Robust Fabric Substrates for Photonic Textile Applications

Liesbeth van Pieterson[1*], Piet Bouten[1], Koen Kriege[1] and Rabin Bhattacharya[2]
[1]Philips Research, High Tech Campus 34, 5656 AE Eindhoven, The Netherlands
[2]Philips Lumalive, High Tech Campus 27, 5656 AE Eindhoven, The Netherlands

ABSTRACT

Textiles are a ubiquitous part of human life. By combining them with electronics to create electronic textile systems, new application fields emerge. In this paper, technology and applications of light-emitting textile systems are presented: a fabric substrate is described for electronic textile with robust interwoven connections between the conductive yarns in it. The fabric robustness, as a function of the electrical reliability of its conductive yarn connections, is shown to hold over large deformations. This fabric is then used to create a light-emitting diode (LED) based photonic textile display. Finally, we will show an example of an application that could make use of such a photonic textile system.

Keywords: Electronic Textile, Photonic Textile, Fabric Mechanics, Fabric Display

1. Introduction

Presently, most applications that use electronic devices are rigid. In order to create new application fields, significant attention is given to the development of flexible electronic devices. These flexible devices can be placed into different categories, depending on the required flexibility, application or product design. Small rigid electronic devices are already incorporated into flexible substrates, like flex-foils. If such devices can also be incorporated into more stretchable substrates, more potential application fields emerge.

One class of substrates that is more stretchable than flex-foils are textiles. Textiles have been used for centuries. They were already mass-produced before electronics ever existed. They have several unique properties, such as being soft, drapeable, lightweight, and in many cases, stretchable. Since we are surrounded by textiles, they are a natural substrate choice for the integration of electronics.

Electronic textiles, or smart textiles, are textiles with integrated electronic functionality (Post et al., 2000; Wagner et al., 2002; Marculescu et al. 2003; Lee & Subramaniam, 2005; Maccioni et al., 2006; Hamedi et al., 2007; Locher & Troster, 2007; Locher & Troster, 2007; Chandra et al., 2007; Nakad et al., 2007; Liu et al., 2008; Lina et al., 2008; Buechley & Eisenberg, 2009).

Depending on the degree of integration, different classes can be distinguished:

- in conductive fabrics, passive electronic functions are realized in textile, such as connections made by electrical or optical fibres and textile antennas, and

- in fibertronics, active components such as transistors and sensors are realized with special textile fibres.

Today, most "smart textile" prototypes are of the conductive fabric types. In many of these prototypes, the electronics are attached as standard available modules to a conductive circuit incorporated into the fabric. Common ways to realize such a fabric are through weaving, knitting and embroidery. Each technology has its own advantages and limitations.

- Weaving allows the realization of multi-layer structures and (limited) isolation of the

* Corresponding author. Tel.: (31) 40 2744659; Fax: (31) 402746321
E-mail address: liesbeth.van.pieterson@philips.com (Liesbeth van Pieterson)

conductive yarns. The fabric is most stretchable in the diagonal direction.

- Knitting offers the possibility to make stretchable fabrics, i.e., most close-to-body, form fitting applications, such as underwear and socks.

- Embroidery has the advantage of freedom in creating circuit designs.

A challenge in all technologies is the processing of the conductive yarns, which through their metal content, perform differently from textile yarns.

In this paper, we will focus on light-emitting textiles. Our photonic textiles are of the conductive fabric type. They consist of conductive yarns interwoven with polyester yarns. Light-emitting diodes (LEDs) attached to the fabric can be individually addressed, which enables the display of (moving) images.

In this paper, special attention is paid to the conductive fabric circuit. It is a passive matrix circuit which enables individual addressing of the components. The robustness of the conductive yarn connections within the fabric is studied when the fabric substrate is deformed. Finally, an outlook will be given on the possibilities for applications that use these substrates as photonic textiles.

