INNOVATIVE PHOTONIC TEXTILES: THE DESIGN, INVESTIGATION AND DEVELOPMENT OF POLYMERIC PHOTONIC FIBER INTEGRATED TEXTILES FOR INTERIOR FURNISHINGS

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Bai Ziqian

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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_______________________________ (Signed)

Bai Ziqian (Name of student)

To My Family

For Their Love, Patience and Support

ABSTRACT

With the emerging development of smart textiles, photonic textiles and clothing are attracting attention from research academics and the commercial market. Polymeric Optical Fiber (POF) integrated textiles have huge potential in the future light-emitting products in interior design, as they possess both the tactility of familiar textiles and the functional purpose of a light source. A review of current research indicates two neglected areas. Firstly, current research has mainly focused on the technological development of POF textiles thus neglecting the design process and the interdisciplinary approaches taken when developing POF textiles. Secondly, the investigation of interactivity is limited as most current products place emphasis on the practical light function of the POF textile. This research will aim to address these research gaps.

This project proposes to investigate the integration and utilization of POFs to create textiles for interior furnishings which can be interactive with the user in terms of change in color, luminescence and surface pattern. The aims of this project are to explore how POF fabric can be utilized as a new media to change the way people interact with textiles and other users, and to design innovative interior soft furnishings which are no longer irresponsive to us, but can react to us, adapt to our behaviors, change color according to our preferences, and therefore merge into our daily life.

In this interdisciplinary research, conventional textile techniques are used in combination with modern technologies throughout the entire process of the development of photonic creations. Weaving, dyeing, printing and embroideries are applied to enhance the surface design of POF textiles. Laser engraving is utilized to obtain the desirable illuminating

patterns on POF textiles. The dual roles of design and technology work closely to create products with both aesthetic appeal and technological functionality with innovation. The process of development POF textile product is optimized. Finally, a design process model is built up to systematically guide the design of photonic product.

By combining the cutting-edge technologies in sensors, communication, electronics, etc., the real-time interactive systems are realized in the developed prototypes. Several innovative photonic interior soft furnishings, textile installations and fashion garments are designed and showcased in exhibitions. Users can control the color, intensity and duration of light by remote control. Under interactive modes, the photonic prototype can sense the stimuli from users, and respond with changing illuminations. Both objective and subjective evaluations are carried out to assess the performance of the prototypes. The results indicate that the engineered prototypes can enhance the interior environment, and the prototypes have the potential to be commercialized.

The interactive photonic artworks offer a different perspective on the relationship between user and interior furnishings. Users can gain co-experience with other users via using interactive textiles as a media. This research provides an insight into the design of interactive interior textiles, and contributes new knowledge and recognition to textile design for interiors and smart fashion.

PUBLICATIONS ARISING FROM THE THESIS

Refereed Journal Papers

1. Bai, Z.Q., Tan J., Johnston, C. and Tao, X.M., (2014) *Connexion: development of interactive soft furnishings with Polymeric Optical Fibre (POF) textiles,* International Journal of Clothing Science and Technology (in press, will be published in vol: 27, iss:6)
2. Bai, Z.Q. and Tan, J., (2012) *Innovative design of polymeric photonic fiber fabric for interior textiles*. Research journal of textile and apparel, 17:10-5.
3. Bai, Z.Q., Tan J., Johnston, C. and Tao, X.M., (2012) *Enhancing the functionality of traditional interior textiles by integration of optical fibers*. Research journal of textile and apparel, 16(4): p. 31-38.

Refereed Conference Paper

1. Zhao, C.C., Tan J., Bai, Z.Q., Hua, T., (2014) *Innovative fashion design via the integration of photonic textile technology,* Fashion in Fiction: Style Stories and Transglobal Narratives Conference, CityU Hong Kong June 12-14
2. Bai, Z.Q., Tan J., Johnston, C. and Tao, X.M., (2013) *Integration of surface printing and laser-engraving technology for design of color-changeable POF fabric*, 13th AUTEX World Textile Conference Dresden, May 22-24.
3. Tan, J. and Bai, Z.Q., (2011) *Innovative design of photonic interior textiles*, 8th International Shibori Symposium, Hong Kong. p.75-77.
4. Tan, J. and Bai Z.Q. (2011) *Integrating Chinese culture and technology for interactive textiles*. Proceeding of 2011 Korean society costume conference. October 22nd.

5. Bai, Z.Q., Tan J., and Tao, X.M. (2011), *Surface printing and photonic fibers for interactive interior textiles*. Proceeding of The Fiber Society 2011 Spring Conference. Hong Kong SAR, China. p. 150-151.
6. Bai, Z.Q., Tan J., and Tao, X.M. (2011), *Interactive interiors: preliminary study of integrating textile embellishment techniques and polymeric photonic fibers for interior textiles*. Proceedings of designing pleasurable products and interfaces conference 2011, Milan, Italy. p.279-282.

Research Awards

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2. Excellent Award, *Linear* at the 1st Contemporary Chinese Fiber Art Exhibition organized by the China National Arts & Crafts Society, Jilin College of Art Gallery. September 2011

Exhibitions

1. Tan, J., Bai, Z.Q., *Lucent illusion,* 14th China textile design competition & international conference 2014, Tsinghua University, Beijing.
2. Tan, J., Bai, Z. Q., Tao, X. M. & Luximon, A. , *Neo-Neon*, “Reflection of Time: Art of Fashion in China 1993-2012”, Today Art Museum, 5-25 Sep., 2013, Beijing, China
3. Tan, J., Bai, Z.Q., Ho, M., etc., “Neophotonics” Exhibition, Hong Kong Medical Science Museum, 1-7 July, 2013, Hong Kong. Reviewed by Prof. Paola Bertola, Professor of Fashion Design, Design Department, Politecnico di Milano

4. Tan, J., Bai, Z.Q., Fang J.P., Clare Johnston, *The white blossom,* The 7th 'From Lausanne to Beijing' International Fiber Art Biennale Exhibition, 8 Nov-15 Dec 2012, Nan Tong, China
5. Tan, J., Bai, Z.Q., Clare Johnston& Tao X.M., *The glowing object*, New Technology Zone of Interstoff Asia Essentials, organized by HKRITA. March, 2012, HKCEC
6. Tan, J., Bai, Z.Q. & Clare Johnston, *Circles,2012,* Beat + Energy Nexus: International Shibori Design Exhibition, Feb, 2012, Fo Shan, China
7. Tan, J., Bai, Z.Q. & Tao X.M., *Rhythm,* "Energy Nexus" exhibition,8th International Shibori Symposium Dec, 2011 – Jan, 2012, Hong Kong
8. Bai, Z.Q, Tan, J. & Tao X.M., *Linear*, "1st Contemporary Chinese Fiber Art" Exhibition，organized by China National Arts& Crafts Society, Jilin College of Art, Sep 2011, China.
9. Bai, Z.Q, Tan, J. & Tao X.M., *Chionis Photonics*, "Future Photonics" Exhibition, Aug, 2011, Hong Kong Innovation Centre. Reviewed by Prof. Robert Young, Professor of Polymer Science and Technology. School of Materials, University of Manchester.
10. Bai, Z.Q., Tan, J. &Tao, X.M., *Sculpting light* exhibited at Ocular Simulacrum, Fashion Gallery. April 2011. Hong Kong

Exhibition Catalogues

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2. Tan, J., Bai, Z. Q., Tao, X. M. & Luximon, A. (2013). Neophotonics. ISBN: 978-962-367-764-6

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1. **Introduction**

1.1 Background

Textiles form powerful interior components as they combine three strong design elements: the emotion of color, the impact of pattern and tactile qualities sensed through visual perception and physical touch (Rowe, 2009). They do much to create the mood of an interior through their contributions to color, texture, pattern or motif, and performance. They soften the contours of the furniture, finish walls and windows, and otherwise enhance the interior. They can make a space more pleasant for work, relaxation, and human interaction. With their soft and comfortable tactility, textiles can offer physical advantages to interiors such as sound absorption, privacy, comfort, enhanced safety and aesthetics, and can also set a mood, establish a theme, and secure an ambience to create a great interior environment. By choosing the right combination of interior textiles, interior conveys a pleasant ambiance, and therefore can be made to reflect individual taste and meet everyday functional needs.

The textile industry is now undergoing a major reconstruction and reorientation from a low-technology industry toward a high-technology enterprise in both apparel and non-apparel applications. Starting from the economic crisis in 2008, consumers have tended to spend less money on consumables (including textile products). With the shrinkage of the global textile market, most key players in the textile industry struggle to place more orders on performance textiles with high added value, which are more appealing to the consumers. These added features include functional materials, high-performance fabrics, smart materials, nanotechnologies, e-textiles, etc. This drives the textile firms around the world to put more effort on textile innovation and become more efficient through technology upgrades. The textile industry is now embracing many technologies and innovations from other domains, such as material science, chemistry, electronics, sensor and many other sectors. Research is ongoing to develop specialty textiles with integrated functions and features used not only for apparel, but also for non-apparel products including interior textiles. Products made from specialty textiles with added value and sophistication emphasize competitive advantages over products made from conventional textiles.

The surface design of textiles constitutes the appearance of the fabric surface in terms of its color, texture, and pattern. The color of any interior textile plays one of the most dominating roles in determining its marketability. Seasonal trends will always significantly influence the consumer and the designer’s choice of colors. The texture of a fabric evokes a visual as well as a tactile response from the user. For an interior, this can be used to advantage by making the surface appear soft, seductive or luxurious. The pattern of a textile is the visual arrangement of elements and motifs on its surface, a character that distinguishes it from any other surface. The pattern might be a result of the fabric construction, such as the knit or the weave, or it may be printed or painted on the surface in color and/or texture. Within a given space, it is desirable for the scale of the pattern to be in harmony with other elements in the room, and also the size of the space in consideration.

For conventional interior textiles, the color and surface pattern are fixed once the fabric is manufactured. Nowadays, as living spaces are getting smaller and people are becoming involved in more diverse activities within compact spaces, there is growing demand for the interior environment to be flexible. Consumers demand interior textiles which are multifunctional, reactive and interactive (Nielson, 2007). It is desirable for the interior textiles to be color-tunable and color-changeable according to the user's preference.

Interactive interior textiles enable individual users to interact with the interiors and flexibly customize their fixed interior surroundings for different purposes. Interactive interior textiles are especially relevant to densely populated cities like Hong Kong wherein most of the population live in compact spaces.

Photonic textiles with interactive a function through the changeable and tunable color can present a pleasing visual effect and customized interior environment to the user, and therefore greatly enhance the interior environment. Nowadays, as our lives become more diverse and personalized interactive interior textiles appealing to lifestyle enhancement and entertainment have the potential to be utilized in value-added products which can enhance quality of life.

With the emergence of polymeric optical fibers (POFs), textiles engineered with the ability to be interactive with the user as well as other surrounding technology are now possible. However, research on interactive photonic textiles is still largely underdeveloped. A systematic study to engineer interactive photonic textiles for interior furnishing application is still lacking, and a comprehensive design model to formulate the process is not available. This study attempts to explore the application of POFs in the design of interior textiles which can be interactive with the user and the environment. It is also proposed to document the whole process, and to develop a design model to standardize the whole process.

1.2 Research aims and objectives

This project proposes to investigate the integration and utilization of polymeric photonic fibers to create textiles for interior furnishings which can be interactive with the user and the environment in terms of change in color, luminescence and surface pattern. The interactive interior textiles allow users to create multi-ambience environments within fixed spaces.

The objectives of the project are:

- To investigate the integration and utilization of polymeric photonic fibers with different textiles to create interactive interior textiles in 2-D or 3-D forms which can enhance and transform interiors via the change of colors and luminescence.
- To experiment with different materials and different processing techniques in order to identify suitable materials, techniques and technologies for use in interactive interior textiles design.
- To examine how sensors and electronic components can be embedded into the interior textiles to detect and respond to the stimuli from the user/ users, and therefore promote interaction between textiles/user, and user/user.
- To explore how interactive textiles can be used as an adaptive media to transfer the ambience of interior spaces to suit different users and purposes.
- To study and document the design process behind the creation of innovative interior photonic textiles, and to build up a comprehensive design model to format the whole design process.
- To conduct a survey to evaluate the overall performance and usability of the developed prototypes, and to obtain an insight into the interaction between human and textiles.

1.3 Significance and values

As interiors are becoming multi-functional, interactive interior textiles appealing to lifestyle enhancement and entertainment are attracting more market demand (Nielson, 2007). Interactive interior textiles that are customizable to the design preference and functional purposes of individual users can help create flexible interiors within fixed spaces. The flexible functionality, adaptability to the end user and surrounding, design aesthetic and tactile quality of the interactive interior textiles enable seamless integration of interior textiles into living environments and maximize the functionality of the fixed interior spaces, and therefore enhance interior environment.

This project proposes to investigate interactive interior textiles by means of polymeric photonic fibers. The focus is on the study to design, develop and create interactive photonic textiles via the exploration of design themes, experimentation of materials, fabrication techniques, surface design and the creation of prototypes. The primary contribution of this inter-disciplinary design research is to bridge the gaps between different disciplines to create innovative interactive textiles by leveraging advanced technologies from different fields like textiles, fibers, sensors, electronics, LEDs, etc. The creative design process model offers a different perspective on the relationship between textile design with aesthetic concern and technological development. The main contributions of this research are listed as below:

1) POFs have been successfully integrated into textile fabrics by different weaving techniques, and a novel mechanism to couple POFs to LEDs is developed. This coupling method enables POFs to be effectively connected to LED light sources, and by using appropriate LEDs, the illumination of POF fabric is greatly enhanced.
2) It has been demonstrated that laser engraving can be used to cut POFs in a predetermined pattern, and therefore side-emission from POF fabric surface occurs.

The engraving pattern can be precisely controlled and customized, allowing designers to achieve different designs with aesthetic interest. By combining and adjusting the color of LEDs, different products can be created and differentiated by a number of novel illuminating effects.

3) Embedding sensors and electronic components into textiles in order to fulfill the interactions between user and photonic textiles, as well as group users have been accomplished. Interior textile furnishing is no longer irresponsive, but can interact with users to personalize and customize the interior environment according to their preferences. Interior textile furnishings with illumination and interactive function add values and features to convectional textiles.
4) A series of illuminating prototypes is created ranging from cushions used for furnishings to fashion apparel. The design themes, moods and inspirations are illustrated. The survey indicates that the developed prototypes have a huge potential to be transferred into commercial products with both domestic and public applications.
5) Based on the experimental development, a comprehensive design model is proposed. This underlying design model provides a standardized process, and paves the way for designers to develop interactive photonic textiles.

The long-term significance includes:

1) This research explores light as a new textile design variable, which brings a new dimension and perspective to textile design. The intangible light is endowed with the properties of tactile quality, texture, silhouette, etc. This enables designers to create more innovative artworks with unique appearance, texture and tactility.
2) With the illuminating and interactive functions, users can control the color, hue, intensity of light emitting from POF textiles to create a personalized atmosphere.

Moreover, they can gain a distinctive experience by interacting with textiles and an extraordinary co-experience by interacting with other people through the interior textiles. This provides a better understanding on how innovative interior textiles can be used as an adaptive media to transfer interior environment into a personalized and customized atmosphere and a social platform.

3) Interactive interior textile prototypes that enhance the functionality of fixed interiors and life quality of the user are developed. The survey reveals that the illumination and interactive function of the prototypes are highly appreciated by the subjects. These prototypes have potential applications in interior products for both domestic use and commercial purpose, for example in commercial and recreational spaces.
4) A better understanding is obtained on how POFs as well as sensors and electronic components can be utilized and integrated into textiles to refine the design aesthetic, tactile quality and initiate the interaction of textiles with the users. The inter-disciplinary design process developed in this study adds new knowledge and know-how to different areas, covering textile design, interior design, interactive design, smart textile design and wearable electronics design.
5) The usability of POF textiles is highly improved by innovative design of coupling and integrating method, detachable electronic components, and user-friendly control devices. The design process is documented and optimized, which provides guides to the future smart textile design, interior design and lighting design.

1.4 Structure of the thesis

This thesis consists of six chapters. In Chapter 1, the background of this project is introduced. The research aims and objectives to achieve are presented, followed by the significance and value of this research. The chapter ends with a description of how this thesis is organized and structured.

In Chapter 2, the literature in related areas is critically reviewed, including smart textiles and clothing, smart photonic textiles, interactive fashion and textile design and design methods for smart textiles. Based on the broad literature review, the research gaps are identified.

Chapter 3 reports the methodology adopted in this project. The approaches and methods employed are discussed, and the reasons to use these methods are justified.

Chapter 4 concerns with how to implement all the approaches and strategies discussed in Chapter 3 to develop photonic textiles. Design practice and experiments are conducted. A survey is carried out to obtain feedback from the users. In the final part of this chapter, the design process is documented and a novel design model of photonic textile product design is built up.

Chapter 5 describes the main results of this project. Based on the preliminary results in Chapter 4, the fabrication technique of POF textile is further improved. Sensors, electronic components and control system are developed in order to attain the interaction between photonic product and user, as well as group users. Three collections of prototypes are created, and a survey is conducted to assess the prototypes.

Chapter 6 summarizes the main findings of this project. Meanwhile, the limitations of the research are explained, and future research work is recommended.

Chapter 2. **Literature review**

Textile is one of the most common materials we encounter during our daily life. Applications of textiles cover almost all our activities. We wear clothing all the time, and we are surrounded by textiles in almost all our environments, no matter home, office, restaurant, hotel, and so on. Introduction of new functions and features to such a common material has become a special area of interest in recent years. Fibers, yarns, fabrics and other textile structures with added-value functionality have been developed for a range of applications (Tang & Stylios, 2006). Textile materials and structures have become an important platform for high-tech innovations.

In this chapter, the research progress in smart textiles and clothing is firstly reviewed. It is followed by a literature survey on smart photonic textiles. Then the advances in interactive fashion and textile design are discussed. Subsequently, the design methods for smart textiles are introduced. Finally, the research gaps are summarized.

2.1 Smart textiles and clothing

The term "smart" has been used to refer to materials that can sense and respond in a controlled or predicted manner to environmental stimuli, which can be delivered in mechanical, thermal, chemical, magnetic or other forms (Tao, 2001). Smart textiles with smart materials and integrated enabling technology represent the next generation of textiles anticipated for use in fashion, furnishing, technical textile, and many other applications. The introduction of smart materials and enabling technology in textile structures offers an opportunity to develop textiles with a new type of behavior and functionality. Smart textiles are introducing a shift in textile, from a passive to a dynamic behavior, from textiles with static functionalities to products that exhibit dynamic functionalities. In the near future, many textile products may be transformed from their present state to multifunctional, adaptive and responsive systems.

With gradual reduction of component costs, the commercialization of many of the smart technologies becomes achievable. The clothing and footwear industry has already started to innovate by incorporating the latest technologies. The clothing and footwear industry have mostly embraced the embedded electronics innovation, perhaps because of the possibility to use cheap components within the smart clothing.

