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Multichannel Optical System for the Quality Control of Digital Printing

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Abstract
Economical efficiency and environmental protection are key elements of modern textile treatment, where chemical fluids are digitally assigned to designated places in a printing-like process. Except arbitrarily designed colour patterns, technology provides the ability to add individual functionalities not achievable in the classical approach i.e. dip dyeing based processes. The precise deposition of chemicals or bonding components like microelectronic chips on a material substrate is crucial in producing multilayered fabrics. This paper demonstrates an optical monitoring system which enables the precise control of the deposition of functional materials or components on fabric. The optical system consists of a set of Fibre Optic Image Bundles (FOIB) connected to a single CCD line camera which enables the correlation in space and time of images acquired from different parts of the area monitored. During the deposition process the system measures fabric surface deformation and detects motion instability, and then adjusts the printing parameters accordingly.

Key words: *digital printing, material deformation control, optical measurement system, fiber optics.*

Introduction

In a traditional process a fabric is entirely dipped in the dyeing reagent, which is not flexible and patterning is limited. In modern textile processing a digital printing system is applied where chemical fluids are digitally assigned to designated places according to the pattern designed [1]. The textile surface can be precisely covered by one or several chemical layers [2]. In this way, various functionalities for different parts of the textile surface can be added [3]. An antibacterial layer, for example, protects the skin against microbes and is useful in medical applications. Hydrophobic/hydrophilic functionality is helpful in the development of protective textiles, ensuring dirt repellence, water repellence and providing improved comfort compared to membrane technology. A fabric with anti-static functionality is applied to protective textiles for work with high voltage installations. Chromic materials deposited on the fabric surface enables the producer to develop a textile sensitive to temperature gradients, radiation or other physical phenomena, which provides sensoric functionality to a textile. A fabric with the controlled drug release function can be applied in medicine. Digital printing technology can be integrated with fabric electronic circuits, micro devices, sensors, displays and other electronic devices to be invented. Since technology offers a broad area of applications, the printing process including interaction between drops and textile has been the subject of extended investigation [4 - 7]. New technology of fabric processing requires a new type of monitoring system. A huge amount of data that should be controlled in real time is a challenge to quality control systems, most of which are based on the fast vision systems that analyse the fabric texture, utilising image processing algorithms [8 - 15]. For fabric feature classification, the fuzzy logic [16], neural network [17] and knowledge-based approaches [19] were applied.

A new approach to the quality control of a fabric is presented in this paper. ***Figure 1*** presents the scheme of a digital textile processing centre where the technology of chemical deposition via Ink-Jet Printing technology is applied.

A real printing system consists of a few units of ink-jet printing heads controlled directly by an ink-jet control subsystem. ***Figure 1*** shows a simplified system which has two heads. Simultaneously the multichannel optical monitoring system controls the printing quality on-line.

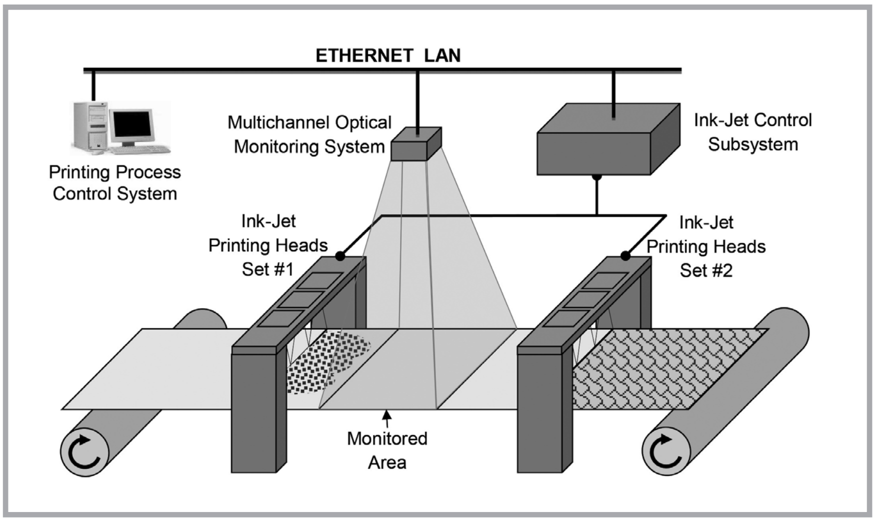


Figure 1. *Digital textile processing centre.*

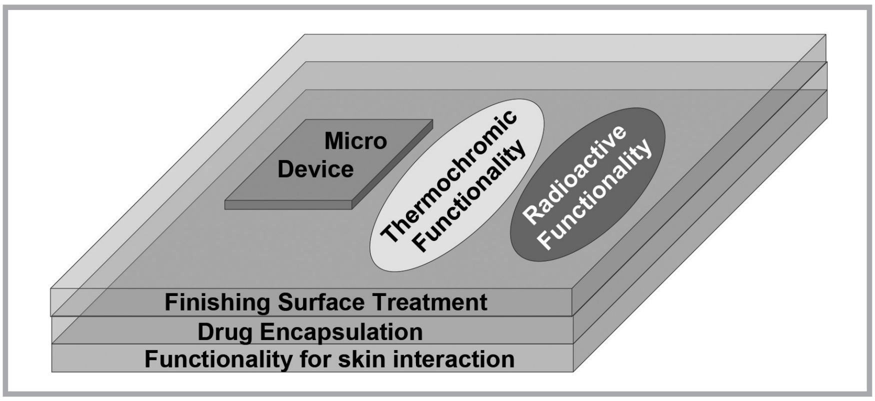


Figure 2. *Multilayered functionalities on the textile during various process steps.*

