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# Connexion

## Development of interactive soft furnishings with polymeric optical fibre (POF) textiles

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## Abstract

Purpose – The purpose of this paper is to investigate how electronic components can be utilized and integrated into polymeric optical fibre (POF) textiles to refine the design aesthetic, tactile quality and initiate the interaction of textiles with the users; and to study the design process of interactive products by using a novel design process model.

Design/methodology/approach – Fashion and textile design methods, textile technology are used in combination with modern technologies such as laser engraving, sensing, short-distance communication technology, throughout the entire process of development of interactive photonics creations.

Findings – The results of evaluation indicate that the engineered prototypes can enhance the interactive function of interior furnishing. The usability of interactive POF cushions is optimized by innovative design methods considering both design and technology.

Originality/value – This research explores to combine knowledge from different disciplines, including textile, electronics, sensor and laser to create interactive soft furnishings. The inter-disciplinary research provides a new perspective on how POF fabric can be utilized as a new media to change the way people interact with their living surroundings. The interior soft furnishings are no longer unresponsive to people, but can react to them, adapt to their behaviors, change color according to their preferences and therefore merge into our daily life. The developed prototypes reshape interior soft furnishing, and therefore have both theoretical and practical significance.

Keywords Interactive textiles, POF fabric, Textile design

Paper type Research paper

## 1. Introduction

Interior soft furnishings are needed by people as an essential element in interior spaces. They provide people with comfort, increase their life standards and help to sustain activities in a more comfortable way (Nielson and Taylor, 1994). They turn the interior space into a personal and special space, and also reflect the user's personality.

As interiors are becoming multi-functional, interactive soft furnishings appealing to lifestyle enhancement and entertainment are more in demand in the market (Nielson, 2007). As suggested by Miriam Backstrom, the artist who creates luminous textile panel for Philips (2014), people are sensitive to movement, color, technique and interaction. Therefore, interactive interior textiles with changeable color and illumination can create a personalized interior environment and communicative platform, as people experience their surroundings through perception, cognition and construct meaning through color (Tang and Stylios, 2006). This research aims to investigate the integration and utilization of polymeric optical fibers (POFs) to create interactive photonic textiles, which can enhance and transform interiors via the change of colors and luminescence. A collection of interior soft furnishings is developed.

## 2. Research background

Photonic textiles with light emission can be realized by different methods. This section reviews the different technologies to develop photonic textiles, from commercial products to experimental prototypes.

### *2.1 Light emitting diodes (LEDs) embedded photonic textiles*

The photonic textiles developed by Philips are probably the best-known representatives for LEDs embedded photonic textiles. By sealing conventional low-cost LEDs into a laminated plastic panel that is flexible and durable enough to withstand constant flexing, the Photonic Textiles group at Philips Research has succeeded in embedding arrays of these LEDs beneath the surface of textiles, making it possible for soft furniture and clothing to come alive with myriad patterns of color light (Graham-Rowe, 2007). Layers of translucent textiles cover the LED panel to diffuse the light so that the pixels flow smoothly into each other and also provide the required level of softness and surface texture. Integrated electronics drives the LEDs to create fixed or moving patterns of light that bring the magic of illumination to the textiles. Their recent research "Luminous Textile" (Philips, 2014) is a unique ambient lighting system that integrates multi-colored LEDs within textile panels. Designed to create "mood walls" that can display dynamic content, the panels integrate lighting into a building's architecture to create decorative and ambient effects. Figure 1 shows a cycling jacket with LED lighting system, which can enhance the safety of cycling at night. This design won the Best of Best Design Award of Red Dot Design Award in 2013 (Langeder and Dils, 2013) (Figure 2).

Illuminating textiles with embedded LEDs emit bright light, various colors according to the LEDs, and therefore create a new and dynamic outlook for textiles. However, the integration of LEDs and relevant electronic devices into textiles appears to be very complicated. Meanwhile, due to the stiff nature of LEDs and electronic elements, the hand feel and tactility of the textiles are significantly degraded.

### *2.2 Photonic textiles with integrated electroluminescent material*

The Interactive Institute had developed interactive pillows (Figure 3) to enhance long distance communication (Dorrien *et al.*, 2014). When one of the pillows is hugged or leaned against, textile patterns are illuminated in the other pillow, which is located in a different place. The fabrics of the pillows are woven with electroluminescent wires and wool and are connected via an internet-based communication platform. The individual pillows can potentially be located nearly anywhere and wirelessly. The pillows add another layer of aesthetic and interpersonal experience in everyday contexts.

Another prototype based on electroluminescent material named "Digital Dawn" (Figure 4) was developed by Loop.pH (Wingfield, 2003), which is a London-based spatial laboratory experimenting across the fields of design, architecture and the sciences. Essentially a solar powered textile, the window lamp uses light sensors to monitor the changing levels of light in the room and then reacts accordingly so that the darker the room becomes, the more the foliage illuminates giving the impression of growth. The designer researched the creative use of light and illumination in an environment to help to alleviate the symptoms of seasonal affective disorder.

Figure 1.
The sporty supaheroe jacket

Figure 2.
Philips “Luminous Textile”

Luminescent fabrics have been created based on photo-luminescent glow yarn technology (Swicofil, 2014). The glow yarn is developed by mixing, melting and extruding polyester chips with photo-luminescent pigments. However, there is no control over the luminescence of the yarn and it cannot be switched on and off. Moreover, for its operation the fabric has to be exposed to a light source for a lengthy duration (sunlight for three minutes, or for 20 minutes to luminescent light) and even then the effect takes place in the dark, which may not be entirely desirable.

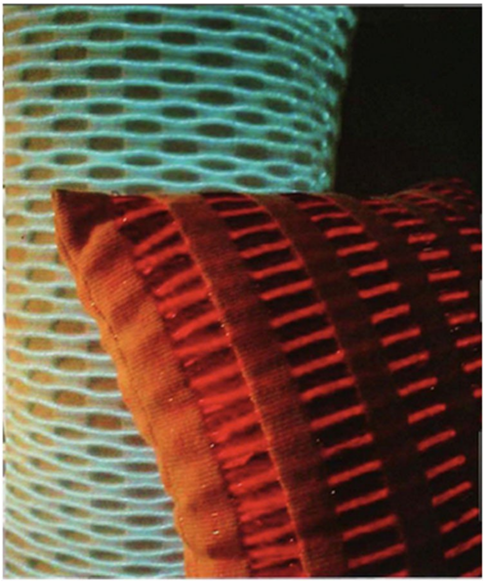

Figure 3.
Interactive pillow

Figure 4.
Digital dawn

Novel electroluminescent yarns based on electro-conductive have been developed which can present a unique luminescent effect (Dias and Monaragala, 2012). The general construction of the electroluminescent yarn is shown in Figure 5, where the base electrode comprises the electro-conductive yarn over which a layer of insulation paste and a layer of EL phosphor ink are applied. To protect the coated layers from moisture and abrasion, a transparent non-conductive flexible encapsulation layer is also applied. The second electrode comprises a similar electro-conductive yarn to the core yarn or a fine copper wire. This yarn is wound as a helix about the coated inner yarn.

With knitted with ordinary yarns, the electroluminescent yarns present a unique luminescent effect (Figure 6).