2.1.1 Smart textiles and clothing for bio-sensing

Smart clothing, which enable computing, digital components, electronics and sensing units to be embedded in them, represent the next generation of clothing. They allow for the incorporation of built-in technological elements in everyday textiles and clothing, and bring more innovation and functionality than one could ask from an ordinary textile. The achievements so far on material processing, textile sensors design, system communication, electronics and many other disciplines have boosted the development of smart textiles and clothing.

Bio-monitoring of physiological parameters in healthcare sector is possibly the most import application of smart clothing. Global demand for healthcare services is rapidly rising as populations increase in developing countries, and as populations' age in developed countries. There is an emerging need to renovate our health management systems. People need to be more and more conscious of their health status, and more interactive with social assistance services. Remote health monitoring will be accepted and used only if the monitoring devices are based on wearable sensing interfaces, are easy to use, and are easily customized.

The simplest smart clothing for bio-sensing consists of conventional rigid sensors incorporated in the textile structure, and connected to batteries and other devices. Sensors that can continuously measure and monitor various physiological functions such as body temperature, blood pressure, heart rate, perspiration, and so on (Stylios & Luo, 2003).

Some smart clothing were already available in the market. NuMetrex® and Adidas® have developed the sportswear named miCoach with bio-monitoring functions. (NuMetrex, 2014). The miCoach training shirt with the knitted textile sensor and a transmitter on chest can monitor the heart rate, respiration when the wearer is under fitness training (Figure 2.1). Another company Polar® has also launched wearable devices for enhancement of training performance (Polar, 2014) (Figure 2.2). Above commercialized intelligent wearable are primarily for bio-signal monitoring. Their target customers are professional runners and peoples who want to record their body's physical parameters like heart rate and respiration when they are doing physical exercises. The designs of the products are appealing to the customers, and they are easy to be used. With the soft substance of textile, the smart clothing seamlessly integrates technologies into our daily life.

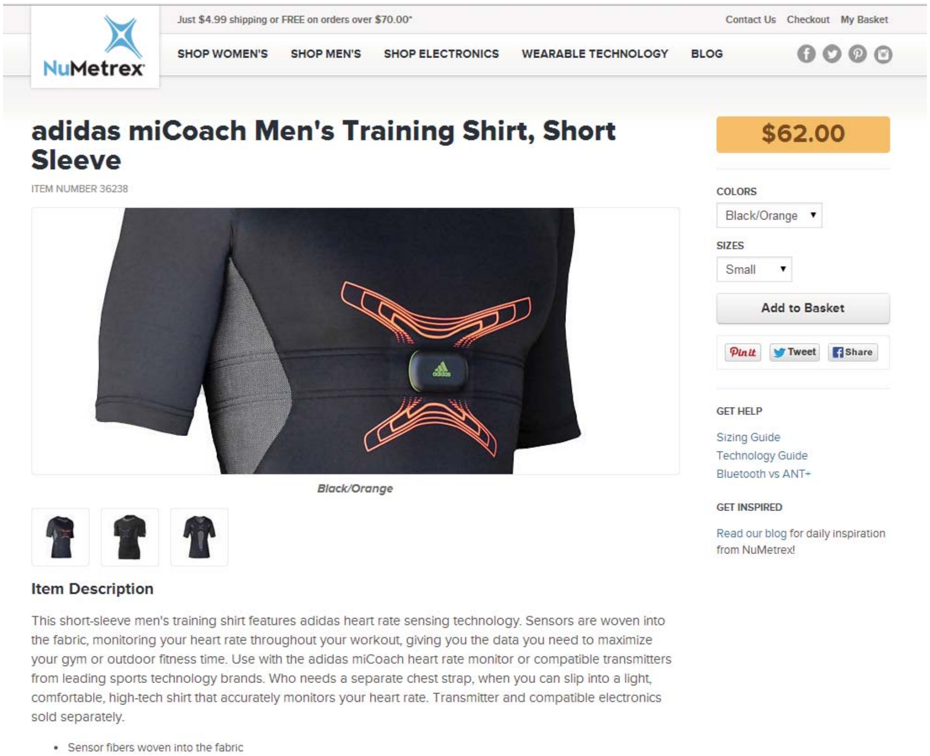


Figure 2.1 Adidas miCoach training shirt

Figure 2.2 Polar heart rate sensor strap

Recent advances in fiber optic technology have significantly changed the smart clothing industry. To date, fiber optic sensors have been widely used to monitor a wide range of environmental parameters such as position, vibration, strain, temperature, humidity, viscosity, chemicals, pressure, current, electric field and several other environmental factors (EI-Sherif, 2005; Inaudi & Glisic, 2008; Udd, 1996). The use of Polymeric Optical

Fibers (POFs) in textile fabrics for sensor applications has recently become more important (Bartlett, et al., 2000; Boczkowska & Leonowicz, 2006; Dhawan, et al., 2005; Diamond, et al., 2008; Tang & Stylios, 2006; Zubia & Arrue, 2001). Generally speaking, fiber optical sensors have distinct advantages comparing to electrical powered sensors: they generate no heat and are compatible to electromagnetic radiation and electrical discharges, which are of great importance in the field of wearable and biomedical devices. Due to their ruggedness in terms of kinking, POFs in particular are suitable for textile manufacturing processes. Besides their safe and easy handling characteristics, the flexibility of POFs enables universal positioning inside the textile structure.

A general overview of optical fiber sensor principles, fiber design and integration into fabrics has been reported in literatures (Dhawan, et al., 2005; Tang & Stylios, 2006; Tao, 2005). Bragg or long period gratings are the most often used sensing principles. Bragg grating fibers used to measure thoracic and abdominal respiration have been reported (Allsop, et al., 2007; Grillet, et al., 2008), where medical textiles have been developed and tested in respiratory plethysmography applications. One of other sensing principles is based on the formation of micro-bends (Endruweit, et al., 2008; Masuda Atsuji, et al., 2006). So far this principle has been implemented only in few textile applications. Sensor arrays, where optical fibers are positioned in both warp and weft direction of weaves, allow the determination of touch (Heo, et al., 2006). A pressure sensor array based on a different approach is presented in some research work (Rothmaier, Luong, et al., 2008), in which elastomeric POFs were squeezed and deformed rather than bent.

For healthcare and health provision, instrumented garments with capability to record physiological, neurological and body kinematic parameters are crucial (De Rossi, et al., 2000). They can provide physicians with data to detect and manage health risks, diagnose at an early stage, recommend treatment, and make professional decisions based on objective information (Lymberis & Olsson, 2003). There are many intelligent clothing applications spanning from a citizens' health watch, to patients' disease and rehabilitation. These intelligent clothing systems are engineered to monitor health conditions of the wearer by incorporating POF sensors and signal acquisition/processing unit into the garment (De Rossi, et al., 2003; Park & Jayaraman, 2003). There are many commercial models available on the market, such as SmartShirt, the Georgia Tech Wearable Motherboard (Jayaraman, 2014) (Figure 2.3), VivoMetrics' LifeShirt, which contains embedded inductive plethysmographic sensors, accelerometer, and a single-channel ECG (Vivonoetics, 2014) (Figure 2.4), and the VTAM project (Weber, et al., 2003) that aims at developing generic clothing technology, integrating biosensors and bio-actuators woven into the fabric.

Figure 2.3 SmartShirt

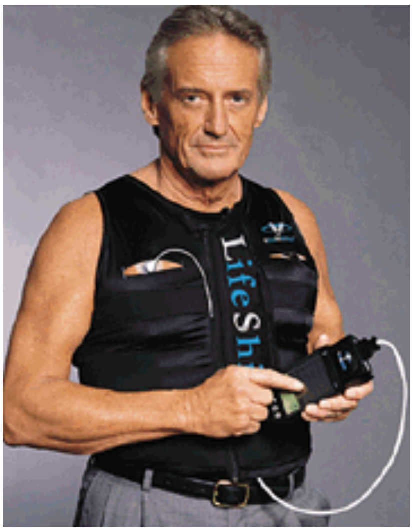


Figure 2.4 LifeShirt

Growth is predicted to occur in performance-driven smart clothing, such as continuous monitoring smart garments for healthcare. However, for smart technologies to be used in the textiles and clothing industry, aesthetic and tactile properties such as the handle, drape and comfort of the fabric and garment have to be acceptable. Weight, durability and useability are also issues that are raised. The successful and elegant integration of and interrelation between the various technologies is a challenge for designers and scientists.

2.1.2 Smart textiles and clothing for leisure

Intelligent clothing that can enhance the lifestyle is another application of smart textiles. Nowadays, as our lives become more diverse and personalized, smart clothing appealing to lifestyle enhancement and entertainment is getting more attention. People are expecting more functions from clothing in terms of interaction with function, even and with other people through clothing, in order to enhance their well-being (Jobling, 2006). Intelligent clothing must cross the boundary into everyday fashion apparel to meet the challenges of future lifestyle needs and consumer requirements (Baurley, 2005a). Meanwhile, fashion designers are also needed to continuously push the limit of their design in terms of concept, creativity, and wearability.

A number of interactive clothing for leisure have been developed. The researcher of the MIT Media Lab, have built Musical Jackets with a touch-sensitive MIDI keyboard embroidered directly into the fabric using conductive thread (Post, et al., 2000). Sound is generated by a single-chip General MIDI wavetable synthesizer, and sequences are generated in a microcontroller.

Italian luxury men's wear brand Ermenegildo Zegna also merged technology into its new collection. The Zegna Icon Jacket (Figure 2.5), utilizes Bluetooth® technology, as well as integrated collar microphone and sleeve command of mobile devices (Zegna, 2014).

Figure 2.5 Zegna Icon jacket, 2014/2015 autum/ winter collection

Another example is Cutecircuit's Hug Shirt (Cutecircuit, 2006), which is a shirt that allow the wearer to send hugs over long distances, using the technology of a wearable Bluetooth. The actuators of the Hug Shirt can reproduce the sensation of touch and warmth, and then deliver it to the other person. There are also some other prototypes for remote interpersonal communication (Baurley, et al., 2007; Randell, et al., 2005; J. Smith & MacLean, 2007).

2.2 Smart photonic textiles

The terminology for describing fabrics which can emit light is not clearly defined at this moment. In some literatures (Cho, 2010; Gauvreau, et al., 2008), "Photonic textiles" is used to refer to fabrics that contain lighting systems and can serve as displays or other uses, even though they include the fabrics that are integrated with flexible arrays of multicolored light-emitting diodes (LEDs) (Philips, 2014). In this study, "photonic textiles" is used when fabrics emit light and act as a light illuminating medium.

The illuminating effect of photonic textiles greatly enhances the color of the fabric, and therefore adds new features to traditional textiles. Illuminating textiles that has been developed so far can be classified into several main types depending on the principle of illumination as discussed below.

2.2.1 LED embedded photonic textiles

LED embedded photonic textiles integrate LEDs directly into textiles, and the light emitting is purely from the LEDs as light source.

Figure 2.6 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 & Dils, 2013).

Figure 2.6 The Sporty Supaheroe jacket

The photonic textiles developed by Philips are probably the best-known representatives for LEDs embedded photonic textiles. By sealing conventional LEDs into a laminated plastic panel which is sufficiently flexible and durable to withstand constant flexing, the Photonic Textiles group at Philips Research has successfully embedded arrays of these LEDs under the surface of textiles, enabling soft furniture and clothing to come alive with myriad patterns of color light (Graham-Rowe, 2007) (Figure 2.7). The LED panel is covered with several layers of translucent textiles to diffuse the light in order that the pixels flow smoothly into each other and the textiles can also provide the required level of softness and surface textured. The LEDs are driven by embedded electronics to create fixed or moving patterns of light that bring the magic of illumination to the textiles.

Figure 2.7 Lumalive fabric

Their recent research "Luminous Textile" is a unique ambient lighting system that integrates multi-colored LEDs within textile panels (Figure 2.8). 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 (Philips, 2013).

Figure 2.8 Philips "Luminous Textile"

Some of fashion designers also attempt to integrate LED into their clothing collection. In

2007 autumn/winter "Airborne" show (Figure 2.9), Hussein pushes the boundaries of fashion by integrating the latest LED technology into his fashion collection (Chalayan, 2007). The collection uses climate as a metaphor and reflects our primal feelings towards nature and the cycles of weather. An LED dress consisting of 15,600 LEDs, combined with crystal, displays short abstract films that correspond to the arrival of a particular season.

Figure 2.9 Airborne

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 appear 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.

2.2.2 Photolumiescent and electroluminescent photonic textile

Luminescent fabrics have been created based on photo-luminescent glow yarn technology

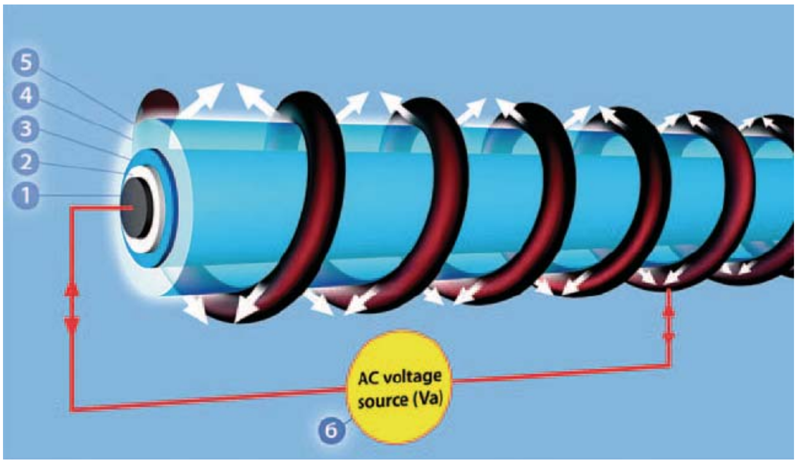
(Swicofil, 2014). The glow yarn is developed by mixing, melting and extruding polyester chips with photo-luminescent pigments. However, the luminescence of the yarn cannot be controlled and it cannot be switched on and off. Moreover, in order to glow the fabric has to be exposed to a light source for a lengthy duration (sunlight for three minutes, or luminescent light for 20 minutes) and even then the effect occurs in the dark, which may not be entirely desirable.

A prototype based on electroluminescent material named “Digital Dawn (Figure 2.10) was developed by Loop.pH (Dias & Monaragala, 2012), 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 of 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 (SAD).

Figure 2.10 Digital Dawn

Interactive Pillows have been developed by to enhance long distance communication (Dorrien, et al., 2014). Electroluminescent wires are woven with the fabrics of the pillows. 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 individual pillows can potentially be located nearly anywhere and wirelessly. The pillows add another layer of aesthetic and interpersonal experience in everyday contexts.

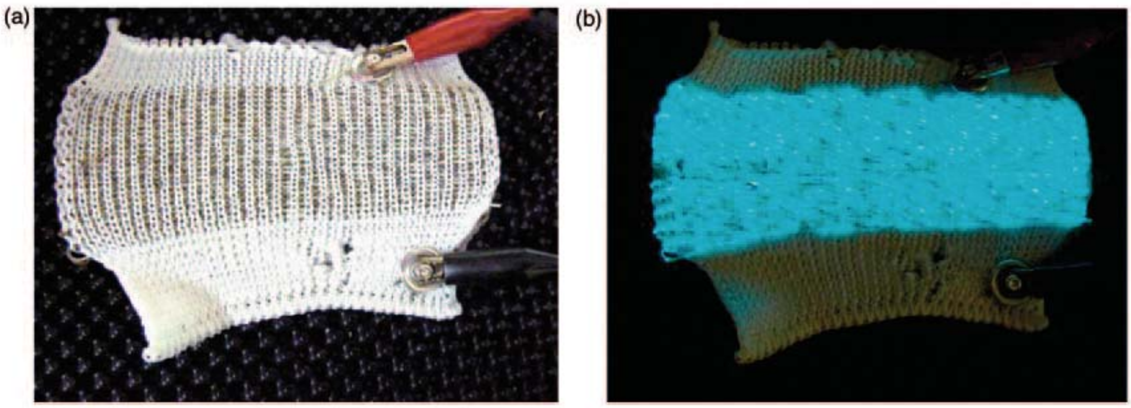
Novel electroluminescent yarns based on electro-conductive have been developed which can present a unique luminescent effect (Dias & Monaragala, 2012). The general construction of the electroluminescent yarn is shown in Figure 2.11, where the base electrode comprises the electro-conductive yarn over 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.



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

Figure 2.11 Electroluminescent (EL) yarn construction

With knitted with ordinary yarns, the Electroluminescent yarns present a unique luminescent effect (Figure 2.12).



(a) Non-excited state; (b) Excited state

Figure 2.12 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.

2.2.3 POF photonic textiles

2.2.3.1 *Development of POF-based photonic textiles*

Light passing through an optical fiber was first demonstrated more than 150 years ago and developed using glass (C. Brochier & Lysenko, 2008). Since the development of plastic fibers in the 1960s, POFs have been found to have many of the same advantages as conventional glass optical fibers. These include low weight, immunity to electromagnetic interference and multiplexing capabilities. Due to the fact that POFs are cheaper to manufacture and easier to be processed than inorganic glass fibers, they have attracted more and more attention in various industrial sectors. Meanwhile, POFs have some inherent good properties, such as high flexibility, low stiffness, and hence susceptible to textile manufacturing process. Therefore, they could be integrated into textiles to add new features.

The history of illuminating textiles based on POFs started in the late 1960s, when DuPont was investigating the field of optical polymers and fiber production. One of their first patents already showed the possibility of weaving POF and altering their cladding in a subsequent step to receive luminous effects (Tracey & Purdue, 1989). Since then, some of fashion, design and architecture products employing POF fabrics have been commercially available in the market. In most cases, a multiplicity of polymer optical fibers are integrated into textile structures connected to a light source at the fiber ends. The illuminating principle of POF fabric is different from the principle of illuminating textiles with embedded LEDs. In the latter, the light is directly from the LEDs. In POF fabric, although the light source may be LEDs, the illuminating effect is accomplished by side-emission of light from POFs.

The illumination intensity of illuminating textiles based on POFs may be less than those based on embedded LEDs due to the energy loss in the transport of light in POFs, however, this can be compensated by several other advantages. Firstly, as POFs are flexible and comparatively soft, they can be readily manufactured into textiles, whilst the handle and overall performance of textiles will not be distinctly affected. Secondly, the light sources (LEDs) are coupled at the ends of POFs, and therefore very less electric wires and other electric components are required. This can greatly enhance the usability and wearability of the illuminating textiles. Thirdly, different techniques can be applied to POFs to promote light emission, and the location of light emission can be customized by treating POFs at different locations. This allows the designer to have more freedom to design different surface patterns, and therefore diversity the surface design.

Practical implementation of photonic textiles is through integration of specialty optical fibers during the weaving process of textile manufacturing. This approach is quite natural as optical fibers, being long threads of submillimeter diameter, are geometrically and mechanically similar to the regular textile fibers, and, therefore, suitable for similar processing.

POF normally compose core material and cladding (Figure 2.13). Light transmits mainly in core material according to total reflectance principle, while the cladding layer protects the core material against mechanical damages.