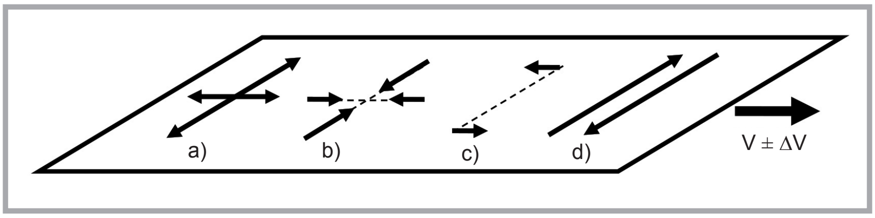


Figure 3. *Examples of typical substrate deformation and movement errors: a) stretching, b) shrinkage, c) skewing, d) translation and velocity (V) variation.*

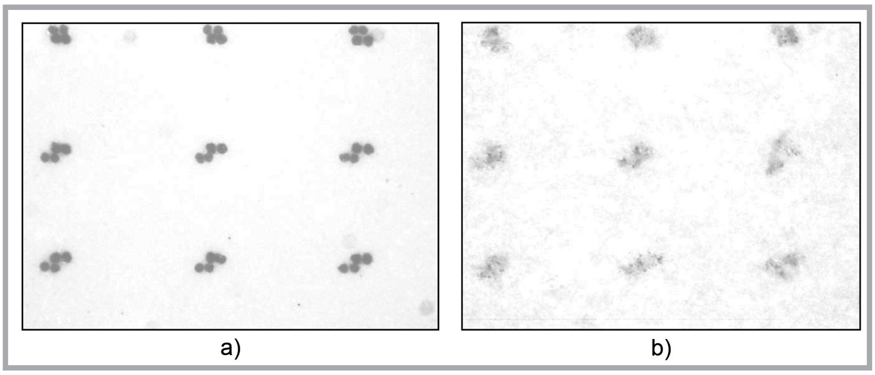


Figure 4. *Patterns (4 dots square) printed on high quality a) and low quality b) paper.*

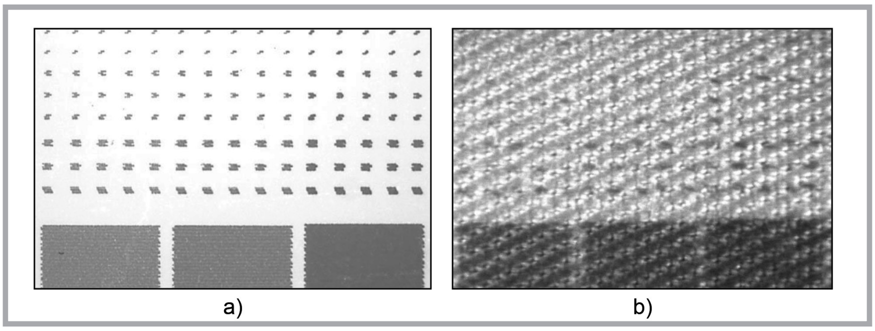


Figure 5. *Patterns printed on high quality paper a) and fabric b).*

An example of multilayered functionalities deposited on a textile during various process steps is presented in ***Figure 2***. The example schematically presents various treatments of three fabric layers arranged for effective skin interaction (bottom layer), drug encapsulation (central layer) and surface finishing (upper layer).

Additionally various local functionalities have been precisely deposited on the fabric surface together with a micro-device integrated with it.

During the printing process, the substrate's movement may be disturbed, depending on chemical or mechanical pretreatment process parameters, like temperature, humidity etc. The pretreatment and functionalisation process can result in some substrate deformations like stretching, shrinkage, skewing and translation.

Except the fact that the substrate width may vary along its length, the substrate length as a whole may become different than before the process. Additionally the substrate lateral position and speed may change during transportation by the conveyer in the printing system. ***Figure 3***. presents possible substrate deformations and movement errors.

All of these undesirable substrate deformations and velocity variations disturb the process of material deposition during printing. Additionally the printer head positioning errors as well as timing errors introduced by the electronic head that controls the dots' distribution deteriorate the printing quality. Despite this, the accuracy of the digital printing process is at the level of a few tens of micrometers, while a substrate's edge translation during transportation on the conveyer is at the level of a few millimeters. This indicates that the printing process is about 100 times more precise than the substrate positioning accuracy caused by the transportation instability and substrate deformation. The design of an optical monitoring system for fabric deformation control was preceded by investigations of the pattern printing process with various functionalities for different substrates including low and high quality paper and textile substrates.

The results revealed that the printing quality strongly depends on the substrate type and yarn structure in particular.

Moreover the same pattern printed on a textile surface is less visible by the optical system than printed on paper. ***Figure 4*** presents magnified images of patterns printed on various materials i.e. high and low quality papers. The patterns to be printed are four dot squares. The printer head errors are clearly visible. In all of the images dots do not form perfect squares. A small pattern on low quality paper or fabric is poorly recognisable and in this case the printing resolution is very low.