2. Experiment

2.1 Conductive Yarns

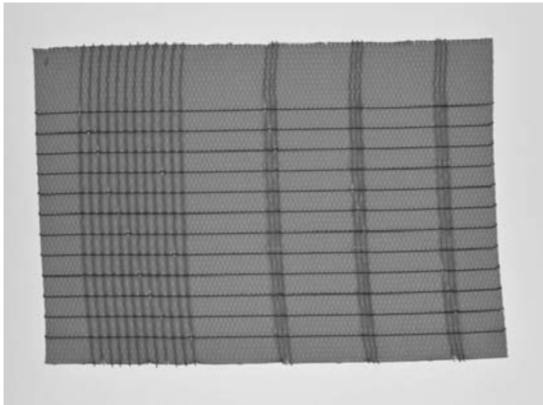
Many types of conductive yarns exist. The two main classes are: 1) metal-coated textile multifilament yarns, and 2) purely metal wires twisted together to form a multifilament yarn. For the fabrics presented and tested in this paper, silver (Ag)-coated textile multifilament yarns, under the trade name Elitex, are used (see Figure 1) (Mohring et al., 2006).

The resistance of these yarns is about 15 ohm/m.

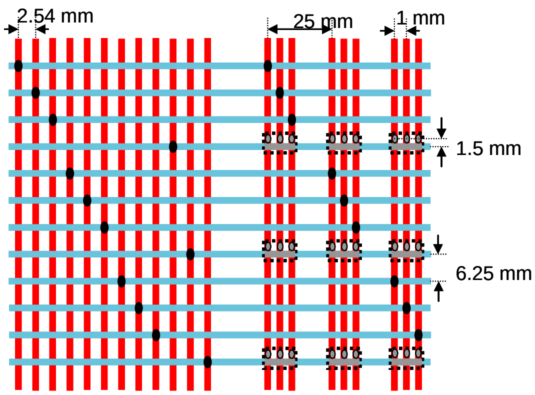
Fig 1. Elitex yarn that consists of Ag-coated filaments

2.2 A Woven Fabric Printed Circuit Board

The photonic textile described in this paper is a woven fabric with interwoven conductive yarns. The circuitry is such that it enables passive matrix addressing of any attached component, and in this case, a three color LED package. Each component has four electrical connections. An example of a matrix type 3-layer fabric is shown in Figure 2a. Figure 2b gives a schematic representation of the conductive yarns in this fabric. The conductive yarns in one direction (warp, blue in Figure 2b) are woven in the front-plane, and those in the other direction (weft, red in Figure 2b) are woven in the backplane. To address this matrix, bus lines are used; they are located on the left side (Figure 2).



(a)



(b)

Fig. 2. (a) Fabric used for photonic textile with 3 x3 LED matrix
(b) Schematic representation of the conductive yarns in the 3 x 3 RGB LED fabric layout.

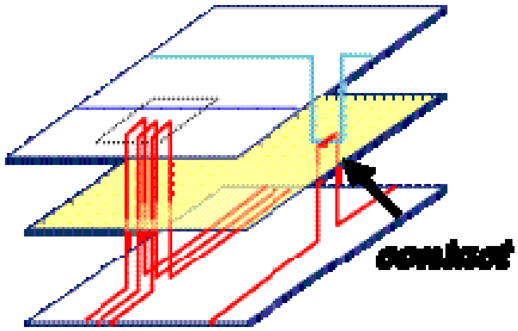


Fig. 3. Schematic representation of 3 layer fabric at contact site

At some points in the structure, a connection is made between the horizontal and vertical conductive yarns. These contact points are indicated with dots in Figure 2b and shown in more detail in Figure 3. At these contact points, a mechanical connection exists between the horizontal and vertical conductive yarns. Also indicated in Figures 2b and 3 are the locations where the components are mounted (indicated by a dashed rectangle). Here, all conducting lines are exposed on one fabric side.