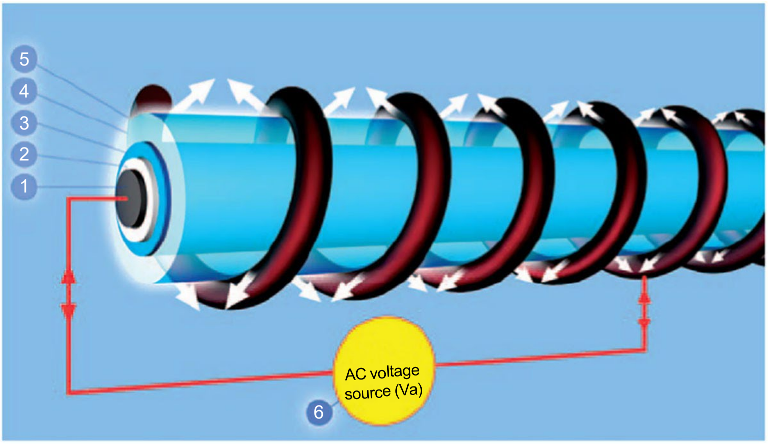


Figure 5.
Electroluminescent (EL) yarn construction

**Notes:** (1) Electro-conductive yarn; (2) dielectric insulation layer; (3) EL layer; (4) dielectric transparent layer; (5) conductive yarn; (6) alternating current voltage source

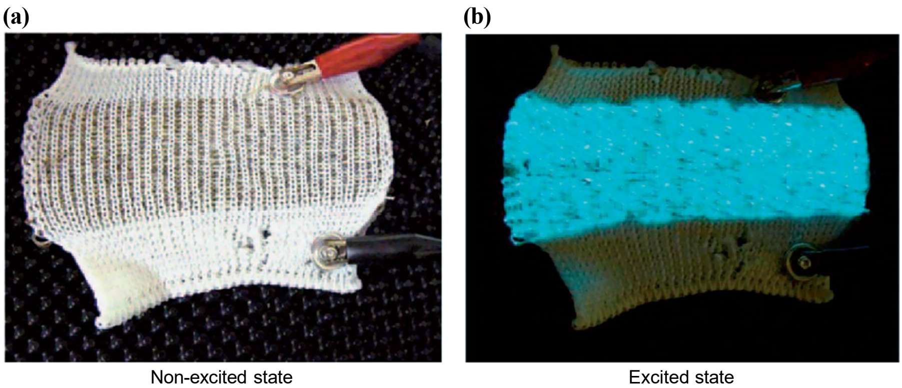


Figure 6.
Electroluminescent yarn inlayed into a fabric knitted from polyester yarn

Fabrics with electroluminescent yarns can present a unique luminescent appearing; however, the development of electroluminescent yarns seems to be very complicated. Also, the color of the electroluminescent yarns cannot be changed to meet different preferences of different users.

### *2.3 Photonic textiles based on photonic crystal fibers (PCFs)*

Recently, novel type of optical fibers, called PCFs, has been introduced. In their cross-section such fibers contain either periodically arranged micron-sized air voids (Morikawa *et al.*, 2006; Knight *et al.*, 1998), or a periodic sequence of micron-sized layers of different materials (Hart *et al.*, 2002; Benoit *et al.*, 2003; Dupuis *et al.*, 2007). By varying the size and position of the fiber structural elements one can design fibers of unique appearances. Some PCFs guide light using photonic bandgap effect rather than total internal reflection. Intensity of side-emitted light can be controlled by choosing the number of layers in the microstructured region surrounding the optical fiber core. When coupled with an optics lamp source, the PCF fibers emit guided color with a unique appearance (Figure 7) (Gauvreau *et al.*, 2008).

### *2.4 POF integrated photonic textile*

Research is also underway to the developments of POF fabrics for illumination purpose. In most cases, POFs are woven into a piece of fabric together with traditional textile yarns, like cotton or polyester yarns. With side-emission treatment, the light, which is from the light source coupled at POF ends, can leak from the fabric surface presenting an illuminating effect. POF-based photonic fabrics have been widely used in illumination purpose, such as illumination elements and textile displays (Harlin *et al.*, 2003), flexible soft screen (Koncar, 2005), Lightex®, the luminous interior textile of vehicles (Brochier, 2014), interior soft furnishings (Lumitex, 2014) and other end-uses (Paul, 1997) due to the fact that they combine the innovative illuminating effect with textile essence. The interactive function, however, between the end users and these POF fabric prototypes has not been fully developed.

A recently developed prototype “LightCloth” realizes the interactive function between the optical fiber fabric and ender user (Hashimoto *et al.*, 2013). The end user can use a RFRI pen to change the light of a photonic chair (Figure 8).

Due to the inherent properties, such as high flexibility, low stiffness, POFs are susceptible to textile manufacturing process to produce photonic textiles. However, as the side-emission of POF photonic textiles is highly depended on the light leakage caused by surface damage of POFs, the illumination intensity is normally inadequate, comparing to the photonic textiles with embedded LEDs. Therefore, POF photonic textiles are not applicable to luminous garment aiming to enhance the visibility during night for safety purpose, as illustrated in Figure 2.

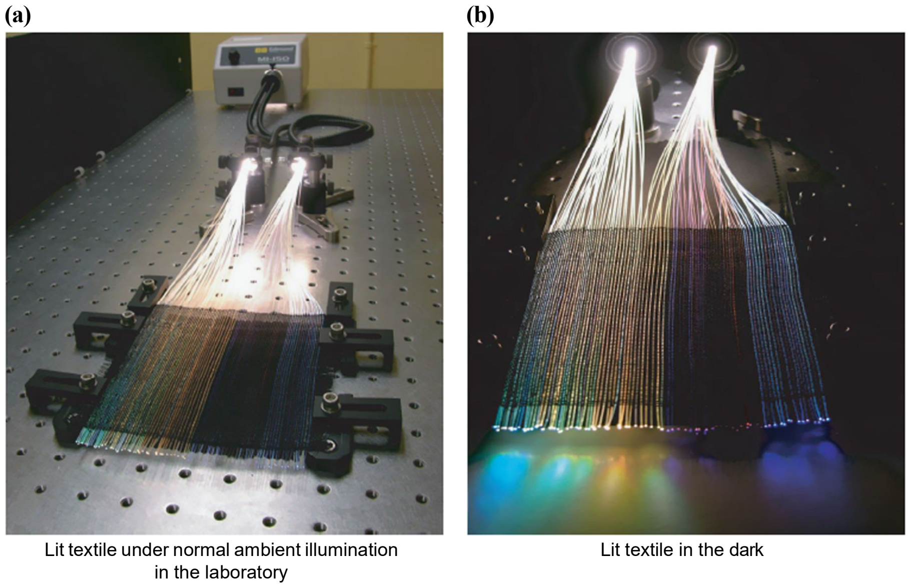


Figure 7.
PCF textile and light coupling set up

### *2.5 Design model*

Design of smart textiles with embedded electronics is different from design of conventional textiles in a sense that the former needs to combine textile design with technology development. In the design of smart clothing, some researchers have been aware that "Designers of smart clothing require guidance in their enquiry into the breadth and significance of the issues" (Dunne *et al.*, 2005). It was asserted that a new product design model must be formulated based on a smart clothing context (Ariyatum and Holland, 2003). The key issues presented by them are that the conventional structure of new product design models would fail to demonstrate the different work methods of the two sectors, electronics and fashion goods. Thus, a new product design model is needed to enhance understanding about the work and communication within the collaborative teams.