Figure 5 presents an image of the same pattern printed on paper and a textile. The paper substrate can be treated as

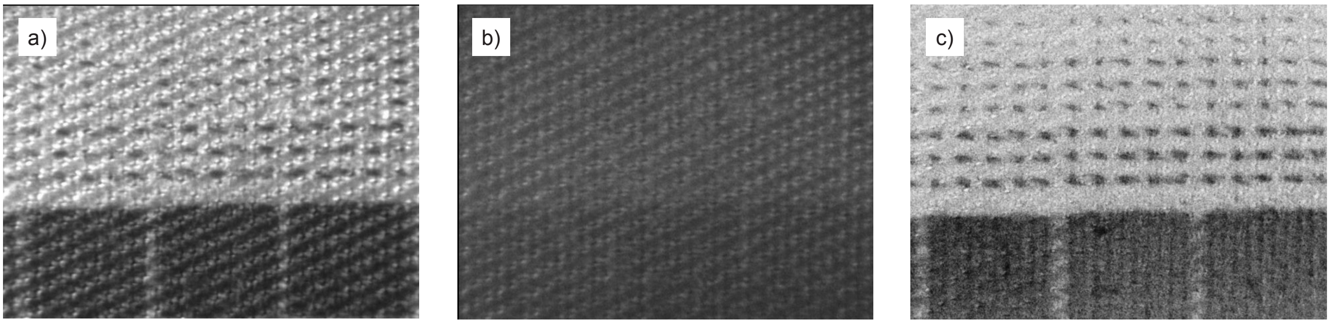


Figure 6. a, b) Images registered at different wavelengths, c) a processed image.

a 2D surface, but the textile, especially of thicker yarn, must be considered as a 3D object. Drops of the agent printed on the fabric are spilt, and penetrate the space between fibres. This indicates that the printing process is not perfect, and therefore the pattern monitoring process is complex. It inclines towards the conclusion that the image resolution (the size of an image pixel) of the pattern monitoring system should be adjusted to the functionalised substrate quality. Such knowledge is necessary to determine the measurement accuracy and error level in the optical control system.

Moreover the image acquisition process suffers from inhomogeneous illuminating light and the wavelength dependence of the fabric reflectivity coefficient. To enhance the quality of the image monitoring system, the INOS developed a dedicated image processing procedure, according to which a few images of monitored areas have to be registered for various wavelengths of illuminating light, and then the image processing procedure is applied. The first wavelength – λ_1 – is highly absorbed by deposited chemicals, while the second –λ_2 – is highly reflected. The digital processing of both images provides a resulting image in which the chemically deposited areas are better visualiaed. Both wavelengths are matched to the control chemicals. Such a measurement system significantly enhances the pattern visibility and enables an efficient textile monitoring process. ***Figures 6.a*** and ***6.b*** present images of the same textile area registered at various light wavelengths λ_1 and λ_2. ***Figure 6.c*** presents the result of the image processing algorithms. The upper part of the image in ***Figure 6.c*** contains many more details than in ***Figures 6.a*** and ***6.b***. One can see small areas with deposited chemicals which would not be visible otherwise. Such an optical technique implemented in the control system enables it to precisely control chemical deposition on the fabric surface.

Further studies show that under some conditions it is possible to monitor the pattern of functional agents covering the textile area, but such a monitoring system is limited to specific applications due to the functional agent detectability under various types of illumination. Also the variety of functional agents and their chemical compositions are not easily detectable in classical imaging systems.

Moreover a monitoring system based on image processing procedures requires large throughput of data transmission lines. A typical image that should be registered by an accurate monitoring system has about 150,000 pixels in a single line. Then more than 33,000 lines should be processed per second if it is required to analyse a fabric area of 1.5 m width at a resolution of 10 micrometers and transport speed equal to 20 m/min. This yields 5,000,000,000 pixels to be processed within 1 s. For efficient data processing and on-line monitoring of printed fabric quality the monitoring system should be powerful including a multichannel, multiprocessor architecture. It should also be equipped with a few cameras whose resolution should be reduced. It is possible to build such a system, but fortunately we have a cheaper solution.

Multichannel optical monitoring system

This system was implemented under "DIGITEX" EU project (No IP 026740-2). The main efforts were focused on the monitoring of fabric deformation and its movement instability during the technological process of chemical deposition on a fabric surface.

Such an approach requires monitoring of the various parts of fabric simultaneously. In this situation all registered images are correlated in space and time, which enables the system to calculate the fabric deformation and its speed instability.

The system does not register an image of a big part of the fabric with very high accuracy. Instead it observes a few small areas of the chemically processed substrate and the system design ensures that all these images are transferred at the same time to a single photodetector. This also ensures that these images are correlated in time with one another, which provides the ability to calculate the fabric deformations and movement instability on-line. The important fact is that the amount of information to be analysed is several orders of magnitude lower than in the case of full 2D image registering and processing.

The main idea is based on the observation of the position of special markers printed close to the fabric edges. The markers can be printed in special inks, the visibility of which is beyond the typical VIS region i.e. 400 - 700 nm. The invisible markers do not disturb the printed pattern (***Figure 7,*** see page 98).