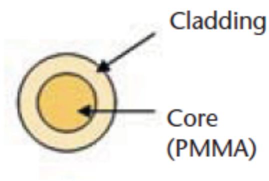


Figure 2.13 Structure of POF

Side-emitting POF can be made in several ways by adding specific scatters or fluorescent additives into POF (Daum, et al., 2002), by mechanically damaging the core-cladding interface, or by bending the fiber axis. Such imperfection can be made on the surface of POF by mechanical notching (Koncar, 2005), abrasion (Im, et al., 2007), or sandblasting (Endruweit, et al., 2008).

The critical angle θ_m of POF is the largest incidence angle for which refraction can still take place; in another word, when the incidence angle is larger than the critical angle, the light will meet the requirement for the total internal reflection, and otherwise the light will be emitted from the boundary (Figure 2.14). If POF is bent, the incidence angle is altered and thus light with θ_1 smaller than θ_m will be partially refracted and light with θ_2 greater than θ_m will be completely reflected. Therefore, the light rays are only emitted on the outside of the bend region, and the light rays inside of the bend region still meet the total internal reflection requirement (Wang, et al., 2013).

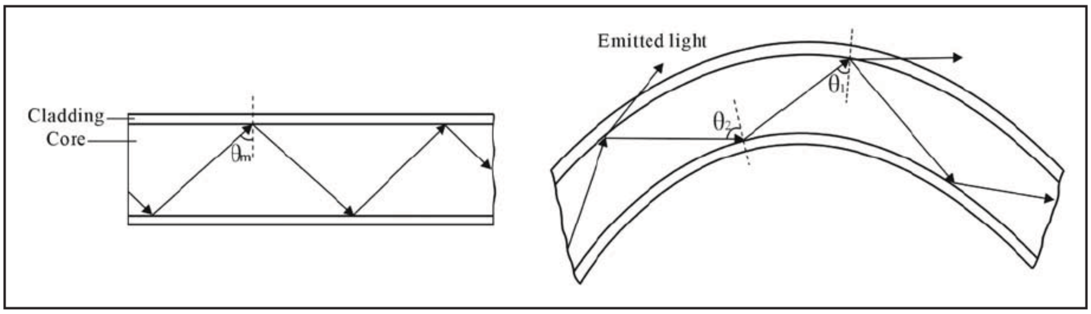


Figure 2.14 Light propagation in straight and bent POF

The main disadvantage of macro-bending approach is due to the high sensitivity of scattered light intensity on the value of a bend radius. In particular, it is challenging to ensure that the fiber is sufficiently bent with a constant bending radii throughout the whole piece of textile. If the fiber bending radii is non-uniform, then only some parts of a textile where fibers have been tightly bend will be lit up. This technical problem becomes especially obvious for wearable photonic textiles in which local textile structure is prone to changes due to variable force loads during wear, leading to 'patchy' looking non-uniformly luminescing fabrics. Major disadvantage of scratching approach is that mechanical or chemical methods used to damage the fiber surface tend to introduce mechanical defect into the fiber structure, thus resulting in reduction of fiber breaking strength. Moreover, due to the fact that there is no control over mechanical scratching or chemical etching, such post-treatment techniques appear to cause a number of randomly located very strong optical defects where light may leak almost completely at a few singular points, making photonic textile appearance unappealing.

2.2.3.2 *Applications of POF photonic textiles*

2.2.3.2.1 Clothing and accessories

An optical fiber display (Koncar, 2005) which integrated optical fibers, LEDs into a jacket to create a textile screen (Figure 2.15) has been reported. The technology is based on woven POF having cladding imperfections (mechanical, thermal, chemical damage) and therefore light emitting sites.

Figure 2.15 Optical fiber display

The flexible display is created on textiles by producing a screen matrix using the texture of the fabric during weaving process. A small electronic device that is integrated into the system controls the LEDs that illuminate groups of fibers. Each group provides light to one pixel on the matrix. Optical fiber screens provide access to simple and animated visual information, such as texts or pictograms.

Illuminated curtains and light generating fabrics for clothing or accessories (Figure 2.16 and Figure 2.17) have been produced as woven and embroidered structures using larger POFs (diameters from 0.25 to 0.75 mm) (GmbH, 2014). Time Magazine (Clayton, 2006) announced a light-radiating 'fabric' made from slender fiber optic cables to create glittery objects, as well as curtains and wall hangings. Enlightenment accessories are especially useful in poorly illuminated or non-illuminated locations.

Figure 2.16 Illuminated bag with solar module

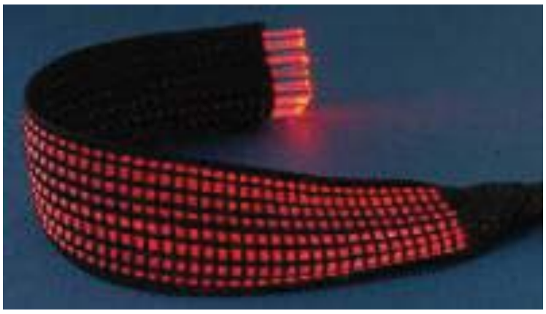


Figure 2.17 Belt with optical fibers woven in

2.2.3.2.2 Interiors

A recent research indicates that apparel made up about 40% of the global textile market in 2010. Technical and interior (home) textiles take over the rest 60% market (Locher & G, 2013). There are great potentials for launching POF interior furnishings for the future market. Although POF fabrics used in clothes with a reasonable light emission are tough and considerably robust in structure, POF fabrics with integrated thicker diameter POFs seem to be more suitable for interior furnishing applications, for public premises, vehicles, and other related applications (Harlin, et al., 2003). Creative luminous POF fabrics have been designed in large scale for ambitious indoor lighting (Brochier, 2014) (Figure 2.18), and for further applications in transport systems and communication (Brochier, 2014) (Figure 2.19 and Figure 2.20).

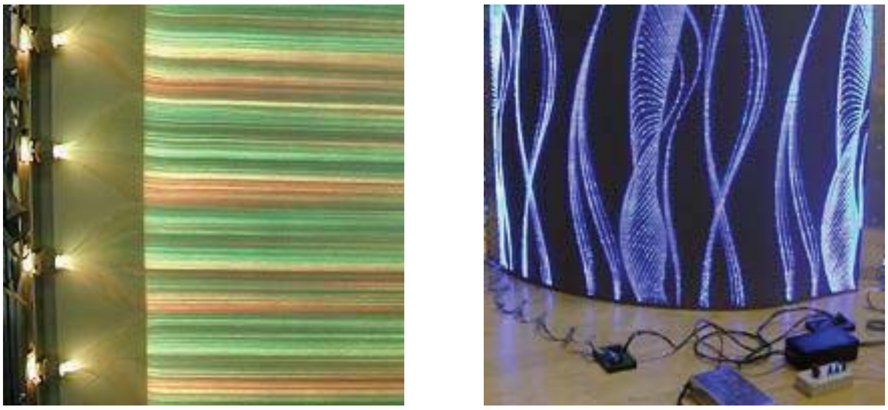


Figure 2.18 POF fabrics for indoor lighting

Figure 2.19 Illuminated strip in a seat

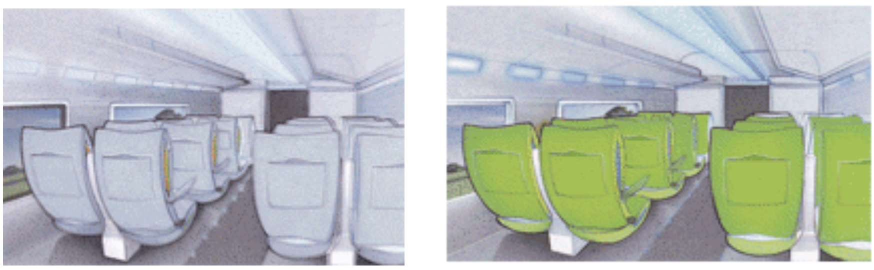


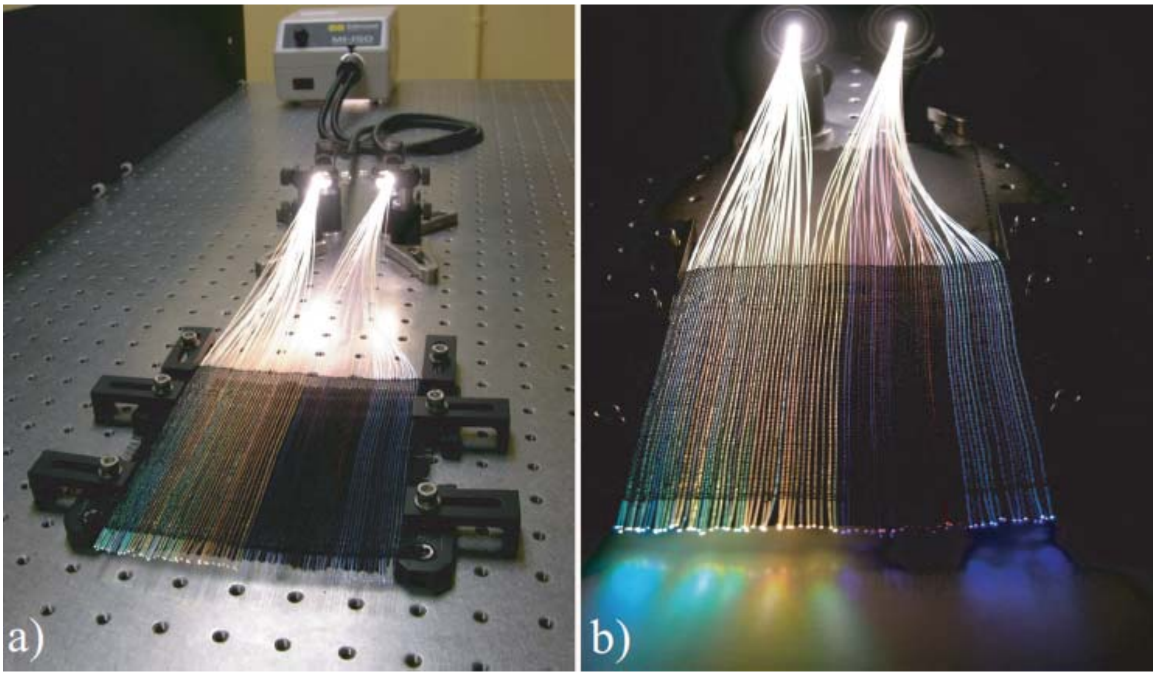
Figure 2.20 Illuminated seats in a railway carriage

2.2.3.2.3 Other applications

Other applications, such as warning devices can also benefit from the main function of POF fabrics for illumination. The active illumination of the textile is much more effective than panels of reflective or fluorescent materials, which are only effective if it is illuminated by light (Paul, 1997). There is also enormous potential for firefighting and police applications. For example, information and warnings could be displayed on clothes, which could increase public safety and help officers and fire fighters to operate in remote and challenging conditions.

2.2.4 Photonic textiles based on PCFs (Photonic Crystal Fibers)

Recently, novel type of optical fibers, called photonic crystal fibers (PCFs), has been introduced. In their cross section such fibers contain either periodically arranged micron-sized air voids (Knight, et al., 1998; Morikawa, et al., 2006), or a periodic sequence of micron-sized layers of different materials (Benoit, et al., 2003; Dupuis, et al., 2007; Hart, et al., 2002). By varying the size and position of the fiber structural elements one can design fibers of unique appearances. Some photonic crystal fibers 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.



a) Lit textile under normal ambient illumination in the laboratory

b) Lit textile in the dark

Figure 2.21 PCF textile and light coupling set up

2.3 Interactive fashion and textile design

Interactive textiles have been researched actively in smart clothing. Nowadays, as our lives become more diverse and personalized, intelligent clothing appealing to lifestyle enhancement and entertainment is getting more attention. People are demanding more functions from intelligent clothing in terms of interactivity which will enhance their well-being (Jobling, 2006). Intelligent clothing must cross the boundary into everyday fashion to meet the future lifestyle needs and consumer requirements (Baurley, 2005a). Meanwhile, fashion designers are also needed to continuously push the design boundaries in terms of concept, creativity, and wearability.

The researchers of MIT Media Lab, have built Musical Jackets with a touch-sensitive

MIDI keyboard embroidered directly into the fabric using conductive thread (Post, et al., 2000) (Figure 2.22).

Figure 2.22 Musical Jacket

The thread, which contains stainless steel filament making it conductive, is embroidered into a standard 4 × 3 character keypad below the right shoulder. The capacitive loading of the body is detected when the thread is touched; the keypad is polyphonic, thus several keys can be hit simultaneously. Sound is generated by a single-chip General MIDI wavetable synthesizer, and sequences are generated in a microcontroller. The jacket is entirely battery operated, with powered speakers in the pockets. Among the smart clothing components equipped in this jacket, textile technology has been applied to the input interface.

Vilkas and Kukkia (Berzowska & Coelho, 2005) are expressive and behavioral kinetic dresses, which were developed by XS Labs (Figure 2.23). Vilkas has a kinetic hemline on the right side that rises over a 30-sec interval to reveal the knee and lower thigh. It is constructed of heavy handmade felt that contracts through the use of hand stitched Nitinol wires. Nitinol, and SMA made of nickel and titanium, has the ability to indefinitely remember its geometry if once treated to acquire a specific shape. Using this characteristic, the Nitinol can be used to create a wrinkling effect.


Figure 2.23 Vilkas dress (left) and Kukkia dress (right)

The Kukkia dress is decorated with three animated flowers that open and close over a 15-sec interval. When heated, the wire shrinks and pulls the petals together, closing the flower. As it cools down, the rigidity of the felt counteracts the shape of the wire, allowing the flower to open. This dress is operated by a microcontroller triggering drivers that send power to the Nitinol. Also, it uses a small rechargeable lithium polymer cells that can power the dress for 2 hr. As the output interface, the shape memory embedded fabric is used.

Another XS Labs newly developed a smart clothing collection called “Captain Electric” (Berzowska, et al., 2010) (Figure 2.24). Captain Electric is a collection of three electronic garments (Itchy, Sticky, and Stiff) that both passively utilize energy from the body to generate power. Reflecting fashion’s historic relationship between discomfort and style, the dresses restrict and reshape the body in order to produce sufficient energy to fuel themselves and actuate light and sound events on the body. Itchy, Sticky, and Stiff conceptually reference safety apparel and personal protection as well as our fears of natural disasters and other states of emergency, personal phobias, anxieties, and paranoia. Using inductive generators, kinetic energy can be converted from the human body into electric energy and are stored within a power cell integrated into the garments. An important aspect of this project was to focus on a seamless integration of form and function with the set of gestures or movements necessary for power generation.

Figure 2.24 Captain Electric- Itchy, Sticky, and Stiff dresses

Touch is a powerful conduit for emotional connectedness. Haptic research includes the design of interactions employing devices through which virtual physical models can be felt, just as we display to our visual sense with graphical displays (J. Smith & MacLean, 2007). Using haptic communication, separated individuals interact with one another through a pair of haptic displays, which are themselves connected via a computer running coupled virtual physical models.

Cutecircuit's Hug Shirt (Cutecircuit, 2006) is a shirt that enables users to send hugs over distance, using Bluetooth technology (Figure 2.25). It has detachable pads containing sensors that sense touch pressure and heartbeat. The actuators reproduce the sensation of touch and warmth. When touching the red areas on the shirt, the mobile phone receives the sensors data via Bluetooth and then delivers it to the other person. The Hug Shirt is built using textile pad type of interfaces, wireless communication, integrated circuit, and rechargeable batteries. The military sees the usefulness in the Hug Shirt by allowing their soldiers to exchange their loved ones far away at home. After nominated as one of the 2006 innovations of the year by *Time* magazine, the Hug Shirt is being prepared to enter the market.

Figure 2.25 Hug Shirt

Communication-Wear designed by the Sharon Baurley’s research team is a wearable technology clothing concept that augments the mobile phone by enabling expressive messages to be exchanged remotely, by conveying a sense of touch and presence (Baurley, et al., 2007). Actuation of hug message takes place via generation of a warming sensation using heatable textiles, symbolizing the warming sensation felt when touched by another person. When a hug or embrace gesture is sent, the heat pads in the back of the jacket heat up. Communication of touch messages takes place between garments via Bluetooth. Physiological arousal, as detected by the GSR sensors, is relayed to the partner by light being emitted from the fiber-optic section. This garment contains a circuit board where a PIC microcontroller for processing is mounted. The jacket also has a 7.2-volt rechargeable battery. This Communication- Wear also contains input interface like touch sensing method or textile-based GSR sensor, output interface (heat-emitting fabric, light emitting fabric), and communication interface such as Bluetooth, integrated circuit, and battery.

As affective computing grown out of wearable computing was suggested by Picard and Healey (Picard & Healey, 1997), smart clothing has started to become concerned with clothing that has the skills to recognize physical and psychological patterns and translate these into emotions. Expressions of emotion also include changes in the autonomic nervous system activity such as accelerated heart rate or increasing skin conductivity (Baurley, 2005b). This is potentially very useful in engineering smart clothing equipped with a series of function sensing of the wearer's physiological signals, analyzing the collected data, and actuating by providing the wearers with appropriate responses.

The Scentsory Design® (SAFItech, 2014) project chooses scent as a tool to improve the mental and physical well-being. The wearer communicates through the sense of smell, by reading and interpreting emotions, enabling the wearer to express their feelings through the delivery of color and scent emitted from clothing. Thus, the item produces a very personal scent, delivering sensations on demand. This kind of smart clothing can alleviate mental and physical health problems through the delivery of odorant benefit chemicals in controlled ways responding to personal needs (Figure 2.26).

Figure 2.26 The Scentsory Design

Smart textiles play an important role in both fashion and interior design domains. Some interactive furnishings featured in current research involve sophisticated computer technology whereby the product is manipulated with touch screen, voice annotations or keyboards (Omojola, et al., 2000). Basically, these are often computers in alternative guises and result in obtrusive designs, which are incongruous to the daily activities of an interior environment. Alternatively textile based products enable a seamless integration into interior environments as the technology can be embedded into everyday objects and offer tactile familiarity and comfort to users.

One intricate design is the “LightCloth”. They provide cushion with embedded optical fiber arrays and sensors. The user utilizes an Infrea Red (IR) pen, which is not connect to the cushion, to interact with the system to design the illumination with desired color(s) (Hashimoti & Suzuki, 2013) (Figure 2.27).

Figure 2.27 LightCloth

The Interactive Institute had developed Interactive Pillows (Figure 2.28) 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. Playing with the expectations of everyday objects, in effect the function of the lamp is integrated directly into the familiar soft form of a pillow.

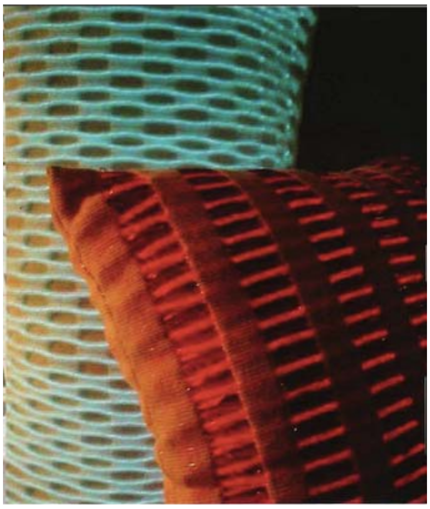


Figure 2.28 Interactive Pillows

Lullaby is an interactive quilt that permits real-time communication with gestures (Elizondo, et al., 2011). It's intended for two members of the same family who want to share bedtime together. The main purpose is to keep an intimate link between two people who are separated. It works in an intimate mental space that is otherwise lost. Communication is established when one user touches the quilt. These gestures are visualized in the other user's quilt and vice-versa (Figure 2.29). This allows real-time communication between them via wireless transmission. Inside the quilt LED matrices are sewn on the material and a matrix of switches inserted. When pressed the switches activate the LEDs.