In another literature, the "Critical Path," a design tool, to guide the design research and development process in the application of smart technologies was proposed (McCann *et al.*, 2005). A design tool was developed to support innovative decision making in the sourcing and selecting of appropriate materials, technologies and construction methods. The process includes identification of end-user needs, fiber and fabric development and textile assemblies, and garment development. To maintain the balance of appearance and function, designers require guidance in their selection and application of technical textiles, style, cutting, sewing and finishing at every stage in the design research and development process.

Baurley (2005) suggested a design methodology for interactive design of smart clothing (Figure 9). The methodology consists of a conceptual framework, user study and design building. The framework is based on observations and research on how

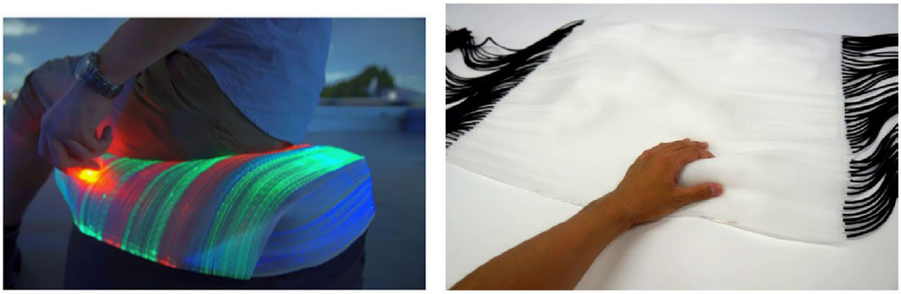

Figure 8.
LightCloth

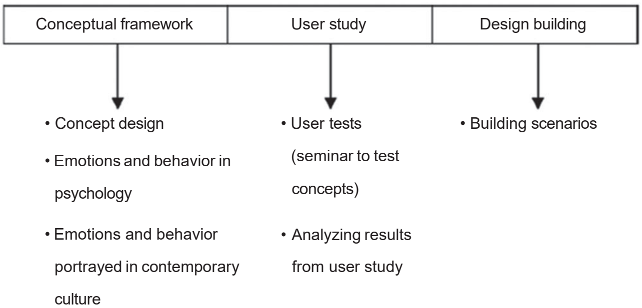


Figure 9.
Interactive design of smart clothing

people use, interact with and experience the conventional clothing. User studies are based on user groups and they are again fed back into the framework.

The design methods above facilitate the design of smart textiles and clothing. There is a lack of methodology, however, in the design of photonic soft furnishing. Existing design models fail to reflect the highly reflective and iterative process in the design of photonic interactive textiles. As the design process of photonic interactive textiles is a highly reflective process whereby designs evolve concurrently and simultaneously with the development of materials, processes and forms, traditional design approach may not apply. A new design method needs to be established.

From the literature review, it is found that only a few photonic textile prototypes can interact with the end-user. Although the attention on multi-disciplinary collaboration for improvement of the usability of POF fabrics has been raised, the usability is still far from satisfactory. There are still some challenges in introducing interactive POF textile into real life:

(1) POF fabric with interactive function in terms of changeable color and tunable color has not been fully developed. The interaction between the user and the POF fabric is very limited.

(2) Improving the usability of POF fabric for daily product is still a big issue. The process of development is time-consuming. The design process needs to be improved.

(3) A novel design method for development of interactive soft furnishing is lacking. The development of this interactive system needs collaboration between design and technological disciplines.

This paper aims to develop interactive furnishings which can interact with user by changeable and tunable color. First, the design method is introduced, and a design model is developed. Second, the technologies to develop interactive soft furnishings are demonstrated, including textile design, laser treatment to cause side-emission, lighting system design and interactive function design. The final product is created after experiments. Lastly, both objective and subjective evaluation are conducted to assess the prototypes.

## 3. Design methods

For the design of photonic interior textiles, the usability of final products needs to be considered. It is very important that the electronics including light sources and control devices are unobtrusive. In addition, most of the interior products need to be lightweight, durable and mobile.

In this study, based on previous research (Tan *et al.*, 2013) a novel design method to develop interactive textiles is proposed (Figure 10). Fashion and textile design methods and textile technology are used in combination with modern technologies throughout the entire process of development of photonic creations. In the design framework, every stage involves the integration of technology and design. The development of one part simultaneously affects its counterpart, and therefore the design process is both continuous and evolutionary as seen in Figure 10. For instance, in stage one, the selection of the material and the design of the creation should work in tandem as both aspects are required to express the design effectively while the strengths and constraints of the materials should also be considered. In stage two which involves the weaving process, it is important to utilize the weaving technique to create an aesthetic

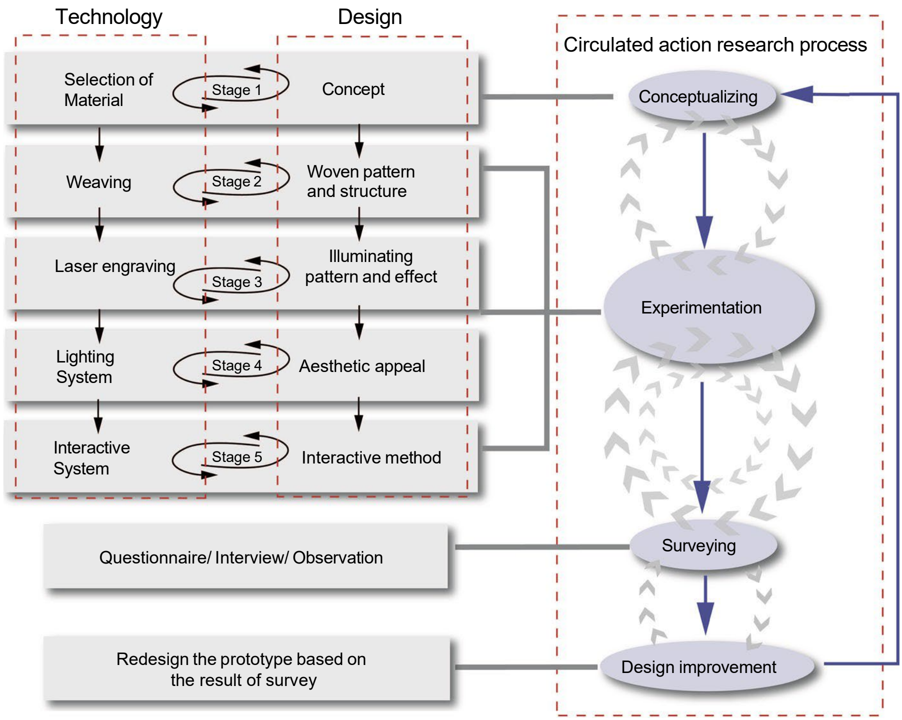


Figure 10.
Design process model

design yet taking account of the fragile and brittle nature of POFs. The design process needs to be continuously revised and refined after conducting numerous practical experiments. In stage three, the lateral illumination of optical fiber fabric is achieved by laser-engraving technology. Laser engraving creates physical damage onto the surface of the POF to create minute cracks which allow light to be emitted. The dual roles of design and technology work closely to create products with both aesthetic appeal and technological functionality with innovation. The fourth and fifth stages of the design process whereby the LEDs and sensors are integrated into the textiles and final creations present challenges to the design aesthetics of the products due to the bulky and obtrusive nature of the electronics. The unobtrusive presence of electronic parts enables the seamless integration of innovative technology into value added everyday products.