The reliability of these metal contact points is vital for the functional reliability of the complete electronic textile. Upon manipulation of the fabrics, the contact may change. In this paper, the electrical resistance of two or more yarns which contain one or more of these contact points is monitored. A mechanical test is used to apply deformations in a reproducible way.

The fabric substrates in this paper are produced on an automated weaving loom managed by the Textilforschungsinstitut Thüringen-Vogtland e.V. (TiTv) in Greiz, Germany. We distinguish three types of samples; those with single conductive yarns in the warp and weft (Sample B), those with double conductive yarns in the warp and weft (Sample H) and samples with double conductive yarns in the weft and single conductive yarns in the warp (Samples G).

2.3 Resistance Measurements

To monitor the resistance of the woven contacts in the fabric, a matrix measurement method was set up. The principle of the method is represented in Figure 4. Programmable switches connect a (two-point) resistance measurement setup to conductive yarns in the warp and weft directions of the fabric. In this way, a series of selected woven electrical contacts can be measured.

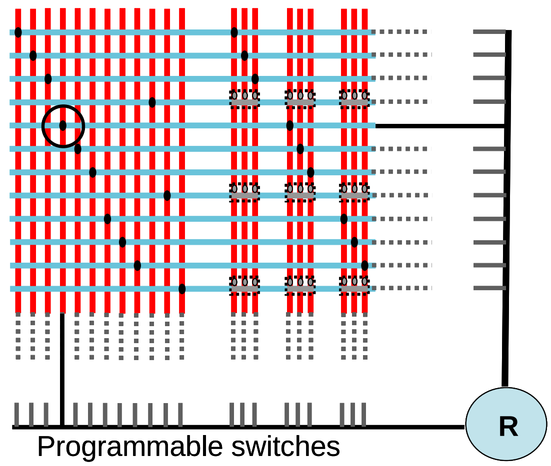


Fig. 4. Schematic representation of the programmable resistance measuring method

This measurement method is realized using a Keithley 2700 multimeter/data acquisition system, equipped with two Keithley 7709 cards with addressable switches. Flat cables (2 m an 3 m in length) with small clamps at the end were used to connect the addressable multimeter to the different conductive yarns in the fabric. Thin wires were fixed to the conductive yarns in the fabric in order to allow maximum deformation freedom during the resistance measurements. The wires were mounted using a (thermal) curable (100^{o}C, 16 hours) conductive adhesive (Loctite 3880, Henkel/ Loctite). At connection sites, a glob top of silicone rubber (PDMS, Sylgard 186, Dow Corning) was applied and cured (90^{o}C, 1 hour) for better fixation of the wires.

2.4 Tensile Testing

An Instron 5566 universal testing machine, equipped with a 500 N loadcell, was used in order to reproducibly apply known forces and/or deformations onto the fabrics. In the tests, the fabric was fixed with pneumatic clamps between flat, 38 mm wide rubber faced fixation plates. The samples were electrically isolated from the frame. Depending on the testing direction, lengths of 70 mm to 100 mm were used. Due to the limited clamp width, the sample was not uniformly loaded over the width. Only contact points between the clamps were electrically investigated. The samples were tested in three directions: weft, warp and diagonal.

The samples were tested in four cycles with increasing maximum load; up to 4 N in the diagonal direction and 8 N in the warp and weft directions. Between the load cycles, the sample was unloaded in two steps: to a low force (0.1 N) and subsequently, another 15 mm displacement at a higher displacement rate. In this step, the sample bends. An example of the displacements during a cyclic loading sequence is given in Figure 5. The compliance of the sample is significantly larger in the diagonal directions (up to a factor of 5-10). To account for this, larger displacement rates and lower maximum forces are used in the diagonal tests.

