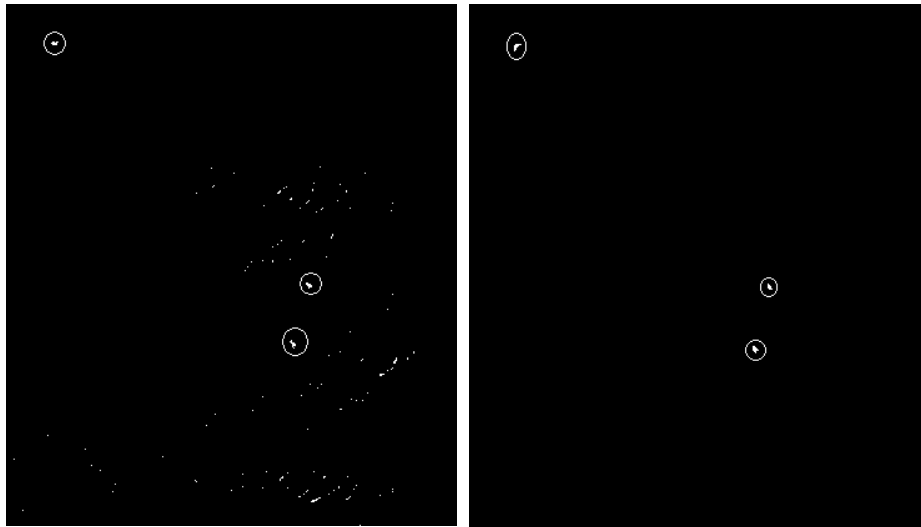


Figure 8. Erosion of the images shown in figure 7 with a disk of 3 pixel radius. The faults are encircled for clarity, note the amount of noise still present in the left hand image which represents the result of erosion on the subtracted image without the SSS routine.

to get rid of the noise and detect the actual defects. Figure 8 shows the result of 3 pixel 'disk' erosion on the above images. Note that the faults are now clearly visible (encircled). However, the erosion of the image without SSS routine still shows some unwanted noise.

4.5 Feed Back Approach

A 'feed back' approach is proposed to make use of the information collected from the tracking routine to correct the lateral scale and shift in the live image before doing the final subtraction in an attempt to reduce the noise in the subtracted image. The horizontal track positions of both the right hand and the left hand side images can be used to estimate the change in the horizontal scale and shift if any, as shown in the figure 9.

The Scale factor can now be defined as x/x_{ref} , while the shift can be estimated by comparing the tracked path location and its corresponding reference track path position, e.g. if the tracked path positions are $x1$ and $x2$, while reference track path positions are $x1_{ref}$ and $x2_{ref}$ respectively, with the centre being 0, then,

$$\text{Average Horizontal Shift} = [(x1 - x1_{ref}) + (x2_{ref} - x)] / 2$$

Where a ' - ' (negative) sign indicates a shift to the right and vice versa.

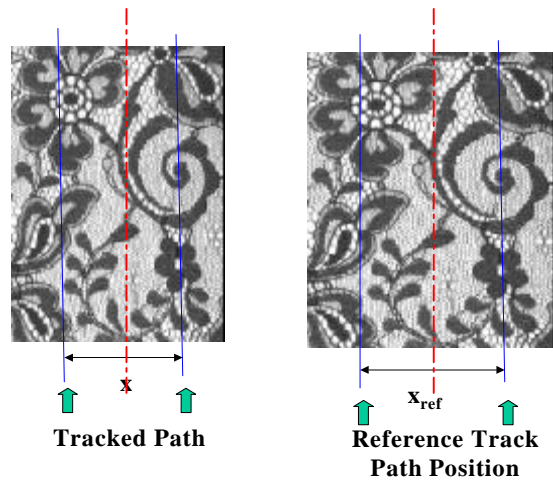


Figure 9. Lateral width and scale adjustment

The ‘feed back approach’ involves using the above mentioned information for every scanned line to correct the one succeeding it, as shown in figure 10.

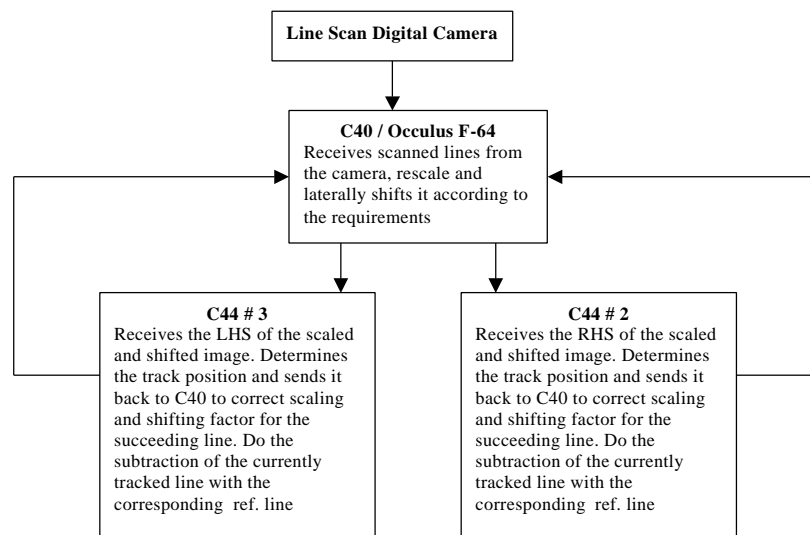


Figure 10. The feed back approach.

Though promising, the preliminary results of this closed-loop approach suggests that further work is needed in defining a better transfer function. However the benefits are significant in terms of processing efficiency because the field of search for the cross-correlation based tracking algorithm can be reduced considerably whilst the lace (and hence the tracked paths) can still move sideways through a large displacement range. Table 1 compares some of the statistics collected with and without the feed back loop in operation. ‘Normal conditions’ are for lace on the drum presented in normal disposition, while ‘worst conditions’ indicate the lace has been deliberately distorted.

The table clearly shows, that although effective, the feed back approach needs some tuning before it can give the desired results. The authors are currently investigating the problem.

Normal Conditions	Processor # 2					Processor# 3				
	Avg. Trk Pos	S.D	Max. Value	Min. Value	Range	Avg. Trk Pos	S.D	Max. Value	Min. Value	Range
Without Feed back	189.96	3.4	195	185	10	192.87	3.83	199	187	8
With Feed back	190.5	2.34	194	186	8	192.25	2.84	198	188	10
Worst Conditions										
Without Feed back	200.49	10.32	213	177	36	184	10.86	209	172	37
With Feed back	197.63	6.07	207	182	25	186.92	8.36	207	179	28

Table 1. Comparison different statistical measures with and without a feed back loop. (S.D. stands for Standard Deviation)

5 Conclusion

The authors have presented a multi DSP approach for automatic inspection of deformable textile webs, such as lace, in real time using machine vision techniques. A direct comparison of the live image of a lace strip with a perfect prototype reference image, on a line-by-line basis is adopted. The effect of inherent distortions in the lace, which can cause false alarms and excessive noise in the subtracted image, is reduced by employing (a) a lateral correction algorithm, which decides the best possible match within three possible lateral positions, (b) a closed loop feed back algorithm which correct the scale and offset of the 'next' live line based on the tracking information obtained from the 'current' line and finally, (c) morphological filtering to remove the residual noise.

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