The design process is a reflective cyclic process which involves continuous improvement of developed prototypes (as illustrated on the right side of Figure 10). Conceptualization, experimentation and surveying are three integral processes; the development in each is reflected in the other. The design process is a continuously evolving and improving until the final products are refined to ensure they meet aesthetic, functional and practical functions.

### *3.1 Textile design*

Jacquard-weaving technology is utilized for the development of POF fabric sample, since it has the advantages of realizing various textile structures of POF fabric (Clayton, 2006; Koncar, 2005; Wang *et al.*, 2012), in addition, reducing the damage of

POFs during weaving compare to knitting. Toray® optical fibers of 0.25 mm in diameter are inserted as weft yarn with blue cotton threads, and the proportion of the optical fibers and cotton threads is 1:1. The warp is white polyester yarn. The essential specifications are shown in Table I.

First, graphic pattern is drawn by CAD. Continues geometrical pattern is designed followed by the trends forecasting of soft furnishing (WGSN, 2014). Second, the weaves are designed by ArahWeave® software. In order to allow as many as optical fibers appear on the surface of the fabric, double-layer weave structure is created by the combination of eight end sateen weave (Figure 11). The density of weft yarn is 46 picks/cm, while the density of warp yarn is 50 ends/cm. Then, the designed pattern is produced by the jacquard-weaving loom Dornier Weaving Loom PTV 8/J with the STAUBLI Jacquard Head JC6. POF fabric sample with dimension of 170 cm/400 cm is successfully developed (Figure 12).

| | Material | Yarn count number | color | density |
|---|---|---|---|---|
| Warp thread | Polyester yarn | 100 Denier | White | 50 ends/cm |
| Weft thread | Blue cotton yarn | 2/32 s | Blue | 23 picks/cm |
| | Polymer optical fiber | 0.25 mm in diameter | – | 23 picks/cm |

Table I. Essential specification of POF jacquard fabric

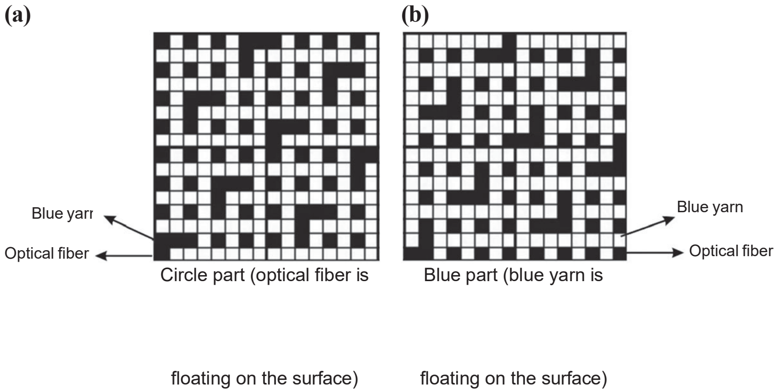


Figure 11. Double-layer weave structure

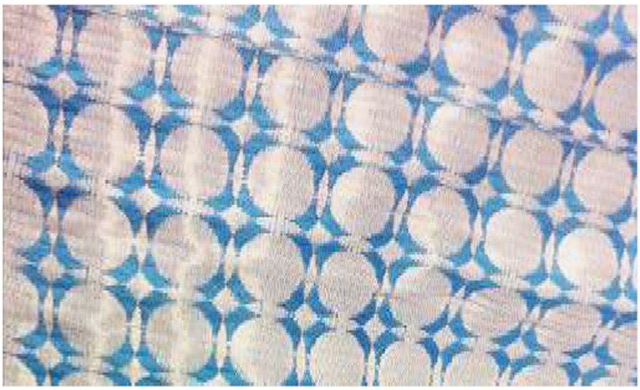

Figure 12. POF fabric sample with circles pattern

### 3.2 Side-emission of POF fabric

Traditional treatments to promote side illumination involve thermal, physical or chemical damages of cladding of photonic fiber (Koncar, 2005). Side notching allows simple figures of light dots, whereas surface abrasion leads to a more even light distribution (Harlin *et al.*, 2003). Alternatively, Bragg gratings or scattering particles such as imperfections in the fiber core evoke light emission (Gauvreau *et al.*, 2008). However, these treatments are very rough and difficult to control, and only simple cutting pattern can be obtained. Laser engraving was employed to create lighting patterns (Bai *et al.*, 2012; Bai and Tan, 2013). Laser engraving is a technology that uses a high-power laser to cut materials, and the engraving can be precisely is controlled by a computer. In this paper, GFK Marcatex Flex-150 $CO_2$ laser, coupled to an Easymark® 2009 laser system is utilized for side-emission. First, the POF fabric is placed onto a platform, and a laser is directed to the fabric surface. The predefined engraving pattern is achieved by repeated laser scanning across the fabric surface. Laser power is determined by two parameters: resolution (in dpi) and pixel time (in $\mu$s). By altering the resolution of the designed pattern and the pixel time of the laser radiation, different engraving parameters can be achieved across the fabric surface and photonic fibers are damaged to different extents, and therefore different side-lighting effects of the photonic fibers are realized.

If POFs are engraved to the same extent, more light is emitted from the cracks which are closer to light source, leading to uneven illumination along POFs length. In order to achieve a comparatively even light emission along the POFs length, the engraving pattern is design to be gradually changed in gray level along the POFs to be treated (Figure 13). The laser machine adjusts the engraving power automatically according to the gray level. At bright area (close to light source), weaker laser is directed to POFs and less cladding is burned, and therefore less light emits from the POFs. At dark area (far from light source), stronger laser is applied to POFs. Hence more cladding is burned out, and more light is emitted from the cracks. In this way, comparatively even light emission along POFs length can be achieved.

### 3.3 Lighting system

Depending on the application of the POF fabrics, various light sources can be connected to optical fiber ends. Bright LEDs (Graham-Rowe, 2007) have been used for illuminating applications due to the fact that the light produced is cool, and the light source can be remotely located. Moonstone® Tri-Color Power LED is used as light source in this study (Figure 14).

This LED adopts eight bit full scale. By mixing the primary RGB color, different colors can be obtained. The color of LED is controlled by a predetermined program based on pulse-width modulation. A number of optical fibers are bundled together and cut. All the ends of optical fibers are then polished and coupled to a LED, which is packaged in a control box (Figure 15), through a customized coupler based on cable gland.