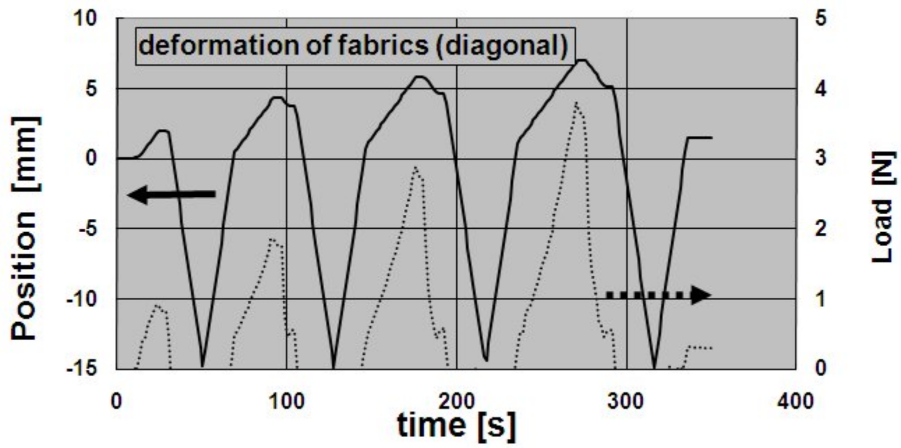


Fig. 5. Measured displacement during the four subsequent loading cycles in a (diagonally) tested fabric.

2.5 Other Methods

Detailed images of the fabric were taken by using a binocular microscope (Leica MZ12) in combination with a digital camera (Leica DFC 320). Photographs were taken with a Canon Powershot A630 digital camera.

For a detailed analysis of some of the yarn connection points, localised X-ray analysis was used (Phoenix Nanomex). The contrast of the X-ray images was enhanced using an image processing program (ImagePro Plus).

3. Results

In this paper, we will show the results for three fabrics with the same basis structure (a 3 layer fabric), but with variation in the number of redundant conductive yarns. The intention of the process variations is to improve the quality of the woven electrical contacts in the fabric.

Figure 6 shows the resistance and load as a function of time for a fabric with single conductive yarns. The fabric was tensile tested in the warp direction. Some of the measured contacts were quite stable during the test (black line F5, grey line B1). Other contacts started to strongly fluctuate in some sections of the test. In cases where the contact was lost ($\boldsymbol{R} > 500\ \Omega$), the signal was filtered. As a consequence of this filtering, the signal goes to zero in the curves. This is clearly observed for curves E4 (grey) in Figure 6.

Figure 7 shows X-ray pictures of a stable and an unstable metal contact. Only the conductive yarns in the fabric are visible. From these pictures, it can be understood that (significant) deformation the fabric can break the electrical connection between two conductive yarns.