Markers (shown in black for better visibility) are printed along two vertical fabric edges parallel to the direction of fabric movement. Four small areas of the fabric observed by the monitoring system are marked by circles. ***Figure 7.a*** presents the fabric without any local deformation, and markers are positioned centrally within all observation areas. ***Figure 7.b*** presents the markers' positions for a local transverse translation of the fabric surface, and those in ***Figure 7.c*** indicate the local transverse stretching of the surface area, while ***Figure 7.d*** shows local longitudinal stretching combined with local transverse skewing. The fabric surface deformations are marked by black arrows. The system enables to detect and

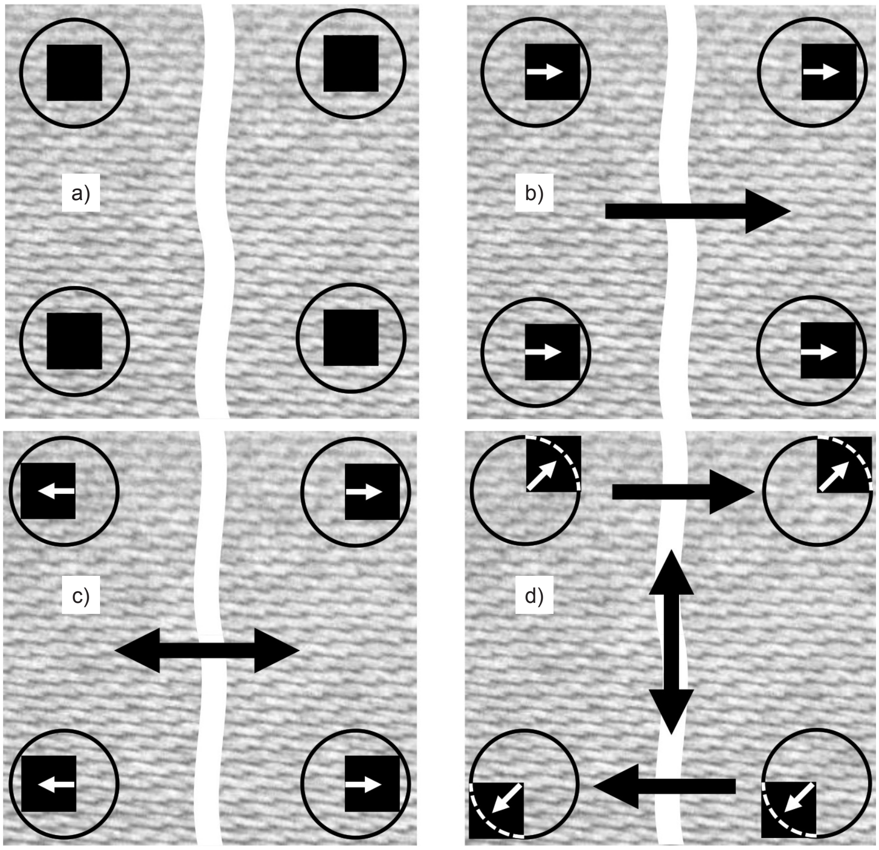


Figure 7. Examples of possible substrate deformations and positioning errors.

measure all possible combinations of local deformations.

The main problem in yielding a solution in this type of monitoring system is how to register images of all areas monitored simultaneously. A solution involving a few cameras and a specially dedicated synchronising electronic board would be complex and relatively expensive. Instead an innovative multichannel system based on a set of fibre optic image bundles (FOIB) was developed.

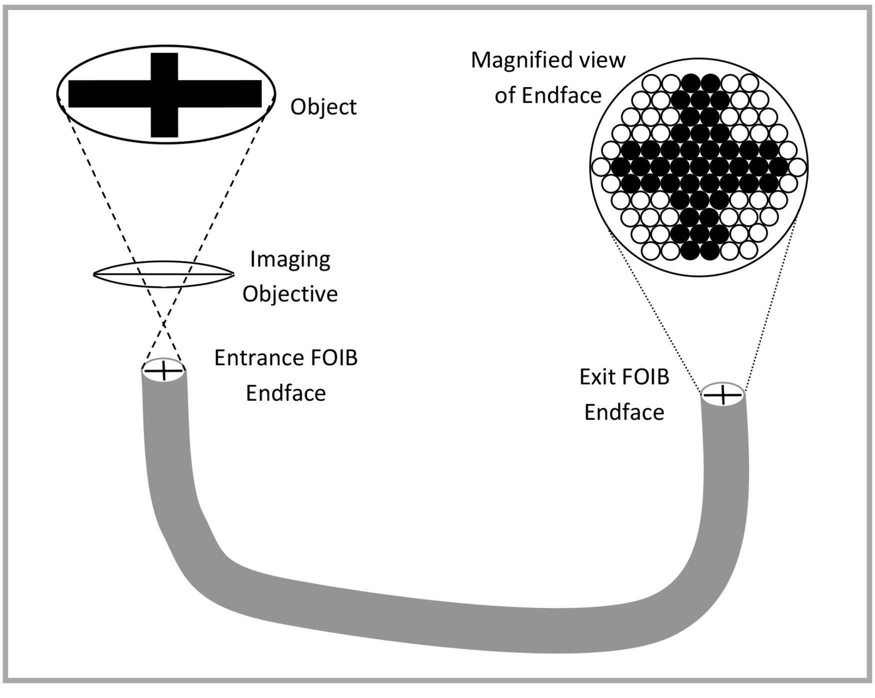


Figure 8. *FOIB principle of image transfer.*

FOIB based measurement system

The system proposed by the INOS is based on a set of fibre optic bundles (FOIB). The FOIBs are a collection of specially arranged optical fibres that can transfer an image from one end-face of the bundle to the other. They are widely used in medicine in endoscopes for observation of inner parts of the human body. A scheme of the FOIB principle is shown in ***Figure 8***.