Figure 2.29 Lullaby- interactive quilt

The quilt is built with an embedded flexible circuit that includes one fabric button switch matrix and two LED matrices. The quilt is made up of a 7-layer system divided a bottom cotton layer with closing clips, a blue LED layer with a flex sensor, cloth separation for isolation, pink LED layer with positive contacts of the fabric buttons, negative contacts of the push buttons in padding layer, padding layer for diffusing light and a quilt cotton cover.

Various applications of POF fabrics have been found in textiles. However, the literatures on application of POF fabrics in interactive textiles, which can be interactive with the user/environment, are very rare. Only a few prototypes have been reported.

A new type of display has been created by France Telecom's Research and Development team (Brochier, 2002). A simple image or text can be displayed on the fiber optical screen which is mounted on a garment (Figure 2.30 and Figure 2.31). The image and text can be changed by the user through a phone or a computer using wireless technology (Figure 2.32). It is also possible, for example, to vary the brightness according to the sound environment using low frequencies. The light gets brighter each time wearers clap their hands or stamp their feet. The image on the screen can also move in relation to the wearer's movements. When out jogging, the image responds to the runner's pace by rebounding or changing.

Figure 2.30 Fiber optical screen

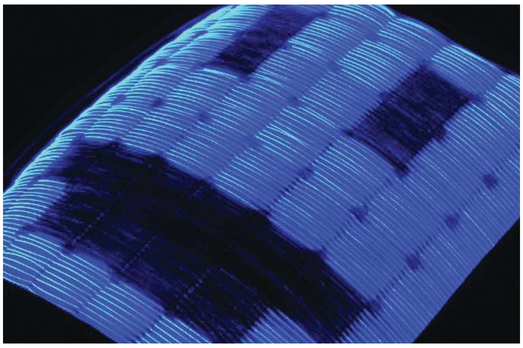


Figure 2.31 A closer look at the screen

Figure 2.32 Display with different images/texts

Another example of interactive textiles is PeR, Perception Rug, which is a knotted carpet in which touch sensitivity and optic fibers are integrated (Deckers, 2014). PeR has the ability to perceive and react to perceptive activity of people. PeR can adapt different perceptive behavior (Figure 2.33).

Figure 2.33 Perception Rug

PeR is designed to show how design theory on perception can be applied in our environment. The most important notion of the theory is that, by nature, perception is always interplay between the perceiver and the perceived. By giving an artifact like PeR perceptive behavior, this interplay can be enhanced resulting in a greater feeling of association and involvement of the user.

2.4 Design methods for smart textiles

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 & 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" (Figure 2.34), 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.

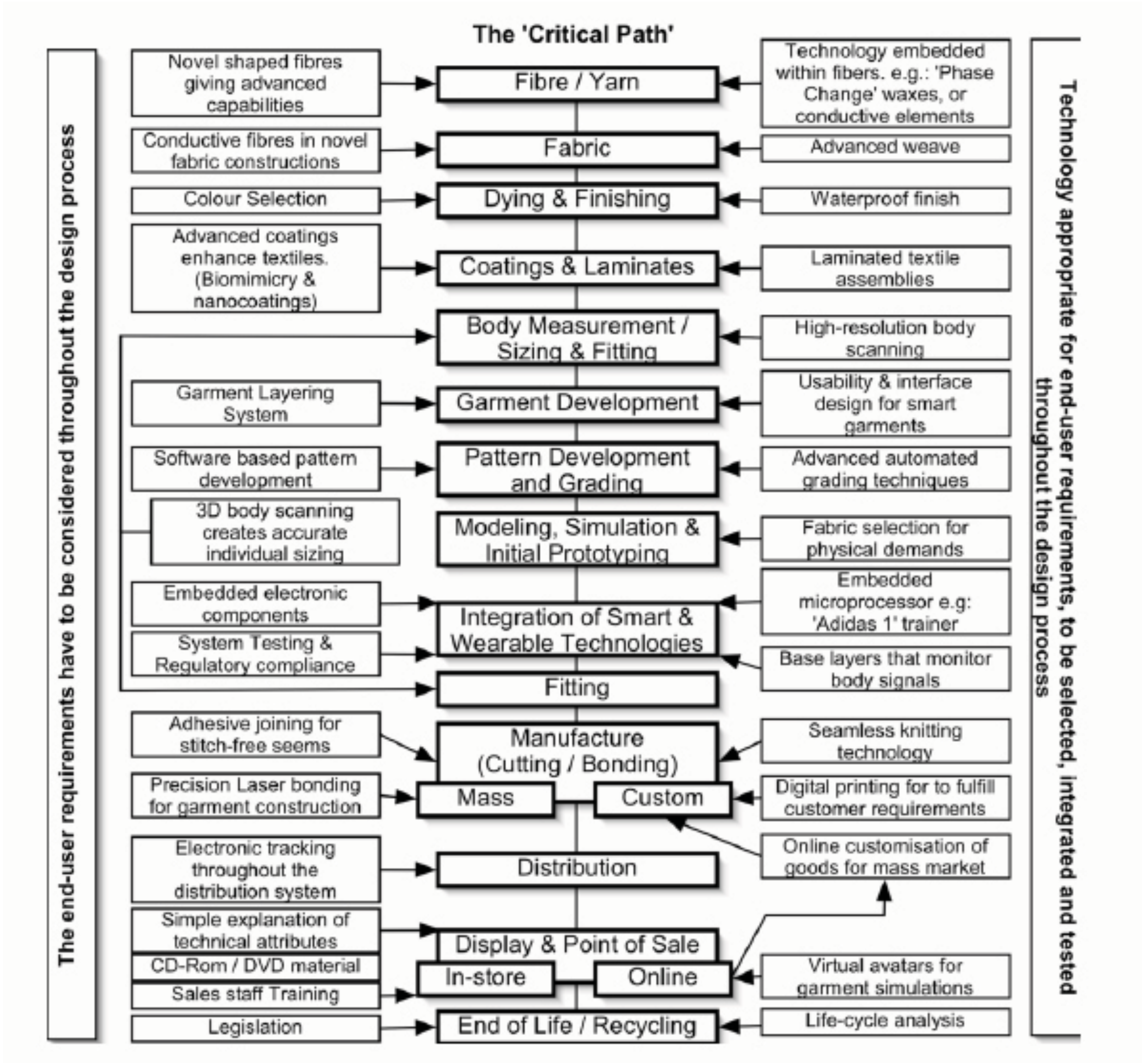


Figure 2.34 Critical path in design of smart clothing

Baurley (Baurley, 2005a)suggested a design methodology for interactive design of smart clothing (Figure 2.35). The methodology consists of a conceptual framework, user study, and design building. The framework is based on observations and research on how 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.

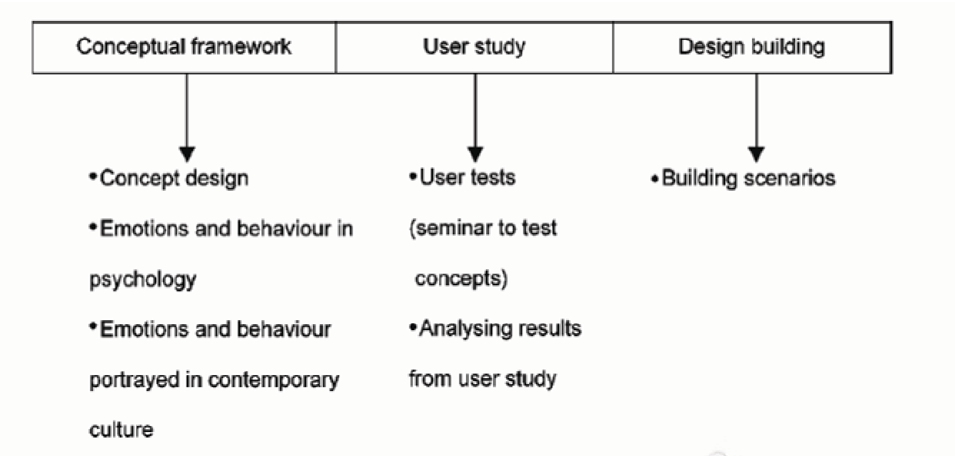


Figure 2.35 Interactive design of smart clothing

To provide early user feedback and facilitate the user acceptance process, it is important to involve potential users of the future services early in the user-center development process (ISO, 1999). It is fruitful to understand what kind of experience the users expect from interacting with such technology and what such requirements do they have that have not yet been recognized.

The two 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. 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.

2.5 Research gaps

Based on the literature review, it is found that although the researches on photonic textiles have been widely conducted, the study on interactive interior textiles with integrated photonic fibers is limited in terms of several aspects:

- Research on jacquard weaving and embellishment including dyeing and printing into interactive interior textiles is still inadequate. There is a lack of systemic research on how to use textile technique and fashion essential to enhance design of photonic fiber integrated interactive furnishing.
- There is a lack of investigation on interior textiles that can be interactive with the user/environment through the changeable and tunable color pattern.
- Different approaches to induce side-illumination of POF fabrics, including thermal, physical and chemical treatments, have been explored in literatures, however, little work has been done on laser engraving.
- Most photonic textiles for illumination are developed by academics from scientific disciplines such as electronics, photonics, and the developed prototypes are always lack of aesthetic and design concerns. Little work has been conducted from a fashion designer's perspective. On the other hand, most fashion designers have insufficient technical knowledge, which may handicap the development of interactive interior textiles.
- Conventional design methods cannot exactly describe the highly reflective process in the design of photonic interactive textiles. A new design model needs to be established.
- The usability of POF textile is not fully developed for the end-users. Some developing processes of POF textiles are still time-consuming.

In order to fill these gaps, this research attempts to investigate and develop interactive interior textiles for interior furnishings with integrated POFs. To design, develop and create interactive textiles include design investigation and development via the exploration of design themes, experimentation of materials, fabrication techniques, application methods, surface design, development of form and the production of prototypes. Different techniques in introducing the optical fibers into the fabric are explored, and different laser-engraving approaches are examined to create various side-lighting effects. Technologies of integrating and coupling the sensors and electronics with the textiles are investigated, and controlling systems are developed. The engineered prototypes enable the user to interact with the textiles via changeable and tunable color pattern, and the prototypes can also be adaptive to the environment by change of color tones. The proposed prototypes possess decorative function in both lit and dark environments, and the color/pattern contrast during day and night is highlighted by the illuminative effect. A collection of interactive interior textile prototypes will be developed, which can promote the interaction and communication between the textiles and the user/environment, and therefore create a personalized interior environment according to the user's preference. The design process is documented and a new design process model is developed.

Chapter 3. **Research methodology**

3.1 Introduction

This chapter concerns the methods used in this study to develop photonic textiles product. The action research used in this study is firstly presented. It is followed by an introduction of quantitative, qualitative and mixed-methods research approaches. Then the design practice and experimental methods employed to develop and fabricate photonic textile are discussed. Survey is adopted in order to evaluate the performance of the photonic prototypes and to improve the prototypes.

3.2 Action research

There are varieties of definitions for action research, and it seems that an agreed universal definition is not available. Generally, action research is regarded as a reflective process of progressive problem solving. It is typically designed and performed by researchers who would like to analyze the collected data using various techniques in order to improve their own practice. Action research can be done by individuals or by groups of people. Action research has been widely used in the domain of social sciences, but its growing popularity as a research approach is probably due to its use in area such as organizational development, education, health and social care. In these areas it has a particular niche among professionals who want to use research to improve their practices.

Applications of action research have been found in various areas with diverse purposes; however the main idea of action research is to continuously improve the practice through iterative actions. The essentials of action research design are considered as per the following characteristic cycle (Stringer, 2007):

- Initially an exploratory stance is adopted, where an understanding of a problem is developed and plans are made for some form of interventional strategy (Plan).
- Then the action is carried out (Action).
- During and around the time of action, pertinent observations are collected in various forms (Observe).
- The new interventional strategies are carried out, and the cyclic process repeats, continuing until a sufficient understanding (or implementable solution for) the problem is achieved (Reflect).

The schematic diagram of the action cycle is shown in Figure 3.1:

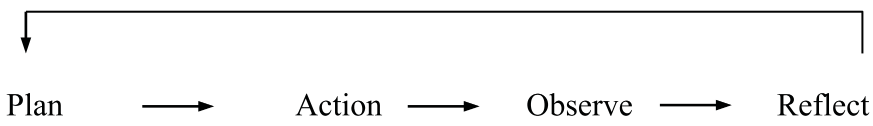


Figure 3.1 Cycle of action research

To design, develop and create interactive photonic textiles includes design investigation and development via the exploration of design themes, experimentation of materials, fabrication techniques, application methods, surface design, development of form and the production of prototypes. As the design process is a highly reflective process whereby designs evolve concurrently and simultaneously with the development of materials, processes and forms, it is valid to adopt the action research methodology in order to cater to the experimental nature of the design process. Action research addresses practical problems in a positive way, feeding the results of research directly back into practice, and its continuous cycle of development and change via research is beneficial to improve practice and resolve problem. Action research comprises of four main stages which works in a cyclic flow: look, think, act and reflect (Stringer, 2007). It allows the researcher to work in various directions of the design progression; processes can be continuously revised, repeated and refined, thus particularly suited for the exploratory nature of the design process. The flow of the research is consistent with the cyclic nature of action research whereby the researcher is able to retract or move forward to various stages of the process while "refining and defining the designs" (Tan, 2005). Based on these facts, action research strategy is employed in this research. As discussed before, the design of photonic textiles involves continuous improvement. The circular nature of action research is shown in Figure 3.2.

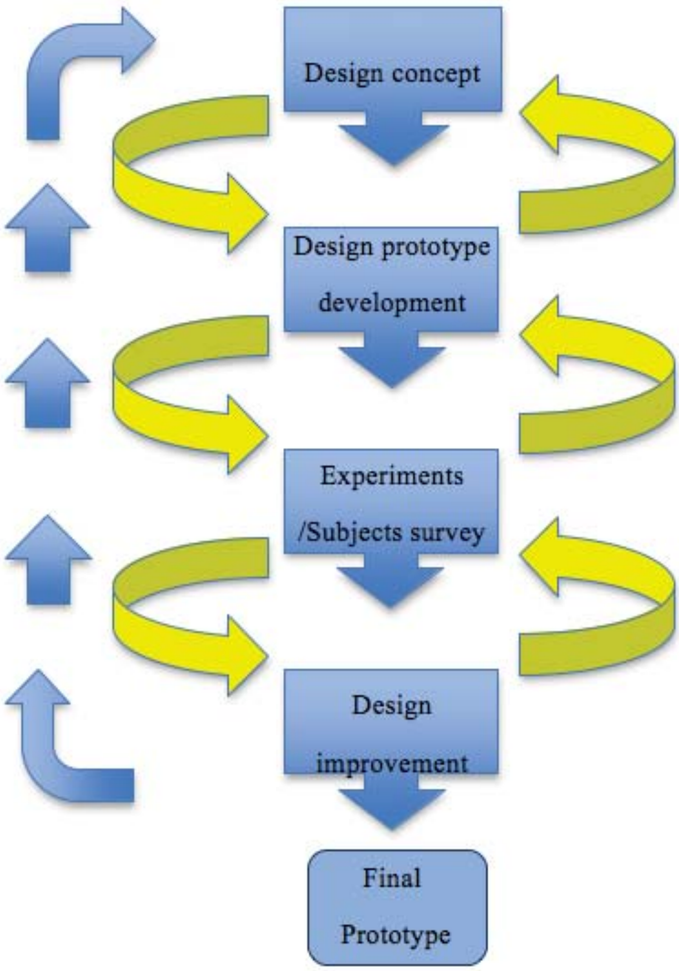


Figure 3.2 Circulated action research process

In the first step, a design concept is developed. This design concept is fundamental and paves the way for development of various prototypes. Based on the design concept, prototypes are produced. The fabrication of prototypes involves experiments with different materials, measurements of variables, and combination of a variety of technologies. Afterwards, experiments are performed to evaluate the functional performance of the prototype, and survey is conducted to assess the usability of the prototype. Based on the feedback from the experiments and surveys, the design is revised accordingly. This iterative cycle will be ended until the final prototype meets the predetermined requirements in terms of functionality, usability and comfort.

3.3 Quantitative, qualitative and mixed-methods research strategies

As discussed in Section 3.2, the interdisciplinary design process in this research is a highly reflective process, and the prototypes need to be continuously improved by the feedbacks from relevant experiments and evaluations. Generally, there are three main approaches in research, namely quantitative, qualitative and mix-methods approaches, and each approach is discussed respectively as below.

3.3.1 Quantitative and qualitative research

Generally speaking, quantitative research concerns the collection and analysis of numerical data. Qualitative research, on the other hand, is concerned with collecting and analyzing information in many forms, mainly non-numeric (Blaxter, 2001). Quantitative research is a research strategy that emphasizes quantification in the collection and analysis of data. By contrast, qualitative research is constructed as a research strategy that usually emphasizes non-numeric data rather than quantification.

Quantitative and qualitative research represents different research strategies and there do exist some striking differences in terms of the role of theory, the techniques employed, and analyzing methods of collected data. However, the distinction is not a hard-and-fast one: studies that appear to embrace typical features of one research strategy may have a characteristic of the other. Each strategy may employ several different research techniques, however there is an overlap between the type of data and the style of research. Many qualitative-style researchers examine qualitative-type data, and vice versa. At first sight, the adoption of questionnaires as a research technique might be considered as a quantitative strategy, whilst interviews and observations might be thought of as qualitative techniques. In practice, however, it is often much more complicated. Actually, interviews may be constructed and analyzed in a quantitative fashion, as when numeric data is collected or when non-numeric data are collected and coded into numeric form. Similarly, survey may allow for open-ended responses and lead to the in-depth study of individual cases.

As either quantitative or qualitative method discussed above has both strengths and weaknesses, the choice of which research approaches to use largely depends on the types of questions being asked in the research study, and different fields of research typically rely on different categories of research to achieve their goals.

3.3.2 Mixed-methods approach

Based on the discussion above, it is recognized that both quantitative and qualitative methods have strengths and limitations. This has led researchers from around the world to develop procedures for mixed methods strategies of inquiry and to take the numerous terms found in the literature, such as multi-method, integrated method, combined method, and mixed method (Creswell, 2003). However, the identification of something called the 'Mixed-methods approach' is relatively new. As an approach, with a recognized name and research credibility, it has only come to the fore after the millennium (Creswell & Plano Clark, 2007; Gorard & Taylor, 2004; Johnston & Onwuegbuzie, 2004; Tashakkori & Teddlie, 2003)

In the areas of science and engineering, quantitative research is predominant probably due to the fact that these areas involve many experiments, measurement of different parameters, collection and analysis of numerical data. However, qualitative methods can bring a new or fresh perspective to existing research in field of science that has been dominated by quantitative methods. When combined with quantitative techniques, qualitative strategies can often help researches to more strongly support their research design choices and final inferences (Shaw, 2003) . A complex research question can be more comprehensively addressed with the use of a combination of qualitative and quantitative (i.e., mixed methods) strategy (O'Cathain, 2009). The combination of quantitative and qualitative methods provides with researchers more benefits and improved information that cannot be obtained when single method is utilized.