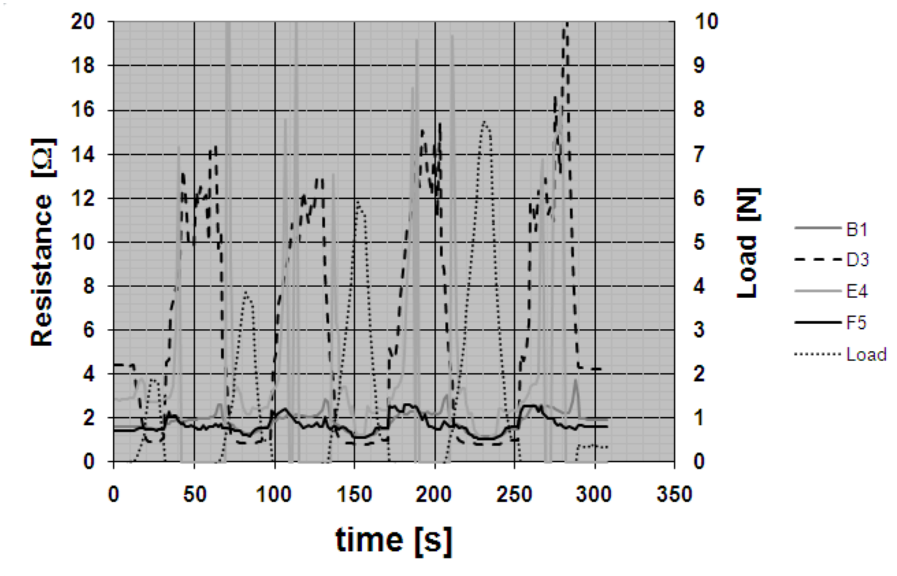


Fig. 6. Resistance of eight contacts in ***fabric B*** as a function of time, tested in the warp direction

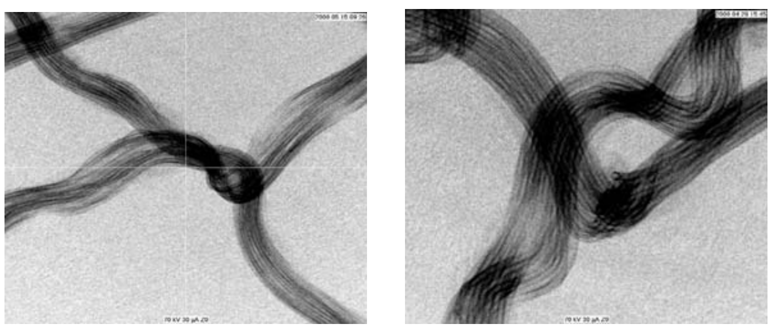


Fig. 7. X-ray images of contact points. On the left, a stable contact, and on the right, an unstable connection, are shown

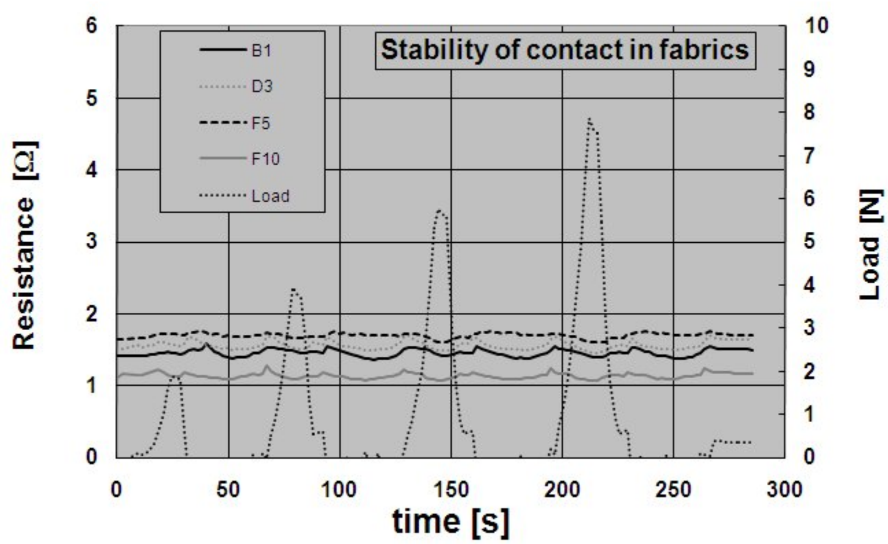


Fig. 8. Resistance of ten contacts in ***fabric H*** as a function of time, tested in the warp direction