The object imaged by the objective at the input end-face of the FOIB is transferred to the output end-face. This is schematically presented in ***Figure 8***, where the magnified FOIB end-face with the transferred image of a black cross is presented. The quality of the transferred image depends on the fibre diameter (which defines the size of the image pixel) and the total number of fibres in the bundle. Each of the FOIB fibres transfers the light intensity of one image's pixel – the elementary part of the image. The amount of light transferred by an optical fibre does not depend on its shape and length (in some range). Optical fibres in the FOIB preserve the mutual relations betwee light intensities in the image's pixels, which are transferred from the entrance to the exit of the FOIB end-faces. Moreover the positions of fibre-ends in the FOIB are fixed and do not depend on the FOIB shape. Thus the geometry of the image transferred through the FOIB is preserved. This geometry does not depend on the FOIB length.

The FOIBs enable the transferring of images of the fabric areas monitored to a CCD camera. The image quality does not depend on the FOIB shape or length. Moreover we can transfer images from various distances with identical magnification using various lengths of FOIBs with identical lenses connected to both end-faces. Therefore the FOIB-based systems are very flexible. Two types of FOIBs were tested in the project. The first one was applied to a model to test the method, which was built with fibres of a diameter of 17 µm (87 fibres across the FOIB diameter). The diameter of the system's FOV was equal to 15 mm. The second type of FOIB was applied in the demonstrator of the measurement system, which was built with fibres of a diameter equal to 3.5 µm (173 fibres across the FOIB diameter). The diameter of the system's FOV was equal to 13 mm.

An example of the FOIB-based Optical Monitoring System is presented in ***Figure 9***.

The 4 channel system analyses 4 relatively small fabric areas, which is sufficient to describe the fabric deformations in rectangles limited by the field of view (FOV) of the objectives IO (***Figure 9***).

Each channel of the monitoring system consists of the FOIB integrated with the FOIB's Imaging Objective (IO). Its FOV is encircled and marked by an arrow. The objective IO images the object within the FOV at the entrance of the endface of the FOIB. The FOV is the maximal area of the image which can be transferred through the FOIB. The FOV diameter depends on the IO and FOIB parameters. The Monitored Area (MA) is a narrow rectangle inside the FOV. The MA is imaged by the IO at the FOIB input end-face and then transferred to the output end-face of the FOIB, located in the object plane of the Camera's Imaging Objective (CIO). The CIO images the MA in the Photodetector Array (PhA) of the CCD Scan Line Camera. The MA width is determined by that of the PhA line. The four MAs are imaged simultaneously in the PhA of the CCD Line Scan Camera. A signal read-out from the PhA defines the Image Line (IL), which contains information about all 4 MAs. An enlarged view of the PhA with four marked images of MAs is presented schematically in ***Figure 9***.

During the fabric movement in the Y direction, subsequently grabbed ILs from the areas observed constitute a full 2D image of the fabric surface including markers. The camera line rate (No. of image lines captured per second.) reaches 68 frames/s, while the number of photodetectors can be as large as 12,288. This provides a continuous image of the 2D area registered. This area is registered line by line, where its resolution in the Y direction is determined by the speed of the conveyer that transports the fabric. Since the registered image is a set of lines, the software can perform very fast and simple 1D image processing and then calculate the XY positions of the subsequent markers.