A mixed-methods approach is one in which the researcher tends to combine quantitative and qualitative approaches. The data collection involves gathering both numeric information (e.g., on instruments) as well as non-numeric information (e.g., on interviews) so that the final database represents both quantitative and qualitative information. The core idea of a mixed-methods approach is that researchers can bring certain elements, which have conventionally been treated as belonging to either quantitative approach or qualitative approach, together within one single project. The mixed-methods approach is problem-driven in a sense that it treats the research problem rather than the strategies used as the primary concern. Researchers can readily use different research techniques, which have been traditionally classified into either quantitative approach or qualitative approach, provided their use yield crucial findings to address the research problem.

Researchers who would like to use the mixed-methods approach can take a number of forms of the mix and it is possible to construct a complex range of possibilities for combining the quantitative and qualitative methods within a single research project. Several common procedures have been suggested (Creswell, 2003), such as sequential procedures, in which the researcher seeks to elaborate on or expand the findings of one method with another method, concurrent procedures, in which the researcher converges quantitative and qualitative data in order to provide a comprehensive analysis of the research problem. The adoption of different forms of mix and procedures is highly dependent on the nature and the complexity of the research problem concerned.

Design of interactive photonic textiles needs multi-disciplinary co-operation. It involves experimental research, which concerns non-numerical qualification, as well as survey, which collects and analyzes numerical data. Single method, either qualitative or quantitative, cannot address the research problem in this project. Considering the nature and the complexity of this research project, the mixed-methods approach is adopted.

3.4 Design practice and experimental research

Research of design discipline is recognized as a practice-based research. Textile and fashion designers are familiar with material, color, silhouette, aesthetics, tactility etc. , and they obtain these knowledge and skills mainly from design practice. The design of photonic textile is very different from design of conventional textile. New design variables need to be defined and studied. The design variables of photonic textiles consist of both tangible elements (tactility, structure, color, material, form), and intangible elements (lights, darkness, light intensity, hue, duration) as illustrated in Figure 3.3

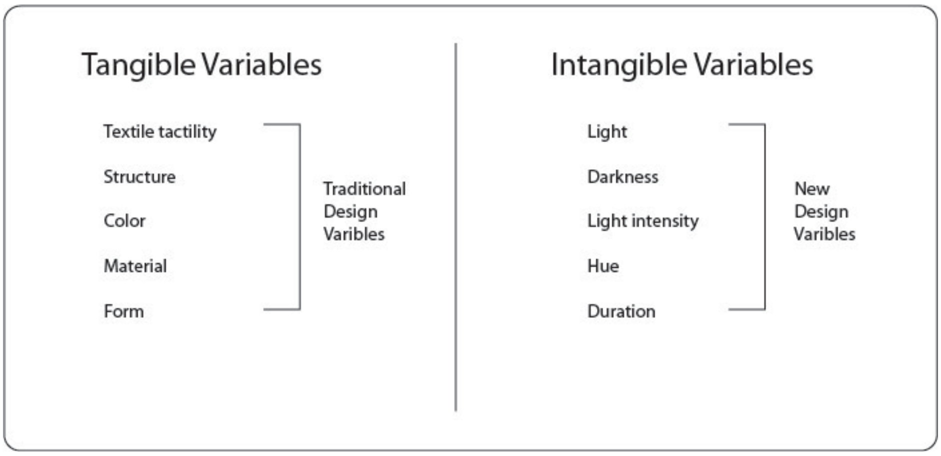


Figure 3.3 Design variables of photonic textile

In this section, procedures, techniques, materials and equipment are introduced and justified. As shown in Figure 3.4, three parts construct the Interactive Photonic Interior Furnishing System (IPIFS), including textile panel, POF and electronic system. Experimental research approach for each part are discussed respectively. The following sections introduce each technique adopted and how to combine all techniques to develop the interactive photonic interior furnishing system.

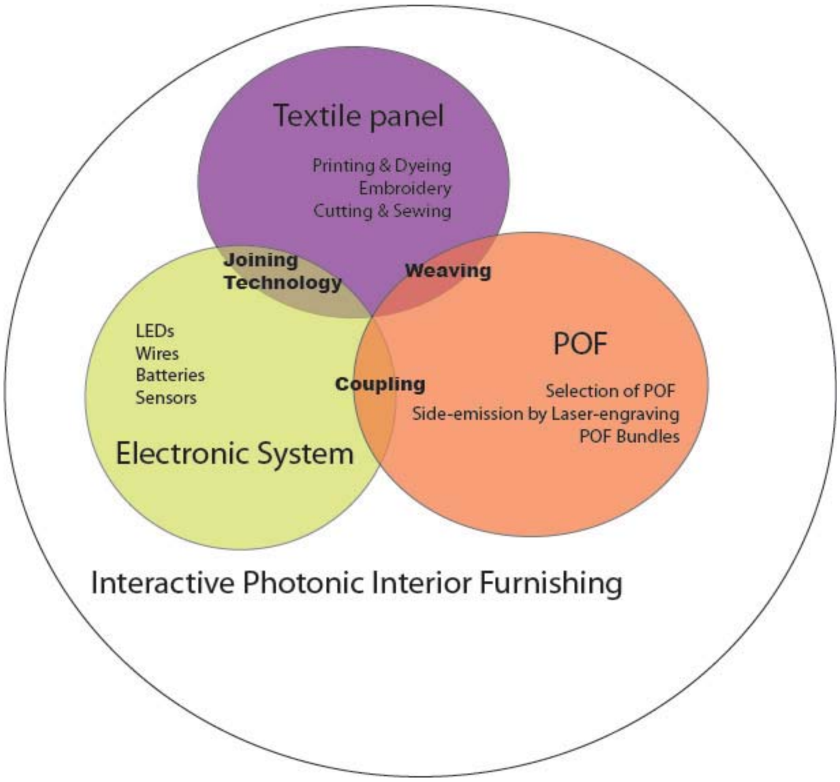


Figure 3.4 Interactive photonic interior furnishing system

3.4.1 Textile Panel

3.4.1.1 *Weaving*

The weaving technology is adopted for integrating POFs into textiles in this research due to the fact that the grid structure of the weave is advantageous as it allows the exact fiber arrangement and position determination (Abouraddy, et al., 2007). Compared to knitted construction, weave structures cause less damage to POFs, since the POFs are not extremely bended over into loops which occurs during knitting process. The construction of the woven fabric is based on three factors: (a) the size of the textile thread, (b) the woven pattern, and (c) the distance of parallelizing fibers. The distance between the parallel lying fibers influences the flexibility of the textile. To support effective light transmission and to avoid hard bending of POFs in woven POF fabrics, open weaves should be used (Rothmaier, Luong, et al., 2008).

Theoretically, POFs can be woven into fabric in both warp and weft directions. For the convenience of changing the yarns, however, usually POFs in warp direction is adopted for hand weaving loom, while POFs in weft direction is adopted for machine weaving loom. Moreover, studies on the luminosity of woven textiles in warp and weft direction demonstrated that POFs woven in weft direction showed better illumination results (Harlin, et al., 2003; Koncar, 2005; Masuda Atsuji, et al., 2006). In this research, machine weaving loom is chosen because of its highly efficient performance. POFs are only woven into weft direction with other conventional yarns. Otherwise, the tactile quality will be great reduced if POFs are in both weft and warp directions.

Woven fabric constructions can be limitless, however most structures are derivative from three basic weaves, i.e. plain weave, twill weave and satin weave. In this project, the photonic fabrics are mainly manufactured by plain weave and satin weave. The POFs are introduced as weft yarns, and the woven photonic fabrics are produced using a loom that controls how the warp and weft yarns interlace. Warp yarns are cotton or polyester threaded under tension through the loom; weft yarns (POFs) are inserted and pushed into place to make the fabric (Figure 3.5). The plain weave is the simplest weave and is formed by yarns at right angles passing alternatively over and under each other. Each warp yarn interlaces with each weft yarn to form maximum number of interlacing. In most satin weave fabrics, each warp yarn floats over four weft yarns and interlace with the fifth weft yarn, with a progression of interlacing by two to the right or the left.

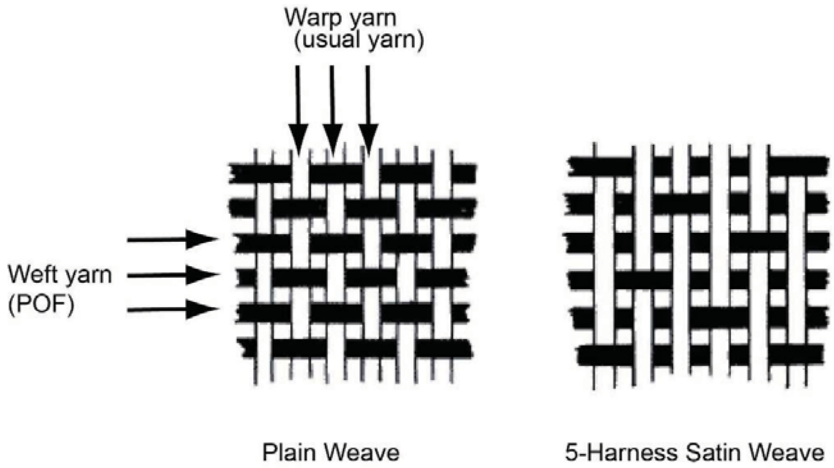


Figure 3.5 Integration POF as weft yarn in plain weave and satin weave structure

By varying the weave structure and incorporating the photonic luminescence generated by the integrated POFs, different surface pattern, texture, color and luster can be created.

3.4.1.2 *Embellishment*

Different embellishment techniques are applied on POF fabric to enhance the overall appearance and the tactile quality of the fabric. Experiments of dyeing, printing and embroidery are carried out to exam how traditional textile embellishment methods can be adopted on POF fabric.

3.4.1.2.1 Dyeing

Dyeing is a process which introduces beauty to the textile by applying various colors onto a fabric. Dyestuffs can be applied onto textile at any stage of the manufacturing of textile – fiber, yarn, fabric or a finished textile product including garments and apparels. Dyeing is normally carried out in a special solution containing dyestuffs and many other chemicals and auxiliaries. After dyeing, dye molecules have chemical bonds with fiber molecules.

The temperature and time controlling are two key factors in dyeing. According to the nature of dyestuffs and the coloration mechanism, dyes can be classified into several groups, such as direct dyes, disperse dyes, reactive dyes.

The application of color or "dyeing" can be achieved during various stages of the fabric's production. However, the optical fiber cannot be heated over 80°C, since the optical fiber may be destroyed at high temperature (Harlin, et al., 2003). Therefore, conventional dyeing and printing methods, which involve heat treatments (curing, heat setting, etc.) do not apply. Due to the nature of POFs, dip dyeing using cold water is adopted to dye POF fabric. Dip dyeing introduces color into POF fabric while keep the damage to POFs at a minimum level.

3.4.1.2.2 Screen printing

Screen-printing has been used to apply dyes or inks to fabric for a long history. Screen-printing is basically a process of using a mesh-based stencil to apply dyes onto a fabric. Normally, a woven mesh is used to support an ink-blocking stencil to receive a desired graph. The dyestuffs or other printable materials are pressed through the open area of the mesh as a sharp-edged image onto a fabric. A blade or squeegee is moved across the screen mesh, forcing or pumping dyestuff through the mesh openings to the fabric during the squeegee stroke.

Due to the low impact on the fibers, screen-printing is applied to the fabric surface to achieve a variety of effects and textures, which enhances the overall aesthetic of the textile. Although the screen-printing technique is a comparatively laborious and time-consuming method, it can be applied on a wide range of fabrics and is capable of producing metallic and textured effects. Therefore, screen-printing technique is adopted to enhance the surface design of fabric.

3.4.1.2.3 Digital printing

Digital textile printing is the process of creating printable designs for fabric on a computer, which can be sent directly from the computer to fabric printing machinery without the use of screens and color separations (J. L. Smith, 2009). The design can be created digitally with almost any graphic design software. The desired pattern with its individual colors is built up by projecting tiny drops of 'ink' (special dye liquors) of different colors, in predetermined micro-arrays (pixels), onto the textile surface (Miles, 2003). The inks used in digital printing are specially formulated for fabrics of different compositions (cotton, polyester, nylon, etc.). During the printing process, the fabric is fed through the printer using rollers and ink is applied to the fabric in the form of thousands of tiny droplets. This process is quite similar to computer controlled paper printers used for office application but on a complicated scale where numerous variables are managed to give the best possible outcome on fabric. As an emerging technology to apply diverse graphs in high resolution onto fabric, digital printing is also experimented to enhance the surface pattern and aesthetic of POF fabric.

3.4.1.2.4 Embroidery

Embroidery is a method of decorating the surfaces of fabrics or garments. It can either be done in a traditional way such as by hand, or in a modern way by machine (McIntyre & Daniels, 1995). Both can create appealing designs and complement each other. Embroidery has been used in textiles and clothing development for a long history. As a tool for design embellishment, although diverse embroidery machines and techniques are available in the market, the main purposes of embroidery remain the same, namely, to decorate and customize the textile or garments to meet consumer needs to represent diverse personalities and follow fashion trends.

This traditional textile design method can also be applied on the interactive textiles. A company named Sternlab combine traditional embroidery technique with Printed Circuit Boards (PCBs) to create wearable electronic which is a good example of combination of textile design and electronic components (Stern, 2008) (Figure 3.6). The motifs is entirely hand-stitched floss make up the embroidery design, stands of conductive thread from pathways for electricity to travel across the surface of the fabric. Even the circuit is explored, the overall design still brings a “soft” feel.

Figure 3.6 LilyPad Arduino Embroidery

In this project, both hand embroidery and machine embroidery are used to enhance the tactile quality and surface pattern of the fabric.

3.4.2 Side illumination of POF fabric

The main role of conventional optical fibers is to transmit light or optical signal to a specified spot. However, if the cladding of the optical fiber is partly damaged by physical or chemical treatments, the light leaks out from the damaged spot and side-lighting will occur. Side illumination of fabric greatly enhances the surface color and pattern especially in dark environment.

Micro-bending of POFs increases the refractive angle of the light and light leaks out. However, in order to obtain very bright POF fabrics, further treatments are always needed to crack or damage the cladding to enhance the side illumination (Harlin, et al., 2003) (Figure 3.7).

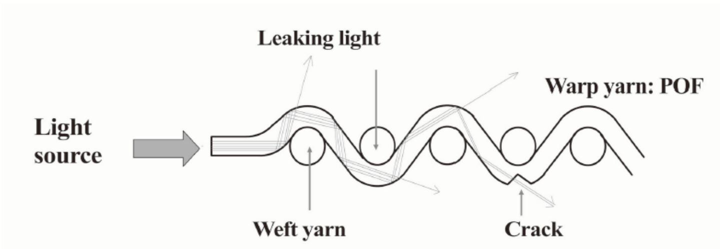


Figure 3.7 Principle of micro-bending of optical fiber (Harlin, et al., 2003)

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. In this research, laser engraving is employed to induce side emission of light.

Laser engraving is a technology that uses a high-power laser to cut materials, and the engraving can be precisely controlled by a computer. This technique has been adopted for the color-fading of denim fabric or surface embellishment on the textiles (Ondogan, et al., 2005; Ortiz-Morales, et al., 2003; Ozguney, 2007). As shown in Figure 3.8, with the laser beam moving from bottom to top of the jeans (Figure 3.8), the dark blue color of the jeans is gradually removed to create a washed-out look (Jeanologia, 2014).

Figure 3.8 Laser-engraving process on jeans by Jeanologia Laser technology

In this project, the engraving is realized through a carbon dioxide (CO_2) laser. It is a kind of gas laser which 42 emits light at a wavelength of 10.6 μm in the far infrared region of the electromagnetic spectrum. A typical schematic diagram of the gas laser is shown in Figure 3.9 (Chryssolouris, 1991).

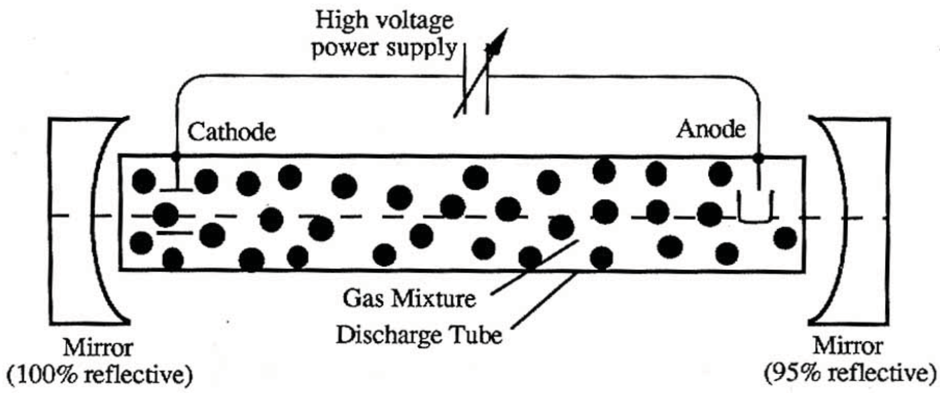


Figure 3.9 General schematic of a gas laser (Chryssolouris, 1991)

Laser engraving system requires different components, such as laser beam generation, beam delivery, work piece positioning and auxiliary devices, for the engraving. A basic laser machine system is shown in Figure 3.10 (Chryssolouris, 1991).

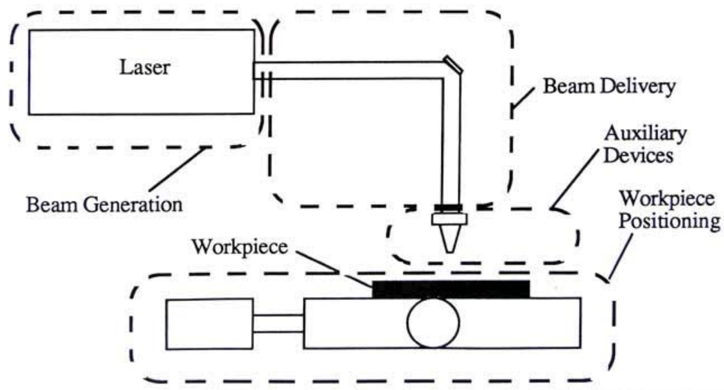


Figure 3.10 Basic laser machine system (Chryssolouris, 1991)

In this study, laser-engraving is adopted to remove part of the cladding of POF, in order that the light can be emitted along the surface of optical fibers (Figure 3.11). The 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 μs). 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. The engraving process is accurately controlled by a computer program.