Compared to the LED used in previous study (Bai *et al.*, 2012; Bai and Tan, 2013), the LED used in this paper (Figure 14) is super bright. As the size of the LED is larger, the number of optical fibers coupled to the LED can be larger accordingly. This advantage can greatly reduce the number of LEDs used for a certain number of optical fibers. On the other hand, traditional method to couple POF bundle with LED needs to use optical glue (Bai and Tan, 2013; Bai *et al.*, 2012; Tao *et al.*, 2008), which is time-consuming. Coupler based on a cable gland avoids the application of optical glue, and therefore, the

Figure 13.
Graphic design pattern for laser engraving

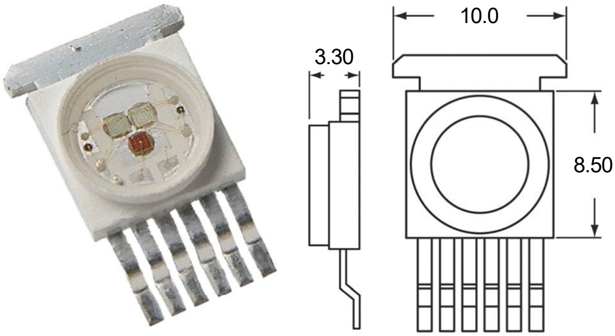


Figure 14.
Moonstone® Tri-Color Power LED light source (the unit of dimension is mm)

time for coupling of LEDs and optical fibers are dramatically reduced. The coupling efficiency is hence significantly improved. A rechargeable battery is adopted as the power of the whole system. All the electronic components are docked in the plastic control box.

*3.4 Design of interactive system*

The rationale of design of interactive POF cushion is to enhance the usability of POF-based soft furnishing in real life. The end users can interact with the interior furnishings and change the color of interior textile according to their own preferences and engage with their living environment. In this section, three POF cushions in

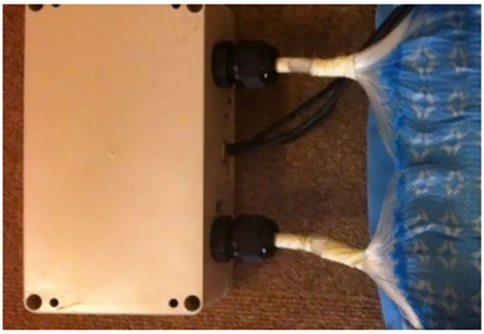

Figure 15.
Control box

different sizes with interactive function in terms of changeable color are designed. Since people always hug or sit against cushions, the interactive function is designed related to touch behavior. Intelligent POF fabric system and communicating system are built up to realize interactive activities between user and cushion, or among multiple users. The whole prototype should be lightweight and have a similar appearance to ordinary cushion.

*3.4.1 Intelligent POF fabric system*. In order to achieve the color-changing function, an intelligent POF fabric system is developed as shown in Figure 16.

Bundles of POFs are connected to LEDs, which are packaged in the control box. Three conductive aluminum foil tapes are placed beneath the POF fabric. The capacity-sensitive foils are used to detect the touch on the cushion and then control the illumination color of the POF fabric through a controlling system. These foil tapes are wired to touch sensors, and all sensors are connected to a printed circuit board packaged in a controlling box. The colors of the LEDs are controlled by sensing the

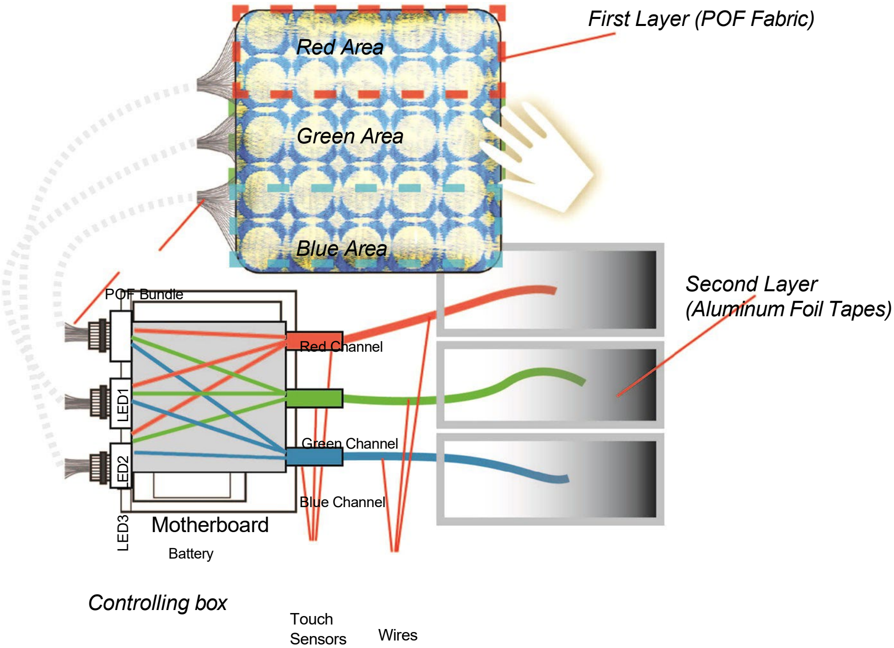


Figure 16.
Intelligent POF
fabric system

change of electric capacity through the conductive tape. Each foil tape is responsible for the control of one primary color (red, green or blue), and the corresponding areas on cushion surface are so-called red area, green area and blue area. For example, if the red area is touched, then all LEDs illuminate red color, and hence the entire cushion surface is red color (Figure 17). When both red and blue areas are touched, the cushion presents a mixed color between red and blue (Figure 18).

*3.4.2 Communicating system design*. Interactive furnishings can be employed as an adaptive media to transfer the ambience of interior spaces to suit different users and purposes. In order to further explore the interaction between interior furnishing and multiple users, three photonic cushions are engineered as a group with communicating function between each other. A digital radio frequency running ZigBee (Wikipedia, 2014), which is a specification for a suite of high-level communication protocol, is utilized to create a personal area wireless network in 2.4 GHz frequency band. ZigBee is based on an IEEE 802.15 standard, and it is a low-cost and low-power wireless mesh network. The low cost allows the technology to be widely employed in wireless control and monitoring applications. Two different interactive modes are developed to exam the interactive function of photonic cushion, i.e., synchronized mode and flash mode. Under synchronized mode, when any cushion is touched and a color is trigged, all other two cushions present the same color (Figure 19). Under flash mode, when one cushion is touched, the other two cushions flash in different colors (Figure 20).