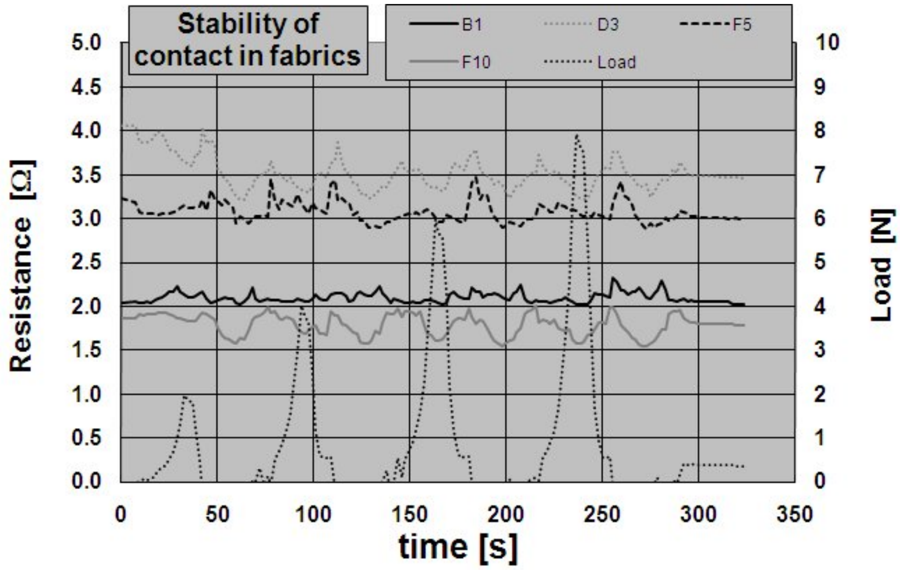
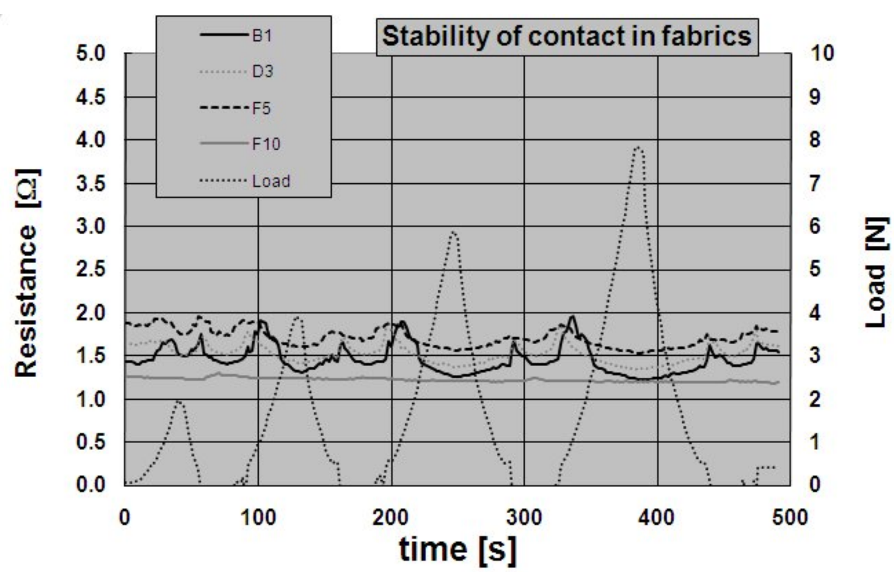


Fig. 9. Resistance of ten contacts in ***fabric J*** as a function of time, tested in the warp direction

Fabrics shown in Figures 8 and 9 have extra conductive yarns in the warp and weft (Sample H) and weft only (Sample J). The redundant lines significantly improve the stability of the fabric. Only at the moment that the load is approximately zero, small spikes in a number of resistance curves are observed. Stable contacts show a typical resistance below 5 Ω. The differences in the resistance level are dominantly due to the different tested (conductive) yarn lengths in the fabric. During the load application cycle they show a resistance variation of up to 1 Ω. Similar results are obtained when tested in the weft direction, as shown in Figure 10.