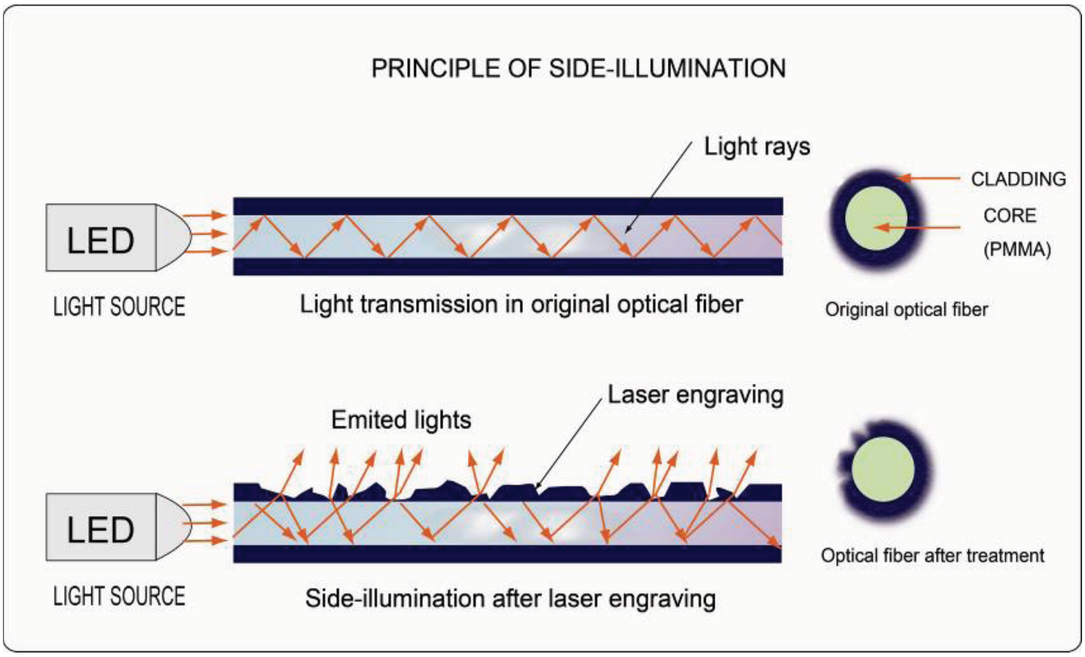


Figure 3.11 Principle of side-illumination by laser-engraving

3.4.3 Electronic system

3.4.3.1 *Light source*

This project proposes to investigate the integration and utilization of POFs to create textiles for interior furnishings which can be interactive with the user and the environment in terms of change in color, luminescence and surface pattern. POF textile is designed as a soft screen, which can transfer the light from embedded light source.

Depending on the application of the POF fabrics, various light sources can be connected to optical fiber ends. Bright light emitting diodes (LEDs) (Graham-Rowe, 2007) have been used for photometric applications due to the fact that the light produced is cool, and the light source can be remotely located. While for radiometric purposes, lasers with a suitable wavelength were used for medical treatment (Tania Khana, et al., 2006) or sensory applications (Rothmaier, Luong, et al., 2008; Rothmaier, Selm, et al., 2008).

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, and therefore the powerful laser light sources are not suitable for this kind of application. Taking all these factors into account, LEDs are used as light source in this research. There are many different types of LEDs available in the market (Figure 3.12).

Figure 3.12 Different types of LEDs

In this study, LEDs with RGB (Red, Green, Blue) colors are used as the light source in order to produce mixed color. Theoretically the tri-primary colors can mix and generate any other colors (Figure 3.13), but human's eyes can only recognize parts of the visible light.

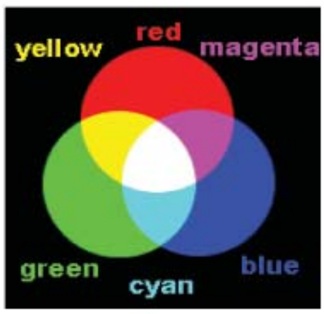


Figure 3.13 Tri-primary colors of light

The colors of LED can be changed and tuned by fine-tuning the primary colors, which can be realized by changing of electric current of LED. Groups of photonic fibers are bundled together and then coupled with LEDs with predetermined sequences (Figure 3.14). With the controlling system, LEDs can generate different colors, and two different colors can mix a third color. By this way, the POF fabric can present a unique appearance with multiple and mixed color.

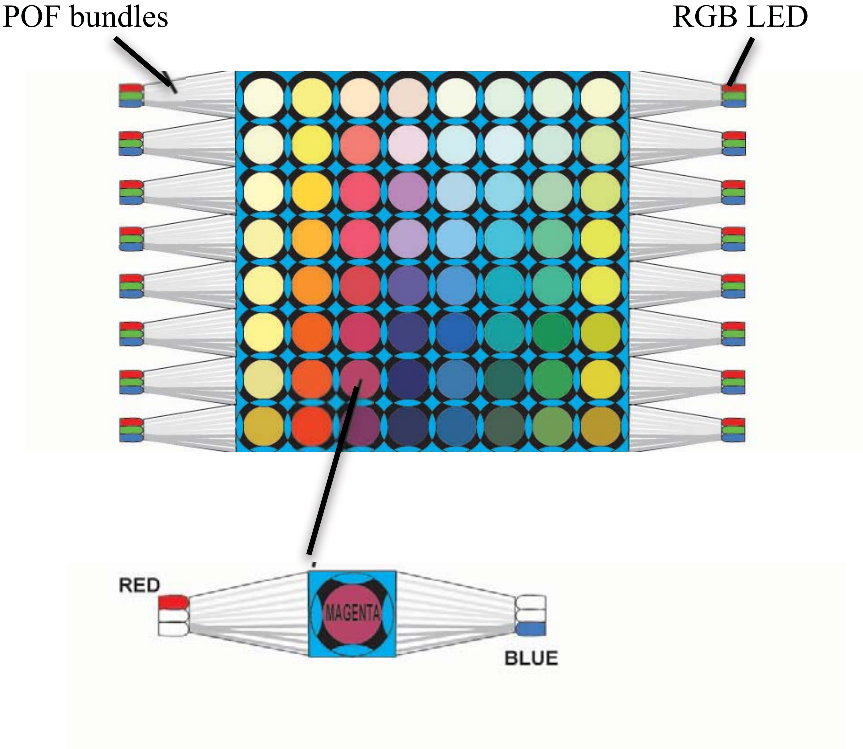


Figure 3.14 Lighting design of POF fabric

The radiation efficiency of POF fabric systems depends considerably on the above described attenuation of the used POF material as well as on inherent coupling losses of the required lighting system. For small batch sizes, handmade connectors for defined bundles of POFs were made (Selm, et al., 2007) with polished surface at the POF endings for reduced transmitting power. Efficient light transmission from the light source into the

POFs is achieved when the area of delivering light overfills the numerical aperture of the fiber bundle (Wilson, et al., 2009). In contrast to glass fibers, POFs show high numerical aperture, and thus, they have a large acceptance angle of about 60° (Daum, et al., 2002), which makes it easy to connect them to light sources.

Different bonding techniques are adopted in this research in coupling LEDs with POFs, which can maximize the lighting efficiency and reduce the coupling loss. LEDs are connected with a branch of optical fibers by optical adhesive or an adaptor, and detailed coupling mechanism will be introduced in next few chapters. All controlling electronics of LEDs are docked in a motherboard (Figure 3.15).

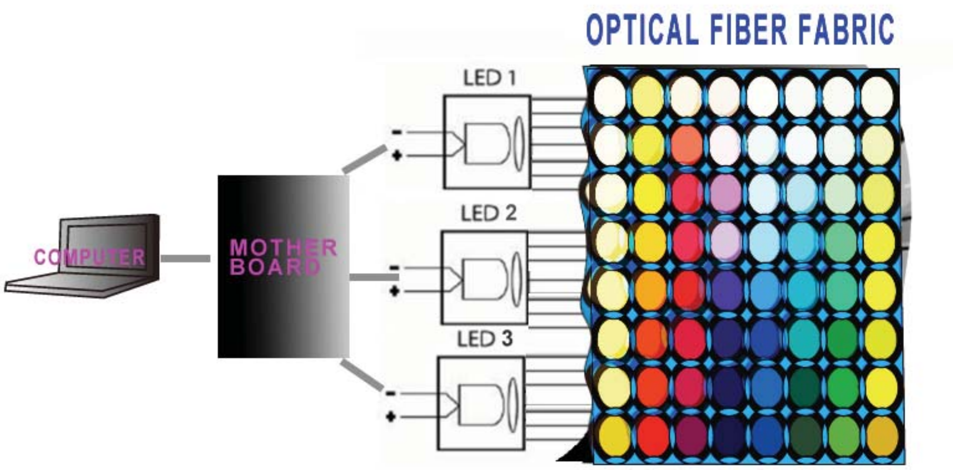


Figure 3.15 Schematic diagram of the POF fabric system

3.4.3.2 *Sensors*

A sensor is such a device that detects and converts a physical input into a signal which can be read by a specific instrument. There are numerous types of different sensors to detect various parameters, such as temperature, humidity, pressure, flow, strain, motion, touch. Applications of sensors can be found almost everywhere ranging from touch-sensitive elevator button to aerospace.

Application of sensors in smart clothing for bio-sensing has been critically reviewed in Chapter 2. The main purpose for incorporating sensors into photonic textiles is to create an interface between user and textiles, and then foster the interaction between user and textiles. With this consideration in mind, touch sensors and motion sensors are employed in this research. Touch-sensitive sensor is embedded into textiles to detect the touch from user. When the textiles are touched by hand, the touch sensor will convert the touch into electrical signals. Then the control system will instruct the photonic textiles to respond to the touch by emitting light, or by changing the illumination, or other modes which are predetermined. In this way, real-time interaction, both user-textiles interaction and user-user interaction through textiles, are realized. The interaction using motion sensors works in a similar fashion, but only differing from touch sensors in a sense that the detecting parameter for motion sensors is movement of an object or a person.

3.5 Survey research

The survey is probably the most widely used data-gathering technique in research (Neuman, 2004). During a survey, many subjects (sometimes called respondents) are asked about their beliefs, opinions, characteristics, etc. Surveys are appropriate for research questions about self-reported beliefs or behaviors. Researchers usually ask about many things at one time in surveys, measure many variables (often with multiple indicators), and test several hypotheses in a single survey.

The main purpose of the survey in this study is to subjectively evaluate the appearance, functionality, color, interaction, etc. of the interactive photonic prototypes. In the survey design, the selected subject is requested to rate the performance of the prototypes. Besides the closed questions, some open questions are also included.

The subjects from 50-100 people will be invited to the survey research after using the photonic textile prototypes. The background of subjects is diverse. Survey were conducted two times in the author's research. The results will be introduced in section 4.3.3 and 5.5.

In the first part of the questionnaire the subject is asked to evaluate the performance of the prototype by rating different aspects of photonic product including design concept, aesthetic consideration, comfort, convenience, illumination and interactive function. Each performance is given a numerical grade from 1 (very unsatisfactory) to 7 (very satisfactory). The overall grade is obtained by taking the average of the grades from all subjects.

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

Question 1: Which interactive mode do you like the most?

Question 2: Do you agree that the prototype can enhance interior environment?

Question 3: Would you like to use this kind of product in your home if it is available in the mass market?

Question 4: Which property is most attractive to you?

----Appearance

----Pattern

----Illumination

----Technology

Question 5: Which property needs to be improved?

----Appearance

----Usability

----Durability

----Change of color

----Interaction with user

----None

3.6 Summary

This research is proposed to develop user-friendly interactive textiles with integrated POFs and electronic components to emit light. This kind of smart textiles can be unobtrusively integrated into our interior furnishings without any intervention with our daily life, and enhance the interior environment. In order to meet the requirements in terms of functionality, usability, appearance, aesthetics, etc., the design of interactive photonic textiles needs multi-disciplinary co-operation. Considering the highly reflective nature in the design process and the complexity of this research project, action research strategy and mixed-methods approach, which combing qualitative and quantitative approaches, are adopted. Action research and mixed-methods approach are neither isolated nor separated. On the contrary, they are mixed in a concurrent and integrated fashion throughout the entire design process. Theoretical research from literature review and experimental research from design practice are both utilized. Different research techniques are used. In each research technique, either quantitative or qualitative data, or both, may be collected; however, overall this constitutes a mixed-methods approach.

Chapter 4. **Design process and experiment implementation**

4.1 Introduction

This chapter presents the process of developing photonic textiles. Experiments were conducted to examine how to implement integration of POFs, side-emission of POF fabric and design of controlling system of light source. Photonic fabric samples with integrated POFs were successfully created by weaving techniques. It was demonstrated that laser engraving technology can be adopted to realize side-illumination of photonic fabrics. The luminous pattern on POF fabric can be customized according to the designer or the customer. Textile embellishment methods were applied to enhance the overall aesthetic of the POF textile. Textile panel, POFs and electronic system work as a unit to realize the color-changeable and color-tunable textiles. Several prototypes of photonic interior furnishings were created and exhibited. A survey was conducted to evaluate the developed prototypes, and the results were discussed. According to author's techno-design practice, a novel design process model was developed for interactive photonic product and future research.

4.2 Experimental design process

4.2.1 Development of design concept

The inspiration of photonic soft furnishing is from the idea intending to redefine the relationship between people and the interior light. The way we turn on the light is always through a switch, and normally we don't touch the light bulb directly with our hands. Even though modern technology allows people to use their smart phone to control the light (Figure 4.1), people still have to employ a hard and cold device as a tool. This raises the following questions: Can light be tangible? Can light be endowed with various tactile qualities and shapes, so that people can interact with the light, even “hug” the light?

Figure 4.1 Light switches (Picture from Belkin Switch)

This project aims to develop innovative photonic textiles as a platform through whose tangible surface people can interact with light and even “shape” light.

The POF fabric can be designed into soft furnishings to realize a tangible and soft lighting environment. As illustrated in Figure 4.2, the design inspiration and sketch of photonic textile furnishings are drafted. In this picture, all the soft furnishings can illuminate, including the curtain, sofa, cushions, ceiling and wall covering. People can hug, touch, sit against or play with light through photonic soft furnishings. These photonic soft furnishings can not only present a unique appearance, but can also enhance the interior environment and make the interior a personalized and customized atmosphere.

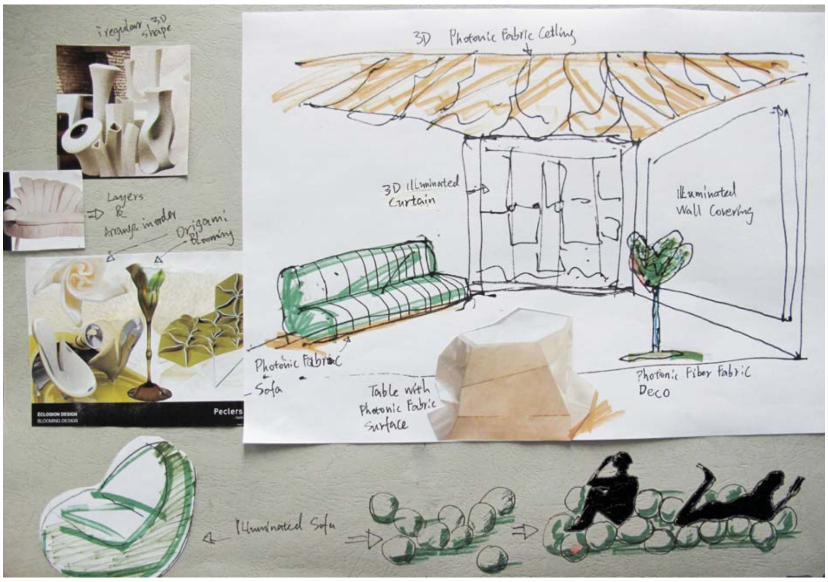


Figure 4.2 Inspiration and design draft on sketch book

4.2.2 Weaving

Weaving was employed in the experiments to introduce POFs into fabrics to create innovative interior photonic textiles. POFs were introduced as weft yarns, while warp yarns are cotton or polyester. Both plain weave structure and jacquard weave structure are developed. Toray® PMMA optical fiber with diameter of 0.25mm was used. In plain weave, the warp yarns are cotton, while in jacquard weave, the warp yarns are polyester.

Photonic fabric in plain weave structure was produced on CCI Automatic Sample Loom SL7900C (Figure 4.3). Figure 4.4 shows fabric sample with small diamond structure. The fabric can illuminate revealing the intricate diamond structure. The content of fabric sample in Figure 4.4 is 50% optical fiber and 50% cotton. Since the fineness of the optical fiber is close to the cotton yarn, the final photonic fabric sample can achieve a soft hand feeling.

Figure 4.3 A photonic fabric with small diamond woven structure

Figure 4.4 Photonic fabric produced by plain weaving

Another photonic fabric sample in plain weave structure is presented in Figure 4.5. Some POFs are intentionally removed in weft direction to create some gaps in order to give the fabric a unique appearance.

Figure 4.5 Photonic fabric produced by plain weaving

Jacquard weaving technology is also utilized for development of photonic textile samples. The photonic fabric is woven on the Dornier Weaving Loom PTV 8/J with the STAUBLI Jacquard Head JC6 (Figure 4.6).

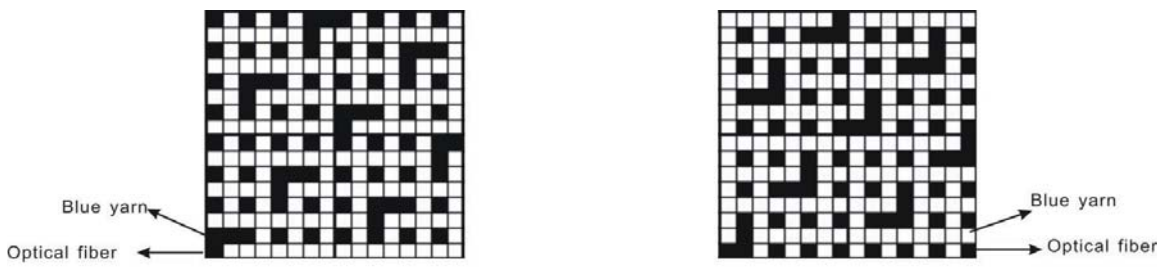
Figure 4.6 Photonic fabric producing on a jacquard weave loom

Toray® optical fibers of 0.25mm in diameter together with blue cotton threads were inserted as weft yarns, and the proportion of the optical fibers to cotton threads is 1:1. The warp is white polyester yarn. The essential specifications are shown in Table 4.1.

Table 4.1 Essential specifications of POF jacquard fabric

	Material	**Yarn count number**	**Color**	**Density**
Warp thread	Polyester	100 Denier	white	50 ends/cm
Weft thread	Cotton	2/32 s	blue	23 picks/cm
	POF	0.25 mm in diameter	--	23 picks/cm

The graphic pattern was drawn by CAD software. Continues geometrical pattern was designed in different scales. The weaves are designed by ArahWeave® software. In this fabric, double-layer weave structure was created by the combination of 8 end sateen weave (Figure 4.7), in order to allow as many optical fibers as possible to appear on the surface of the fabric. The density of weft yarn is 46 picks/cm, while the density of warp yarn is 50 ends/cm. In the end, the designed pattern was produced by the jacquard-weaving.