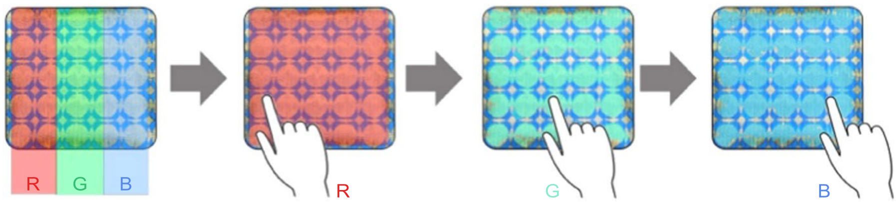


Figure 17. Color of cushion when different area (red, green or blue) is touched

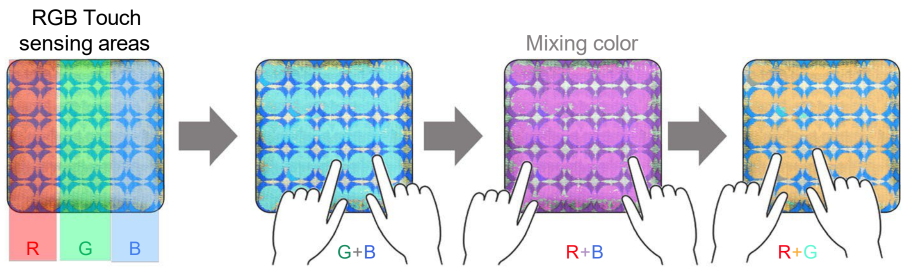


Figure 18. Color of cushion when more than one area are touched

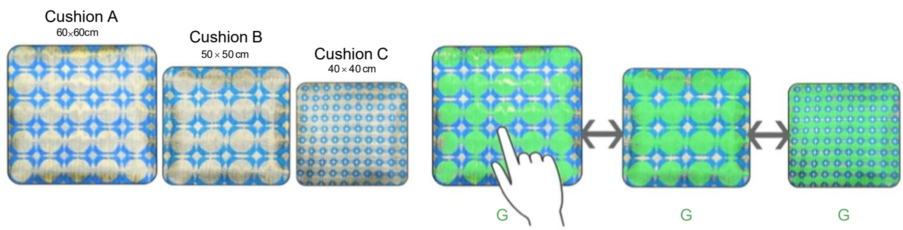


Figure 19. Synchronized mode

In order to control all the electronics to realize the designed interaction for individual cushion, a controlling system for cushion is designed. A central control console system is also designed to control the communication between all cushions. A schematic diagram of the control system is illustrated in Figure 21.

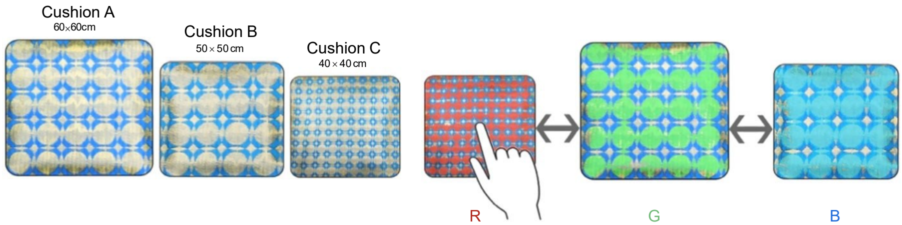


Figure 20.
Flash mode

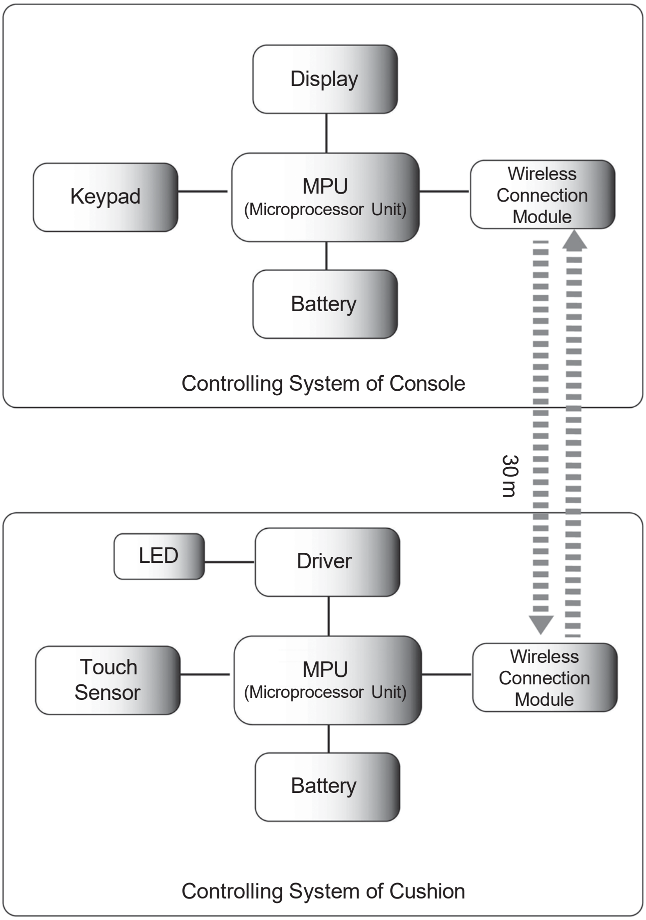


Figure 21.
Controlling
system design

## 4. Results

### *4.1 Developed prototypes*

A collection of interactive POF soft furnishing named "ConneXion" is created, and the collection has been exhibited (Tan *et al.*, 2013). Cushions of different sizes in 60/60 cm, 50/50 cm and 40/40 cm are designed in order to fulfill different demands from users. The POF fabrics are cut and sewn into the cushions as faces. Light is emitted from the surface of cushion due to the damage of POF cladding caused by laser-engraving treatment.

Figure 22 presents the inside structure of interactive photonic cushion. Optical fibers are bundled and connected to LEDs by the tailor-made coupler (cable gland). All the electronic components including LEDs, microprocessor unit (MPU), battery, driver, communication module are packaged in a detachable plastic box. RGB color areas are determined by three aluminum foil tapes which are connected to the touch-on sensors by wires. The aluminum foil tapes can detect the touch signal and transmit the signal to MPU in order to realize the color-control by touching.

By touching different areas on cushion, different RGB channels are triggered, and different colors on cushion surface can be achieved. When green area is touched, green channel is triggered and all three LEDs emit green color, and therefore the cushion illuminates green color. When green area and red area are touched simultaneously, all LEDs emit yellow color, and then the cushion presents yellow color Figure 23.

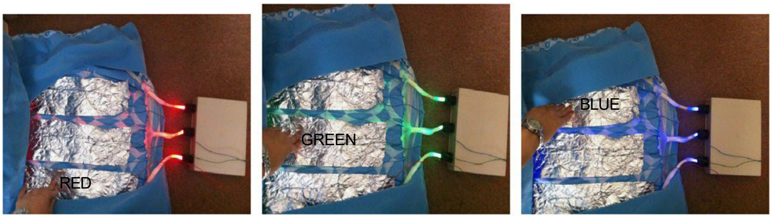


Figure 22. Inside structure of the cushion. When different areas are touched, different colors are triggered

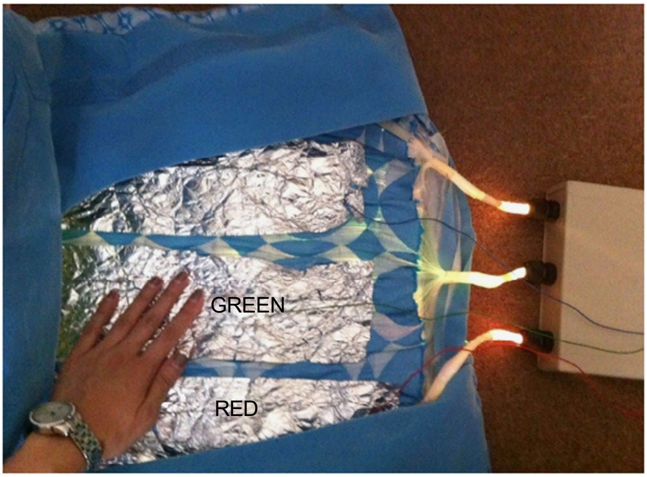


Figure 23. When green and red areas are touched at the same time, yellow color is illuminated

An intelligent control system is built up by utilizing wireless communication technology. Three cushions can work individually (individual mode) or work together (interactive mode) under the control of a console (Figure 24). The console is in small size and easy to control.