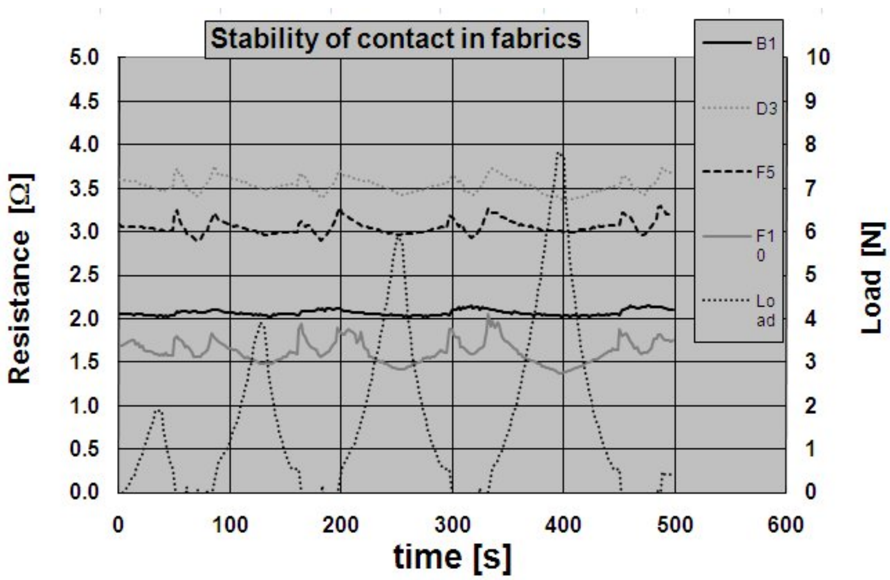


Fig. 10. Resistance of ten contacts in ***fabrics H (left) and J(right)*** as a function of time, tested in the weft direction

Figure 11 shows a microscope picture of a fabric with redundant conductive wires, which clearly shows the adjacent weft lines (yellow arrows) in a standard weaving process. The green arrows indicate the position where weft and the warp yarns are interwoven. Note that adjacent to this position, an opening exists in the weft. The higher bending stiffness of the metallised yarns, in combination with the yarn loop adjacent to the contact, might cause this opening. Looping of the conductive wires from opposite sides causes a fixation of the crossing wire and hence stable connections.

In summary, stable connections between conductive yarns can be made in a three layer fabric using Jaquard weaving and single or double conductive yarns. This allows one to build a robust conductive textile that can have multiple conductive yarns connected to each other in both the warp and weft directions.

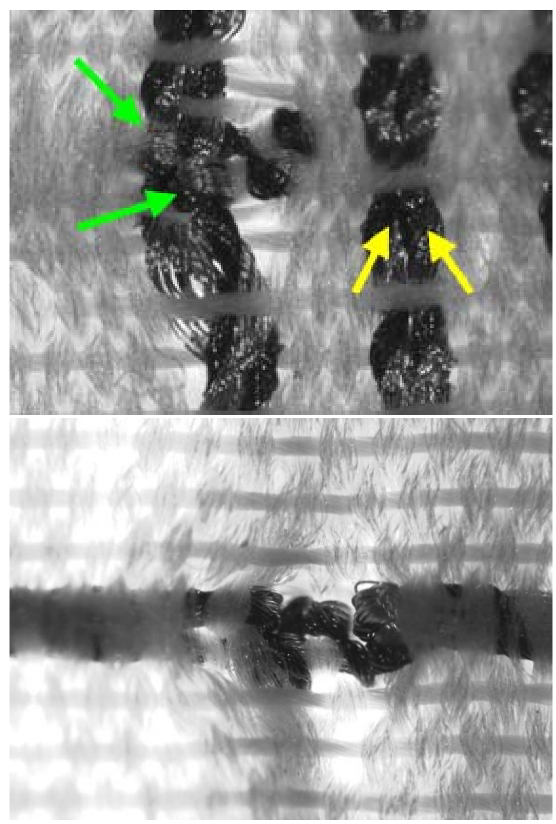


Fig. 11. Via contact in fabric H, observed from
(***a***) backside, and
(***b***) front side of fabric