(a) (b)

Figure 4.7 Double-layer weave structure diagram

(a) Circle part (optical fiber is floating on the surface)

(b) Blue part (Blue yarn is floating on the surface)

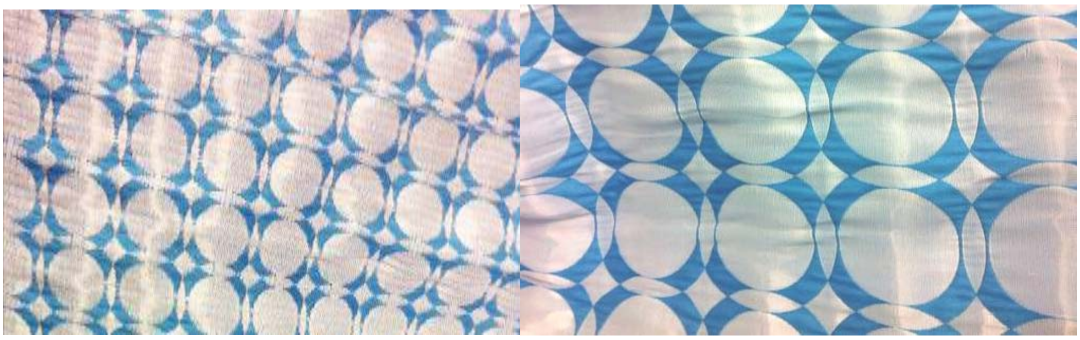


Figure 4.8 Photonic fabric produced by jacquard weaving

Both plain weaving and jacquard weaving were applied to produce photonic textile. Table 4.2 illustrates a comparison of sample loom used for plain weaving with jacquard loom used for jacquard weaving in the fabrication of photonic fabric.

Table 4.2 Comparison of plain weave and jacquard weave

	Sample loom	**Jacquard weaving loom**
WEAVING SPEED	Slow	Fast
FABRIC DENSITY	Thin	Thick
HAND FEEL	Soft	Stiff
DESIGN WHILE WEAVING	Can stop the machine to redesign or remove the weft and warp while weaving.	Once the parameter of the machine settled, it is difficult to be changed.
PATTERN OF WEAVING	Limited	Unlimited
APPLICATION OF PHOTONIC FABRIC	Cushion, sheet, curtain, 2-D decoration	Sofa, chair, wall-covering, rug, 3-D decoration

Generally, the speed of sample loom is much slower than that of jacquard loom. The photonic fabric made from sample loom is thinner than the fabric made from the jacquard loom. The density of POFs in the jacquard fabric is larger than that in the plain weaving fabric, and therefore the hand feel of plain weaving POF fabric is softer than that of jacquard weaving POF fabric. The jacquard loom can provide more solutions to complicated weaving pattern and structure. Once the parameters of the machine are settled, it is difficult to change them in the weaving progress. However, the sample loom is more flexible because it can be stopped at any time, which is an advantage for the designer to change and adapt the design as the design process evolves.

4.2.3 Side-emission of POF fabric by laser-engraving

Color and surface pattern are two of the most important factors in determining the appearance and aesthetics of interior textiles. They play important roles in setting interior environment. This research attempts to develop innovative photonic textiles which can present illuminative color under gloomy conditions. With the lighting function, the prototype can serve different decorative purpose during lit and unlit states, enhancing its visual aesthetic and design viability. As introduced in section 3.4.2, side illumination of the POF fabric is an essential process of developing the lighting function. In this section, the experiment was conducted to examine the appropriate parameter of laser-engraving for the POF fabric.

Laser engraving is applied to photonic fabrics to realize surface illumination under gloomy environment. The laser engraving is carried out by using a GFK Marcatex Flex-150 CO_2 Laser, coupled to an Easymark® 2009 laser system. The laser machine and the specifications of the machine are shown in Figure 4.9 and Table 4.3 respectively.

Figure 4.9 Laser machine system

Table 4.3 Specifications of laser machine

Parameters	*Specifications / Features*
Manufacturer / Model	GFK Marcatex FLEXI-150
Laser medium	CO_2
Laser class	Class 4
Wavelength	10.6μm (10.4 – 11.2μm)
Wave mode	Pulsed
Power (W) || Energy (mJ/p)	Power: 100W (60 – 230W) || Pulse energy: 5 – 230mJ; Pulse activation time: <45μs
Beam Divergence	<2.5mrad; Linear polarization perpendicular to laser head

(Resource from the Hong Kong Polytechnic University, CO2 Laser Engraving Machine, User Training Materials)

The intensity of laser engraving should be accurately controlled in order to ensure a precise and appropriate damage of POFs to realize side-emission. As shown in Figure 4.10, if the POFs are engraved too much (lower part of Figure 4.10), light will leak immediately at the small treated area, and light cannot travel over the whole fiber length, which makes the side illumination uneven. On the other hand, if the POFs are not sufficiently engraved, only a small amount light will emit from fabric surface, which greatly reduce the illumination intensity. In order to obtain an optimal damage of POFs and therefore to obtain a maximum illumination intensity from the fabric surface, experiments using different resolutions, pixel times and engraving repeats (one complete laser treatment cycle over the fabric based on the predetermined engraving pattern is one repeat) of laser treatment were conducted.

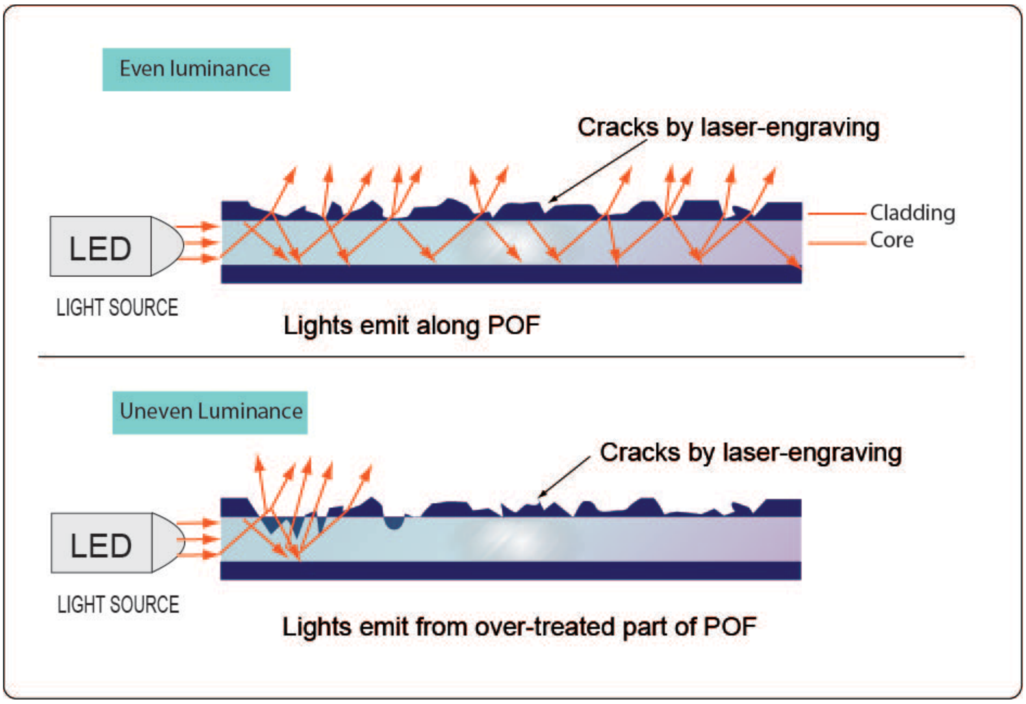
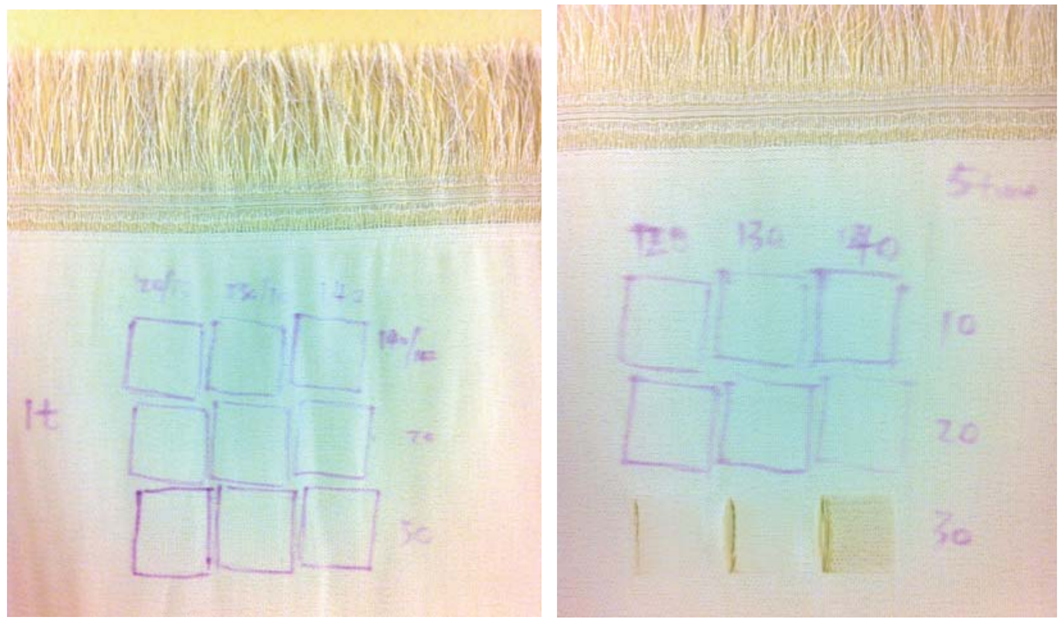


Figure 4.10 Laser engraving

A series of POF fabrics were treated by laser with different resolutions (10 dpi, 20 dpi and 30 dpi), different pixel time (120 μs, 130 μs and 140 μs) and different engraving repeats (1, 5, 7 and 9 times). The treated POF fabrics are illustrated in Figure 4.11 and Figure 4.12

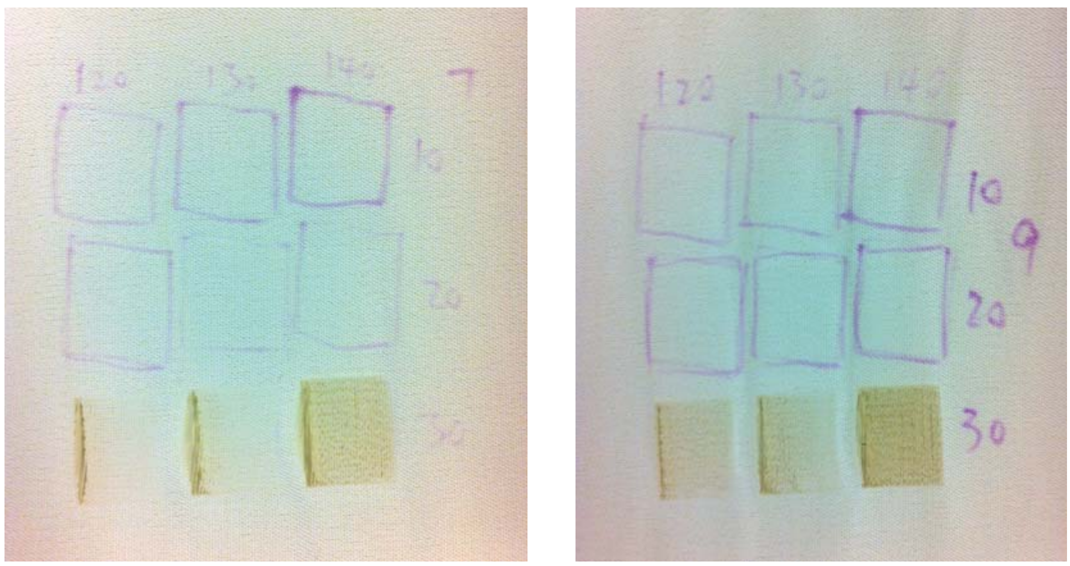


a) One engraving repeat b) 5 engraving repeats

Pixel time from left to right: 120μs, 130 μs and 140 μs

Resolution from top to bottom: 10 dpi, 20 dpi and 30 dpi

Figure 4.11 Laser engraving with different parameters



a) 7 engraving repeat b) 9 engraving repeats

Pixel time from left to right: 120μs, 130 μs and 140 μs

Resolution from top to bottom: 10 dpi, 20 dpi and 30 dpi

Figure 4.12 Laser engraving with different parameters

It is observed from Figure 4.11 and Figure 4.12 that POFs were seriously damaged when 30 dpi was used (except 1 repeat), which suggests that the laser intensity is too high. In order to further examine the detailed engraving effect on the POFs of other treated fabrics, the treated POFs are observed by Field Emission Scanning Electro Microscope (FE-SEM), and some of the SEM pictures are listed from Table 4.4 to Table 4.8.

Table 4.4 SEM pictures for POFs treated with 30 dpi

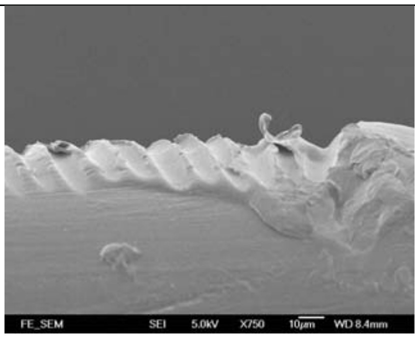
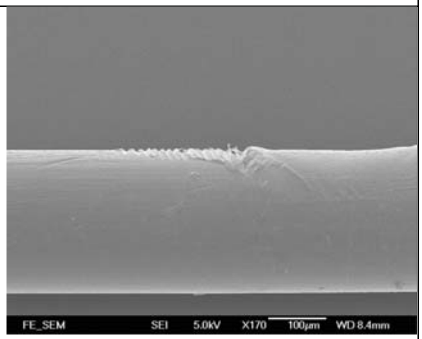
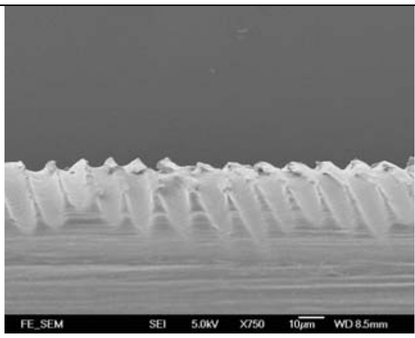
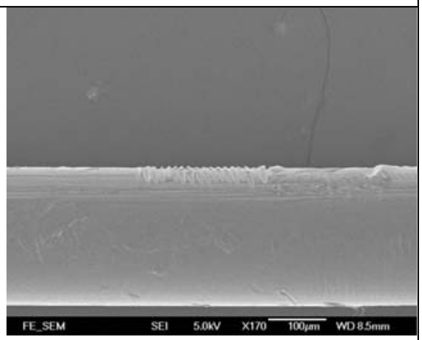
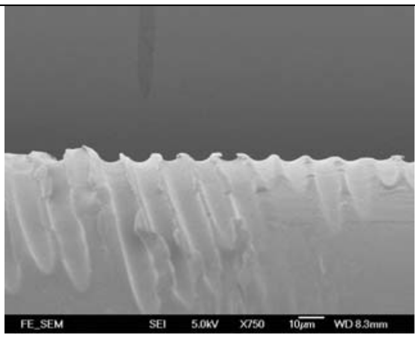
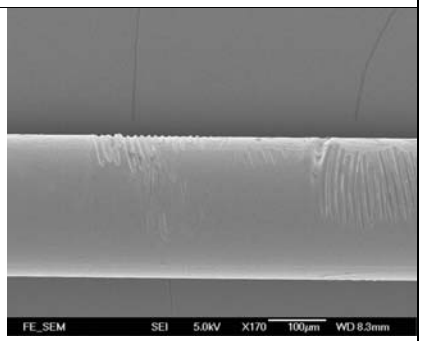
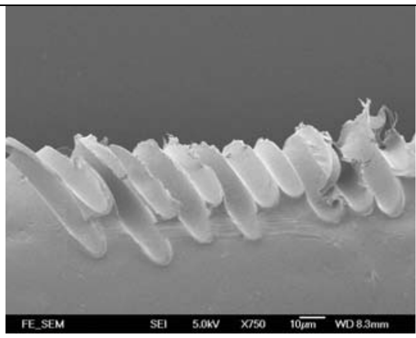
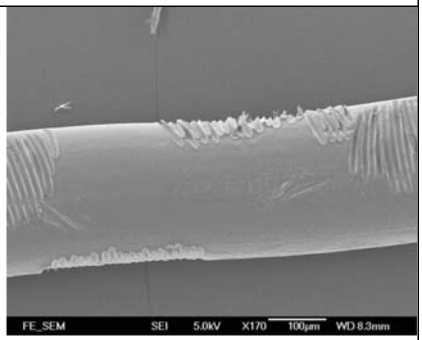
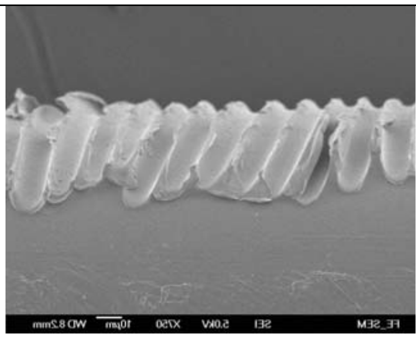
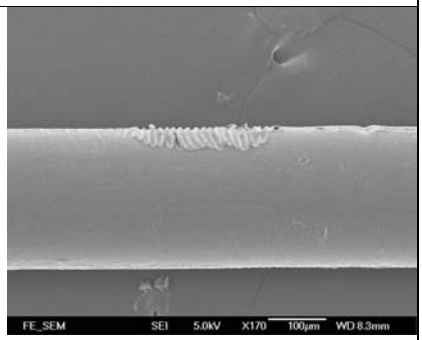
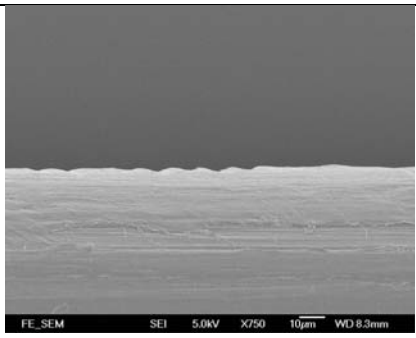
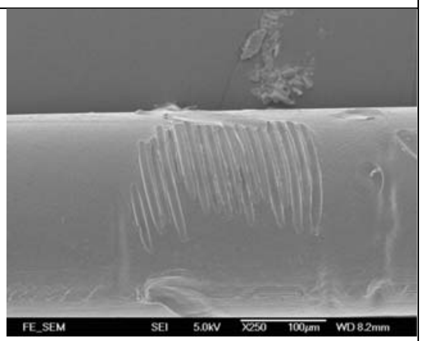
dpi	μs	repeat	X750	X170
30	140	1		
30	130	1		
30	120	1		

Table 4.4 indicates that when POFs are treated with 30 dpi and 1 repeat, it seems that the

engraving depth is not sufficient. Considering the fact that POFs have been severely ruined when engraved with 130 dpi and 5, 7 and 9 repeats, it can be concluded that laser engraving with 30 dpi is not suitable to treat the POFs used in this research.