Individual mode and interactive mode can be switched by pressing the button on the console. The max distances for wireless communication can be 30 meters between the cushion and the console. Under the individual mode, user can change the color of each cushion by touching the surface of the POF fabric. Under the interactive function, short-distance communicative function is turned on. Two interactive modes are developed, i.e., synchronized mode and flash mode. Under synchronized mode, when one cushion is touched, the other two cushions show the same color at the same time (Figures 25 and 26). Under flash mode, when one cushion is touched, the other two cushion flash in different colors (Figure 27).


Figure 24.
Console

Figure 25.
Synchronized mode – when only one area is touched

Figure 26.
Synchronized mode – color is mixed when more than one area are touched

Figure 27.
Flash mode

*4.2 Evaluation*

*4.2.1 Subjective evaluation*. A survey is conducted to evaluate the usability of Connexion. The purpose of the survey is to obtain the preferences of end users and then provide suggestions to further improve the design in the future work. The background of subjects we interviewed are very diverse, including financial manager, doctor, housewife, company owner, hotel manager, fashion designer, interior designer, students in different levels, tourist, retiree, etc. The subjects were given an introduction of the exhibition and the products, and then the questionnaire was finished by each subject. Totally 90 peoples were invited to participate this survey. All subjects were classed into four groups according to the ages of subjects, namely, Group 1: under 25 years (38 peoples), Group 2: 25-34 years (24 peoples), Group 3: 35-44 years (16 peoples), Group 5: above 45 years (13 peoples).

In the first part of questionnaire, the subject was asked to rank the performance of Connexion according to a seven-point scale. As design concept, comfort and appearance are some of the most important aspects of textile quality, and these properties constitute the primary elements to drive the consumers to purchase the textile products, in the first part of the questionnaire the subject was asked to evaluate the performance of the prototype by rating different aspects of photonic cushion including design concept, aesthetic consideration, comfort, convenience, illumination and interactive function. Each performance was given a numerical grade from 1 (very unsatisfactory) to 7 (very satisfactory). The overall grade is obtained by taking average of the grades from all subjects. The following illustrations show the quantitative results (Figure 28).

In order to examine if the difference between grades of different properties is statistically significant, single-factor ANOVA is performed to analyze the variance for all age groups, and one of the results (Group 1 under 25 years old) is presented in Tables II and III.

Above results indicate that there is a similar trend for all age groups. For all subjects, they are satisfied with the prototypes in terms of design concept, aesthetic consideration, illumination and interactive function, with overall rating above 5.5. Two main drawbacks of the prototypes include comfort and convenience. Not surprisingly, the comfort and hand feel of the prototype is less satisfactory due to the introduction of POFs and the rigid nature of POF. Further study is needed to experiment with different materials to improve the hand feel of POF fabric.

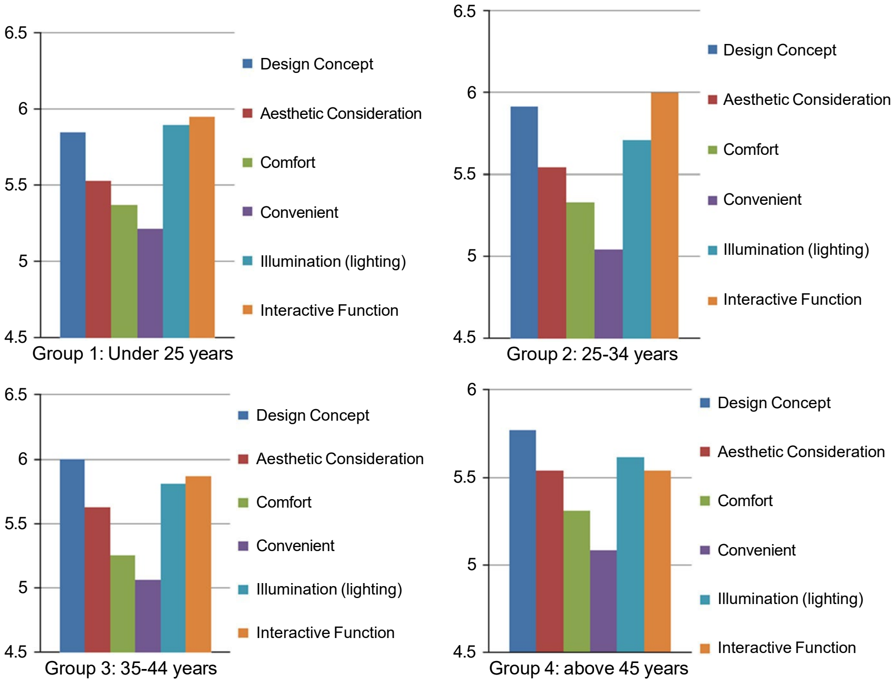


Figure 28.
Numerical grades of different attributes for different age groups

Table II.
Statistics summary

| Groups | Count | Sum | Average | Variance |
|---|---|---|---|---|
| Design concept | 38 | 222 | 5.8421 | 0.6771 |
| Aesthetic | 38 | 210 | 5.5263 | 0.9587 |
| Comfort | 38 | 204 | 5.3684 | 1.1038 |
| Convenience | 38 | 200 | 5.2632 | 1.4424 |
| Illumination | 38 | 224 | 5.8947 | 1.1238 |
| Interactive function | 38 | 226 | 5.9474 | 1.1323 |

Table III.
ANOVA results

| Source of variation |
|---|
| Between groups |
| Within groups |
| Total |

Notes: Since *p*o0.05, this suggests that the difference between grades of different properties is significant. For all other age groups, similar results are found

Another challenge is the convenience to use. This prototype uses a control box with rechargeable batteries to control all electronics. The batteries need to be recharged for continuous use, which appears to be inconvenient for some users. However, comparing to electric wire connected to alternating current, rechargeable battery seems to be more favorable due to its mobility and flexibility.

In second part of the questionnaire, close-ended questions are designed, including the following questions:

*Q1.* Which mode do you like the most?

*Q2.* Do you agree that Connexion can enhance interior environment?

*Q3.* Would you like to use this kind of product in your home if it is available in the mass market?

The responses to *Q1* are summarized in Figure 29.
It is interesting to note from Figure 29 that the subjects in Groups 1, 2 and 3 like flash mode the most, while the subjects in Group 4 prefer individual mode. The results reflect that most of the users below 45 years old recognize the flash mode as their favorite probably due to the dynamic color of the flash mode. However, flash light seems not appealing to the elderly.

Figure 30 presents the results of *Q2*. Most subjects (71 percent in Group 1, 79 percent in Group 2, 82 percent in Group 3 and 85 percent in Group 4) agree or strongly agree that Connexion can enhance the interior environment.

The responses to *Q3* are shown in Figure 31. Most subjects would like to use this kind of product at their home, and these products seem to be more attractive to people below 45 years old. The results are quite positive. This indicates that the users are quite interested in the interactive photonic cushions. The result also reveals that interactive photonic soft furnishing has huge demands if it can be commercialized.

*4.2.2 Illuminance evaluation*. As illumination is one of the main highlights of the prototype, an illuminance meter (Figure 32) is adopted to test the illuminance of photonic cushions.