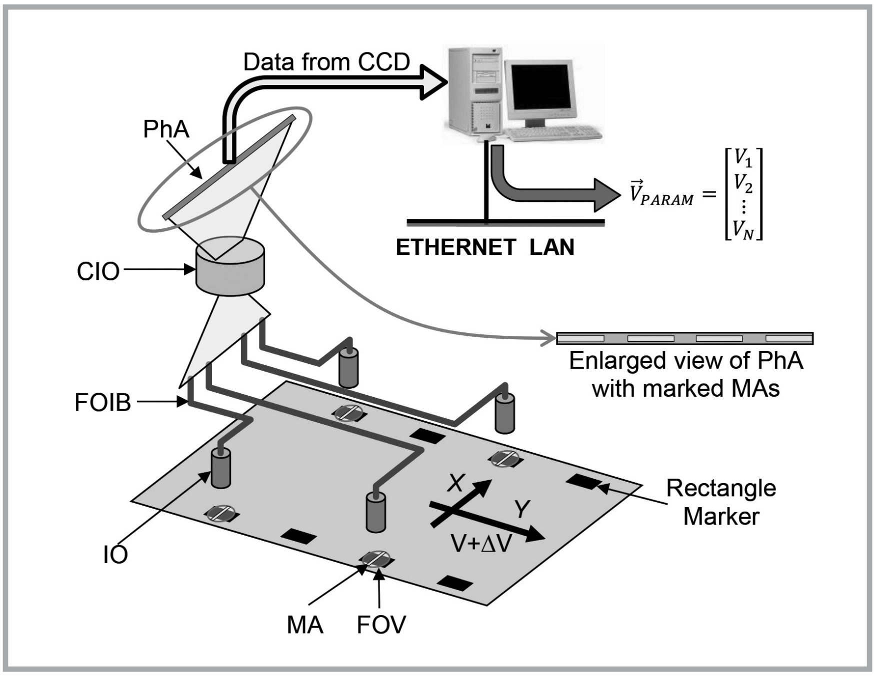


Figure 9. *Four channel FOIB based optical monitoring system.*

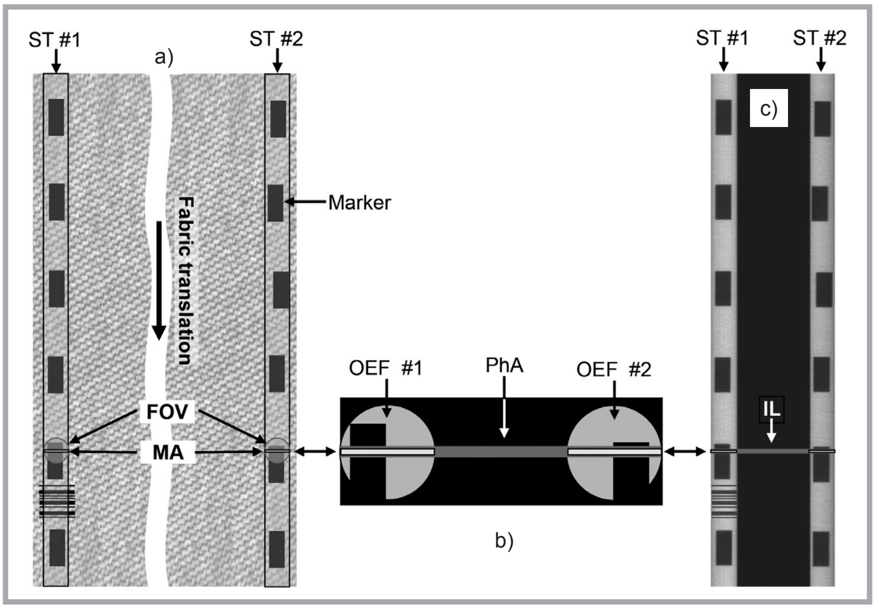


Figure 10. *Image formation in the two channel Optical Monitoring System.*

The data of the 4 MA registered in 4 channels of the monitoring system is naturally synchronised and correlated in time and space. This provides information about the mutual markers' displacements and, as a result, the substrate deformation as a whole.

Next the PC computer calculates the parameter vector V_{PARAM}, which describes the fabric deformation, and sends it by an ethernet line to the printing process control system. This enables the controller to make on-line corrections for the next stage of the printing process and to dispose chemicals properly in the desired places on the fabric, even if it is deformed during the preceding printing procedures. The measurement process of deformations in the four channel monitoring system is independent of the variation in the conveyer speed. Such a system directly measures the distances between markers and then fabric deformations. Such distances do not depend on the conveyer's speed if it is stabilized.

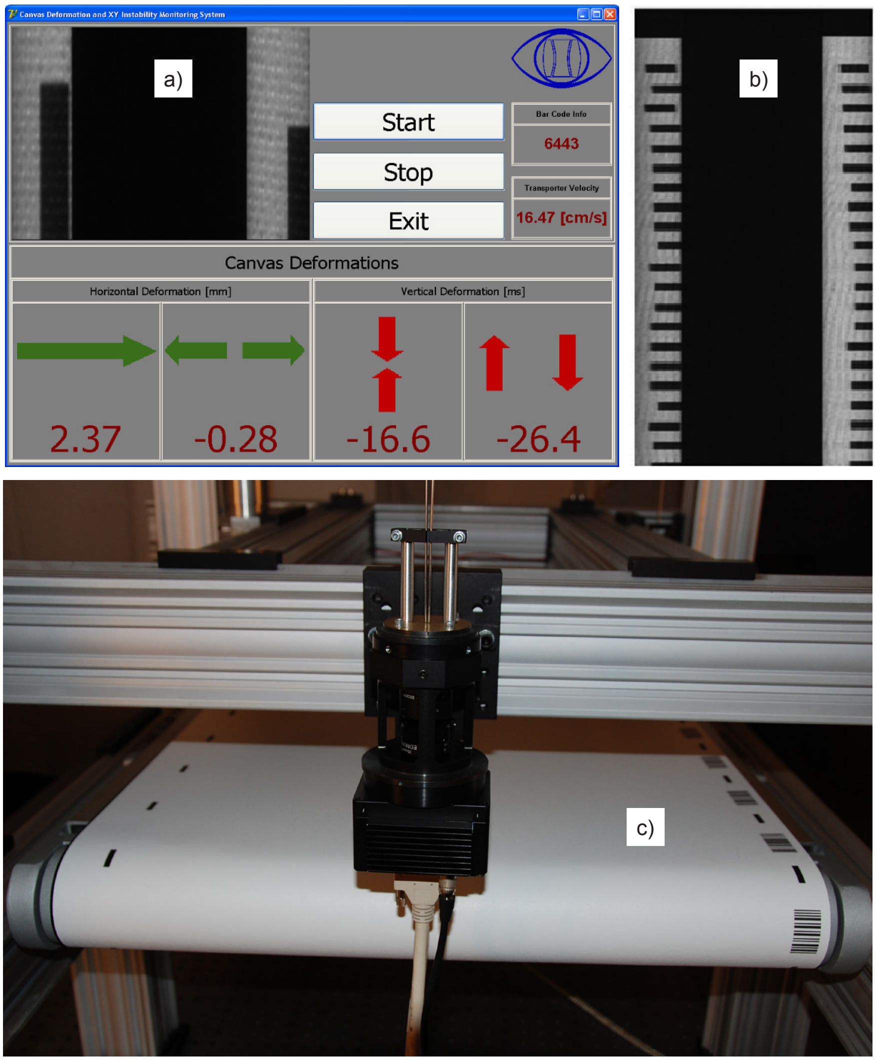
The demonstrator included 2 channels of the system, which is the minimal system configuration capable of calculating most of the fabric deformations, checking its accuracy as well as estimating the accuracy of the four channel system. An optical monitoring system can also be applied to read additional information about the processed fabric. for example the actual fabric position, chemical compositions, customer data etc, printed in the form of barcodes and placed between markers. In addition, the system can be used to control the speed of the conveyer.