4. Application Examples and Outlook

When LEDs are attached at appropriate contact positions, a light-emitting fabric, with individually addressable pixels, can be created. LEDs can be attached to the fabric using conventional processes from electronic industry, such as soldering and glueing, or using processes derived from the textile industry (in which the LED is placed on an interposer) such as stitching or lamination. In general, these connections are sufficiently reliable for the applications mentioned below. More information on component attachment methods and reliability thereof will be published in a forthcoming paper. Such a fabric system not only can display millions of different color combinations, but also be used to display dynamic images. Due to its textile nature, this photonic textile enables the use of light in new ways and innovative products, which create an experience that would be difficult to create in other ways.

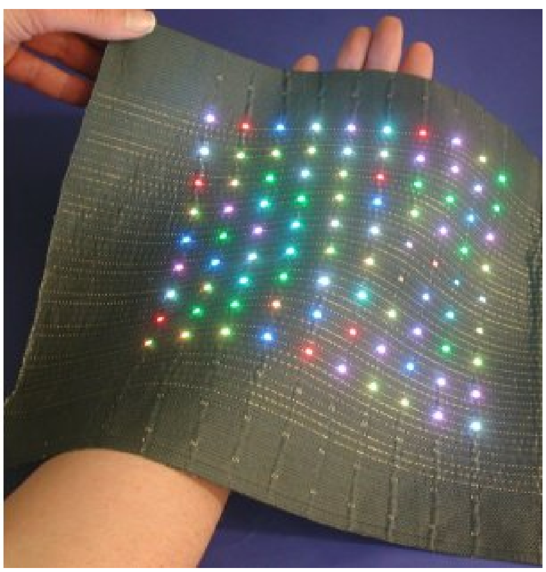


Fig. 12. Light-emitting fabric: conductive yarns are interwoven with polyester yarns and LEDs are attached at the crossovers

Figure 12 shows an example of a multicolour light emitting textile. Due to its rugged substrate design, this system is particularly suited for use in wearable applications. In many potential wearable applications, the light emitting fabric represents only half of the total application. The visual experiences displayed by the fabric, the software necessary to upload and control these images, as well as the user interface necessary to control the complete application, all constitute the other half of the application.

One application area which has been explored has been in wearable messaging/mood setting platforms for the event and exhibit market. In this application, a light emitting fabric can be placed in tandem with a complete communication system in order to provide an effective mobile messaging/mood setting platform. The completed application system consists of a light emitting fabric, controller for the textile that includes a user interface for selecting different content, rechargeable battery that can be connected to the controller system, remote control that can wirelessly control a set of controllers, software that can be used to create and sequence content (downloadable to each controller via a USB connection), and specially designed garments that can accommodate the light emitting fabric and the controller system.

This system is designed with modularity in mind. Each part of the application is engineered in order to increase the functionality of the system without adversely affecting the application overall user requirements. For example, by keeping the garment and the fabric separate from each other, the need to wash the garment is separated from the fact the light emitting fabric is not yet washable. Moreover, users can feel free to change the garment without having to buy another light emitting fabric substrate. In another example, as seen in Figure 13, the use of a wireless remote control in combination with a local user controller, allows for the synchronization of messages across multiple light emitting fabrics while still allowing individuals to locally control their content if they choose to do so.

Although this application has been successfully deployed in the event and exhibit market, it can also be used for many other possible markets, such as interactive gaming, social networking, and even education. With proper modifications to the various components in this system, new application possibilities in architecture/furniture, health, and well being and safety can also be realized.

Fig. 13. Synchronized messaging over multiple light emitting garments

5. Conclusion

In conclusion, we have shown a fabric substrate for electronic textile with robust interwoven connections between the conductive yarns in it. This fabric robustness, as a function of the electrical reliability of its conductive yarn connections, is shown to hold over large deformations. This fabric is then used to create an LED based photonic textile display. Finally, we have shown an application example that could make use of such a photonic textile system.

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