The illuminance was measured in a darkroom. The measurement was performed at ten different locations selected randomly on the surface of the cushion for each RGB colors. The results are pre presented in Table IV.

The illuminance measured at different colors is in the range of 0.02-0.5 $lm/ft^2$, which is in a level of TV lighting under dark environment. This illuminating level provides a certain level of illumination, and meanwhile presents a sparkling and unique

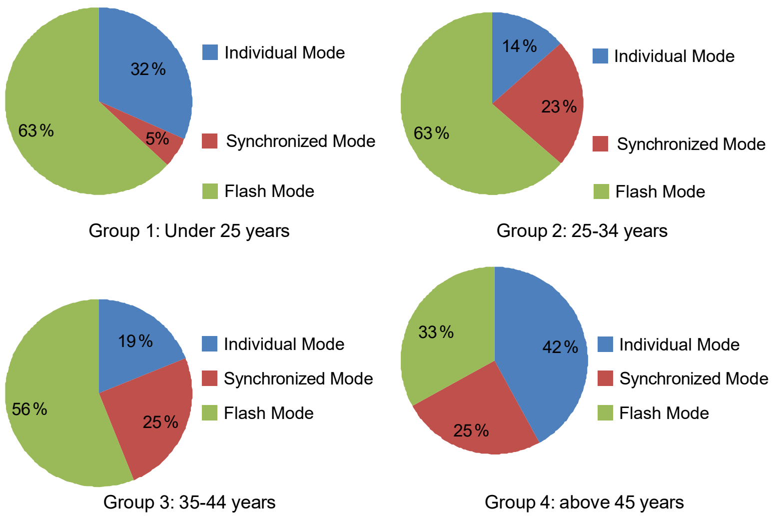


Figure 29. Responses to *Q1* – which interactive mode do you like the most?

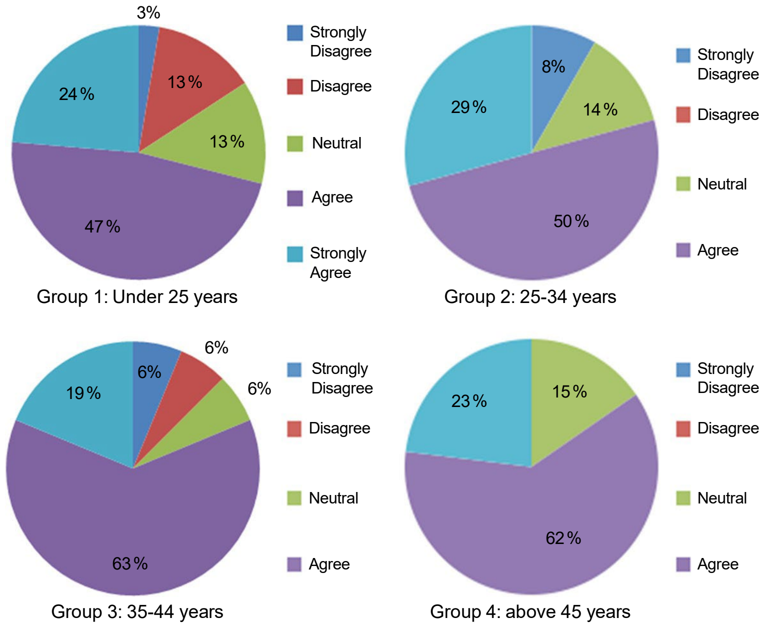


Figure 30.
Responses to *Q2* – do you agree that Connexion can enhance interior environment?

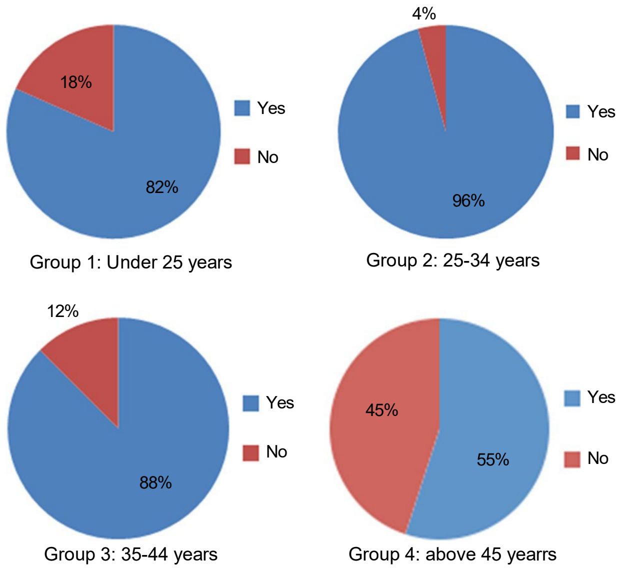


Figure 31.
Responses on *Q3* – would you like to use this kind of product in your home if it is available in the mass market?

appearance under darkness. It is also founded that the illuminace level of green color is the highest, blue color is the lowest and red color is in the middle. This observation is in agreement with the luminous specification of LED (Table V).

Table IV also indicates that for all three colors, the variation of illuminance measured at different locations is quite significant. Due to the flexible and uneven


**Figure 32.**
Illuminance meter

| | Lowest | Highest | Average | SD |
|---|---|---|---|---|
| Red | 0.07 | 0.37 | 0.265 | 0.191 |
| Green | 0.05 | 0.73 | 0.375 | 0.309 |
| Blue | 0.01 | 0.06 | 0.025 | 0.015 |

**Table IV.**
Illuminance for different colors ($lm/ft^2$)

| Color | Luminous flux (lm) Min. | Typ. | Max. |
|---|---|---|---|
| Red | 33 | 40 | 56 |
| Green | 43 | 55 | 95 |
| Blue | 9 | 13 | 19.5 |

**Table V.**
LED luminous flux specification

nature of fabric in combination with the difficulty to control the light emission averagely, even illumination over the fabric surface still remains a big challenge.

## 5. Conclusion

The POF textiles can be effectively applied onto soft furnishings to create a communicative platform. Interactive POF cushions are successfully developed in this research which enables the single user or multiple users to change and mix colors of interactive cushions by touching the surface of the POF fabric. Wireless communication network and sensing technology are integrated to build up an intelligent system. Two interactive modes are developed therefore three cushions also can interactive with each other under the synchronized mode and flash mode. The usability of interactive POF cushions is optimized by innovative design methods considering both design and technology.

Research on interactive soft furnishings is very limited. This research explores to combine knowledge from different disciplines, including textile, electronics, sensor and laser to create interactive soft furnishings. A novel design model to address the highly reflective nature in the process to develop interactive soft furnishings is proposed. The inter-disciplinary research provides a new perspective on how POF fabric can be utilized as a new media to change the way people interact with their living surroundings. The interior soft furnishings are no longer unresponsive to people, but can react to them, adapt to their behaviors, change color according to their preferences, and therefore merge into our daily life. The developed prototypes reshape interior soft furnishing, and therefore have both theoretical and practical significance.

This study has several limitations. First, it is suggested from the survey that the comfort and usability of POF-based textiles need to be further improved. Second, the interaction between the prototypes and user is limited to several modes. Enhancement on the interaction and the controlling system is deserved to be further studied. Finally, the color spectrum of the illuminating prototypes is not sufficiently broad. Interactive photonic cushion could show more color combinations by further development of controlling system of LEDs.

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