Figure 10 (see page 99) demonstrates a scheme of the monitoring process and image formation in the two channel monitoring system. The figure schematically presents the monitored fabric with markers, with two FOVs encircled and marked by arrows with two MAs inside (marked as narrow rectangles). The fabric translation enables the CCD Line Scan Camera to record line by line images of two strips (ST #1 and ST #2) along the fabric edges. The strip width is adjusted to the maximal marker translation expected and is equal to the diameter of the imaging objective FOV.

Figure 10.b presents the situation in the image plane of the CCD Line Scan Camera. Two images of the output end-faces (OEF) of 2 FOIBs can be observed. The PhA position is schematically marked in the figure by an arrow.

The MA are marked in the plane of PhA (***Figure 10.b***) as narrow rectangles. Subsequent signals from PhA- i.e. image lines (IL) – constitute the 2D image presented in ***Figure 10.c***, where one of the image lines is marked in the figure by an arrow.

The monitoring system detects changes in the markers' positions and then calculates the deformation type and its values. The INOS developed an automated demonstrator of technology which includes a two channel optical monitoring system controlled by INOS-developed software. The software has been highly optimized so that the need for the user to interact during the process could be minimised, which is especially important in the case of industrial application.



Bar Code Info: 6443

Transporter Velocity: 16.47 [cm/s]

Horizontal Deformation [mm]: 2.37, -0.28

Vertical Deformation [ms]: -16.6, -26.4

Figure 11. *Screenshots of the system control software a) & b), photograph of demonstrator c).*

The 2D image of the MA is composed of subsequent image lines captured during the time interval -Δt. A single IL contains images captured by both sensors simultaneously. The extraction process of markers is divided into two stages: the learning phase and on-line measurement phase. The learning process should be performed once per substrate processing, enabling the system to detect the reference position of markers. During the measuring step, which is the on-line process, coordinates of the markers are calculated in real time automatically.

The software allows the system to measure in real time the base parameters i.e. longitudinal and transverse positions of markers along both fabric borders (XR,YR – markers' coordinates inside the strip ST #1; XL, YL – markers' coordinates in the strip ST #2) and the fabric speed (V). The coordinates above are calculated in reference to the base line determined during the learning process. Coordinate XR,L = 0 means that the marker's center lies in the proper position and there is no fabric deformation.

These data allow the system to calculate derivative parameters like:
(XL+XR)/2 : fabric shift in X direction
(XL-XR) : fabric stretching/shrinkage in X direction
(YL-YR) : fabric skewing in Y direction
(YLn+YLn-1)/2 : fabric stretching/shrinkage in Y direction of left fabric side
(YRn+YRn-1)/2 : fabric stretching/shrinkage in Y direction of right fabric side

These parameters provide full information about the fabric, which allows the system to control the printing process. According to industrial partner requirements, the monitoring system measures the following parameters:

- lateral stretches and shrinkages in the range of 0 ± 7.5 mm,
- lateral translation in the range of 0 ± 7.5 mm,
- longitudinal stretch, shrinkage, skewing in the range of 0 – dist. between markers
- longitudinal translation from base position in the range of 0 – dist. between markers

- The distance between the fabric and the optics was close to 100 mm

The pixel's dimension in the object plane was equal to 128 μm. The light homogeneity together with advanced image processing algorithms increased the precision of the marker's position to a subpixel level. The accuracy of detection of the marker's position is (for thin yarn) at a level of 40 micrometers. This accuracy can be increased by application of an FOIB with a higher number of fibres.

Figure 11.a presents the user interface of the application that controls the two channel optical monitoring system. Its left upper window displays the temporary image registered by the CCD Line Scan Camera. Two panels in the upper right part of the application form display the fabric (canvas) speed and information readout from the barcode.

Barcodes printed between the markers can include some additional information like the type and serial number of a material. The bottom panels display information about the fabric's horizontal and vertical deformation, recorded by the computer and forwarded via the Ethernet line to the printing process control system.

The deformation type and its value are displayed in two forms – graphically as arrows and numerically. The graphical presentation is noticed more easily by the operator especially if the deformation is out of the acceptable range, hence immediate human interaction is required. The green arrows indicate that the deformation is within the acceptable range and can be corrected during the next stage of the printing process. The red ones indicate the out of range deformation, where the printing process should be stopped. The ranges of acceptable deformation depend on the fabric type, chemicals deposited on the fabric and deposited pattern details. Their values are adjusted by the user.

In the image presented the transversal deformations are translations combined with fabric stretching, while the longitudinal (parallel to the fabric movement) ones are combinations of shrinkage and skewing. For the two channel system the vertical irregularities of the position of the markers can be measured according to the time elapsed between the subsequent marker's entrance into the sensor FoV. Knowing the distance between subsequent markers on the fabric before the deformation as well as the conveyer speed, one can calculate the expected time that should elapse between the detection of two subsequent markers. The deviation of this value is the measure of fabric deformation.

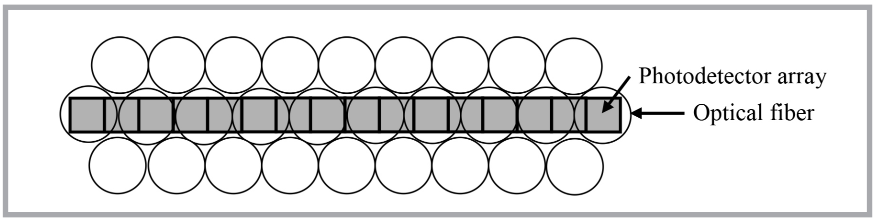


Figure 12. *Low density FOIB fitted to photodetector elements.*

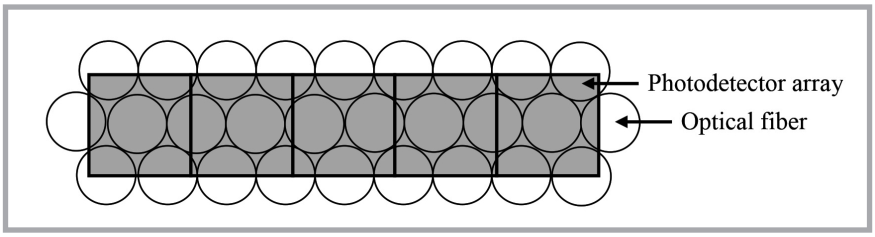


Figure 13. *High density FOIB fitted to photodetector elements.*

The panel "Vertical deformation" (***Figure 11.a***) contains the numbers indicating the time deviation (in ms) from the values expected. The 1D CCD camera has a line repetition ratio equal to 36 000 lines/sec, hence image lines are registered every 27.78 μs, which is the time resolution for the detection of the markers' positions.

Figure 11.b presents an image of fabric strips (1 meter length) registered in the optical monitoring system by the CCD Line Scan Camera. The image is contracted by about 10 times in the lateral direction to show the entire image registered. ***Figure 11.c*** presents a photograph of the demonstrator, where the conveyer with a fabric covered by markers and barcodes with a camera module with two FOIBs are visible.

The parameters of the FOIBs, IOs and CIOs and the pixel dimensions of the CCD line scan camera should be adjusted to obtain an optimal performance of the monitoring system. The IO parameters together with the FOIB diameter define the magnification of the marker's image transferred by the FOIBs and the diameter of the FOV.

On the other hand, the parameters of CIO, the number of optical fibres in the FOIB (the fibre diameter), and the pixel dimensions of the CCD Line Scan Camera define the monitoring system resolution. The CIO magnification defines the diameters of the fiber image in the plane of the PhA. It is rather difficult to perfectly adjust the cores of optical fibres with cells of the photodetector array so that they are positioned accurately face to face.

The situation where the diameter of the fiber image is close or slightly higher than the pixel's diameter is presented in ***Figure 12***. This appeared when the FOIB with 17 μm fibres was applied. The 1D CCD camera pixel dimension was equal to 10 μm. The resolution of such a system is defined by the pixel dimensions, but the image registered is not homogeneous, which decreases the accuracy of deformation measurements.

On the other hand, if the fibre's image diameter is much lower than the pixel dimensions, the image quality (homogeneity) is much higher, but the image resolution is much lower, as presented in ***Figure 13***. This is the case of the demonstrator where an FOIB with 3,5 μm fibres was applied.

This means that the parameters of the monitoring system components should be adjusted to given monitoring applications. We applied two types of FOIBs with fibre diameters close to 17 μm and 4 μm.

Conclusions

The new printing technology controlled by an optical control system ensures precise application of a wide range of functionalities (chemicals functionalising the processed fabric) like anti-bacterial, photo- and thermo-chromic, anti-fire, controlled release etc., including intelligent encapsulation techniques, thin layer coating with patterning of either organic or inorganic hybrid materials, as well as new techniques for the integration of smart sensors.

Effective process control reduces the total amount of chemicals required to achieve the functional effect desired as well as a significant reduction in waste (e.g. water, discharged products) coming from the finishing process.

The optical control system presented has been successfully tested in a quasi-industrial environment and can be easily transferred to a production line. Moreover it can be immediately reconfigured according to the customer's requirements, thanks to its modular construction.

System application extends far beyond the textile industry. With this method any production line of tape-like objects can be controlled. The optical signal used in this method can be transferred over long distances without loss of information. The lack of any electronic elements in the imaging part of the system allows it to be applied in a harsh environment with high electric or magnetic fields, which frequently disturbs electronic systems.

Thanks to the FOIB's bending ability, the system configuration is very flexible and can be easily modified according to production requirements.

Acknowledgements

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