Table 4.5 SEM pictures for POFs treated with 20 dpi and 140 μs

dpi	μs	repeat	X750	X170
20	140	9		
20	140	7		
20	140	5		

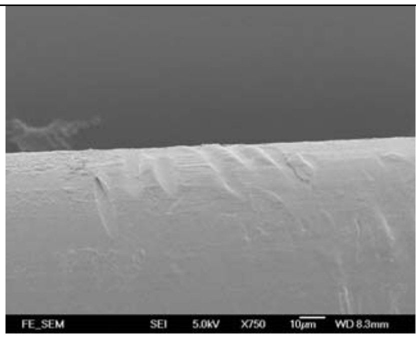
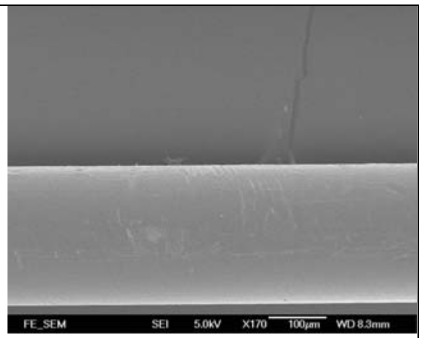
20	140	1		

Table 4.6 SEM pictures for POFs treated with 20 dpi and 130 μs

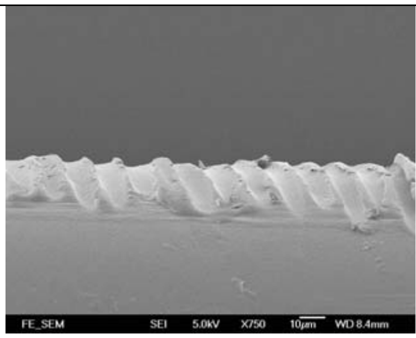
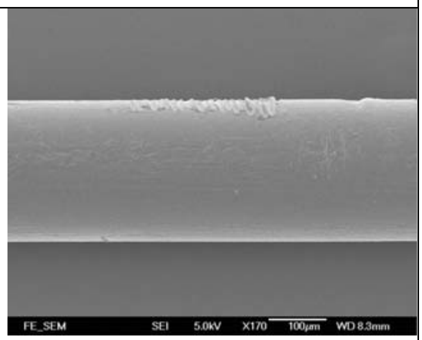
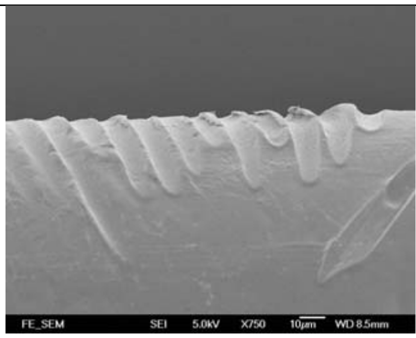
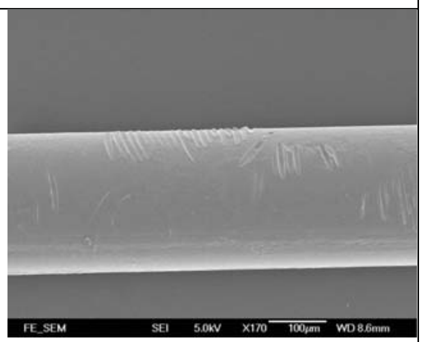
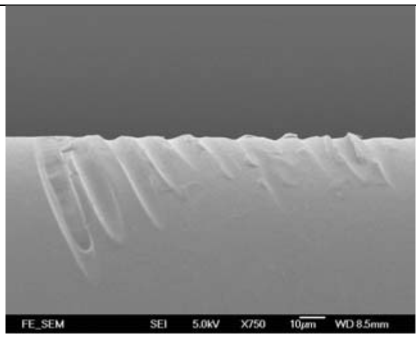
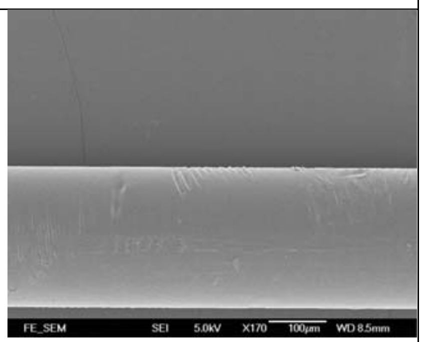
dpi	μs	repeat	X750	X170
20	130	9		
20	130	7		
20	130	5		

Table 4.5 and Table 4.6 suggest that POF fabric is treated with 20 dpi and 130 μs for 7 to 9 repeats, the engraving on POFs are acceptable, while when other parameters are used, the engraving appears to be insufficient.

Table 4.7 SEM pictures for POFs treated with 20 dpi and 120 μs

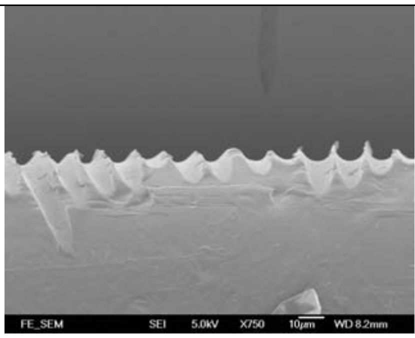
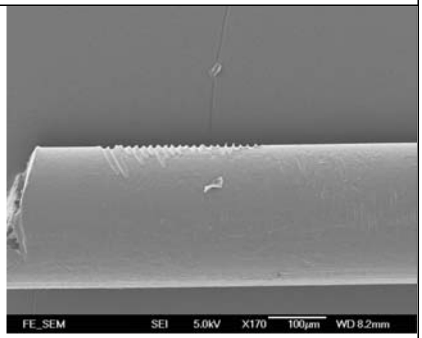
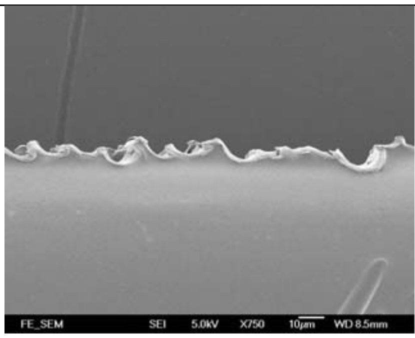
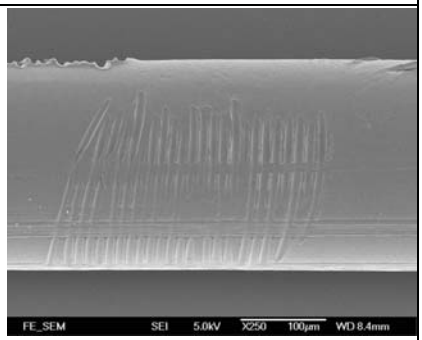
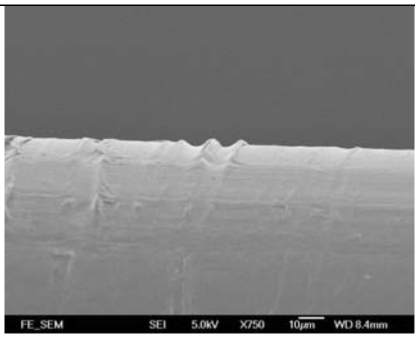
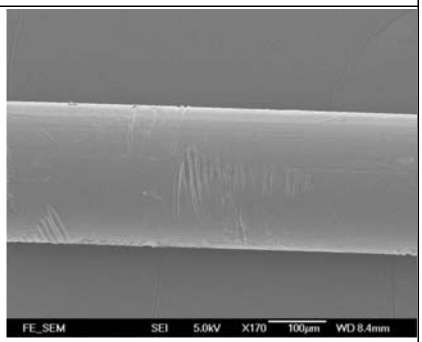
dpi	μs	repeat	X750	X170
20	120	9		
20	120	7		
20	120	5		

Table 4.8 SEM pictures for POFs treated with 10 dpi and 140 μs

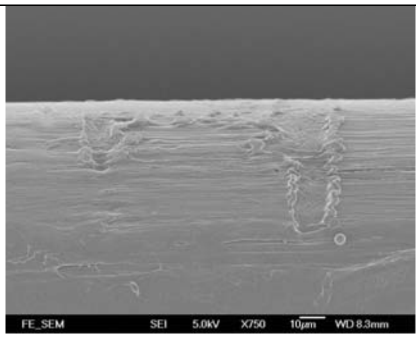
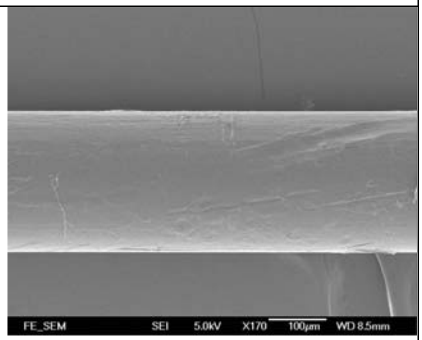
dpi	μs	repeat	X750	X170
10	140	9		

Table 4.7 and Table 4.8 illustrates that when POF fabric is treated with 20 dpi and 130 μs or 10 dpi and 140 μs, the engraving is insufficient even if the POF fabric is scanned by laser for 9 repeats. Based on the above findings, it is concluded that when POF fabric is engraved with a resolution of 20 dpi, a pixel time of 130 μs and 7-9 engraving repeats can achieve a satisfactory removal of POF cladding, and therefore accomplish a satisfactory illuminating effect. Hence, these parameters are used for all laser treatments in this research.

In order to achieve an even light emission along the POFs length, the engraving pattern is designed to be gradually changed in grey level along the POFs to be treated (Figure 4.13). The laser machine adjusts the engraving power automatically according to the grey level. In a dark area, stronger laser is applied to POFs. Hence more cladding is burned out, and more light emits from the cracks. In a bright area, weaker laser is directed to POFs, and therefore less light emits from the POFs. In this way, comparatively even light emission along POFs length can be achieved.

Figure 4.13 Graphic design pattern for laser engraving

Several other design graphics for laser engraving are shown in Figure 4.14 and Figure 4.15.

Figure 4.14 Skull pattern for laser engraving

Figure 4.15 Abstract pattern for laser engraving

Figure 4.16 and Figure 4.17 present the illuminating effect after laser engraving (integration of LEDs and electronics are discussed in Section 4.2.5). Through these prototypes, it has been demonstrated that laser engraving technology can be applied to photonic textile and enable light to emit from specific areas in a predetermined pattern. The illuminating pattern can be well controlled and customized according to the designer. The colored light emitted from these prototypes is reliant on the LEDs.

Figure 4.16 Illuminating effect after laser engraving (skull pattern)

Figure 4.17 Illuminating effect after laser engraving (abstract pattern)

4.2.4 Embellishment

4.2.4.1 *Dyeing and printing*

Considering the rigid nature of POF and its fragility to heat, dip dye using cold water is utilized to dye the fabric (Figure 4.18). During dip dyeing, the fabric is hanged on one end and the other end of the fabric is dipped into dye solution. Due to capillary action, the fabric absorbs the dye solution and the fabric is therefore colored. No heat treatment is needed in dip dyeing. The photonic fibers do not take in the dye. It is the cotton yarns that absorb the dye to create the colors.

Figure 4.18 Photonic fabric swatch by dip-dyeing

Printing is applied to fabric surface to enhance the surface pattern of textile under bright circumstance. Both screen-printing and digital printing are applied on photonic fabric. By screen printing (Figure 4.19), different appearances and texture are realized by utilization of various kinds of pigments (Figure 4.20 and Figure 4.21).

Figure 4.19 Screen printing on photonic textile with frame and squeegee

Figure 4.20 Fabric swatches

From left to right: dip-dye, fine metallic powder screen print, expandex screen print and pigment screen print

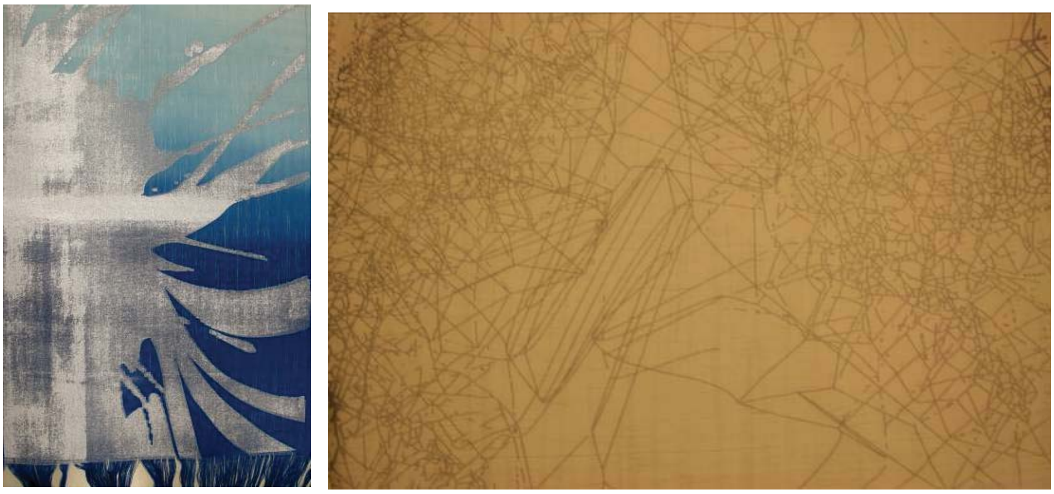


Figure 4.21 Screen printing with metallic powder

Several patterns are designed for digital printing on photonic textiles. The process of digital printing includes the following steps.

Step 1: Pre-treatment

Before digital printing, surfactant was sprayed onto the fabric to be printed. This improves the absorbency of the fabric and helps coloration of the fabric by print ink.

Step 2: Printing

During printing, the fabric was rolled into the printing machine. The reactive ink was jetted onto the fabric surface.

Step 3: Post-treatment

Conventionally the printed fabric is steamed in order to fix the color. The fabric is then laundered to remove excess pigment. However, for photonic fabric with integrated POFs, the fabric cannot be treated at a high temperature due to the poor thermal stability of POFs (Harlin, et al., 2003). Therefore, no particular post-treatment is performed for photonic fabric. The printed fabric is placed at in open area, and air-dried. One limitation of this non-steaming treatment is insufficient color fastness. Attempts to overcome this problem will be investigated in future experiments, like spraying Search Scotchgard™.

Digital printing can be applied to textiles of various texture, structure and composition. The number of colors and the size of the pattern are theoretically unlimited, and this makes the production of full tonal (photorealistic) prints possible. The printing can be completely customized and personalized. Bearing these advantages in mind, digital printing is employed in this research to create an attractive surface pattern on the fabric. Figure 4.22 illustrates a photonic fabric which is being printed.

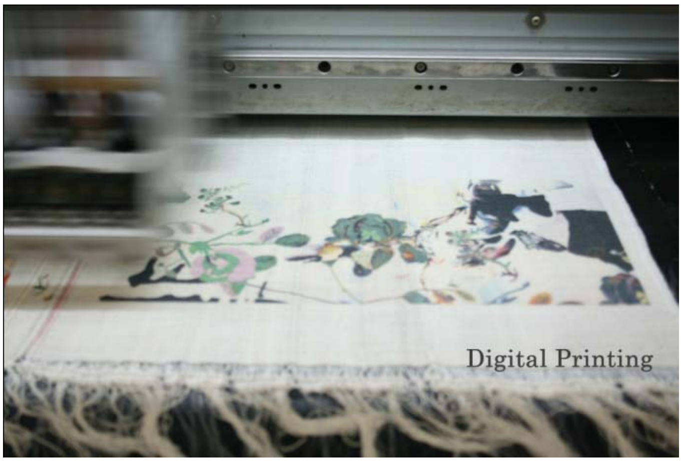


Figure 4.22 Digital printing on photonic fabric

Several fabric samples after digital printing are shown in the following pictures (Figure 4.23 and Figure 4.24).

Figure 4.23 Digital printing of flora patterns on POF fabrics

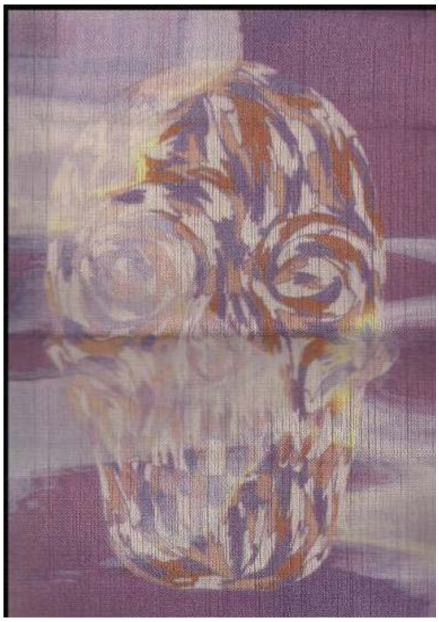


Figure 4.24 Digital printing of skull pattern on POF fabric

4.2.4.2 *Embroidery*

Both hand embroidery and machine embroidery are adopted to enhance the surface pattern of POF fabric. Due to the flexibility of hand embroidery, certain threads can be embroidered at particular places to avoid the damage of POFs (Figure 4.25).

Figure 4.25 Hand embroidery on POF fabric

The rigid and fragile nature of POF means that it breaks easily when exposed to embroidery needle puncture. However, when POFs are woven with cotton or polyester yarns, the resulting POF textile is more resilient and is susceptible to machine embroidery. During machine embroidery, the speed of the machine is specifically set to be low to avoid the damage of optical fibers. Machine embroidery is successfully applied on the POF textile using the Tajima TMCE 61202 machine as shown in Figure 4.26 and Figure 4.27. The application of embroidery on POF fabric enables the conventional flat surface of woven to have enhanced texture which increases both the tactile and visual appeal of the textile. With integration of LED as light source, the sample of embroidered POF fabric can emit light (Figure 4.28)

Figure 4.26 Tajima TMCE 61202 embroidery machine

Figure 4.27 Embroidered POF fabric

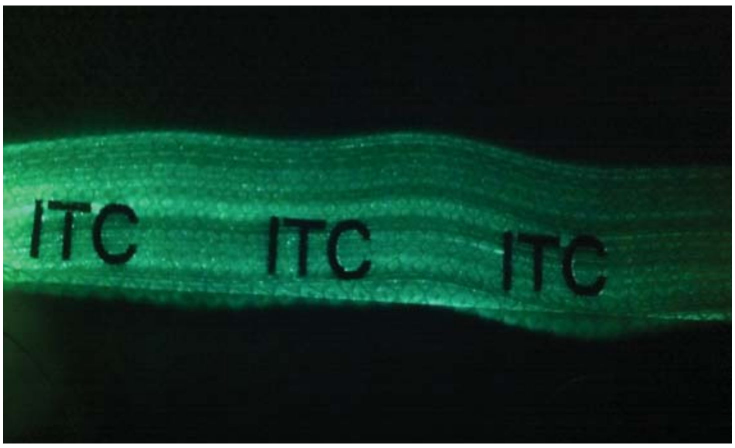


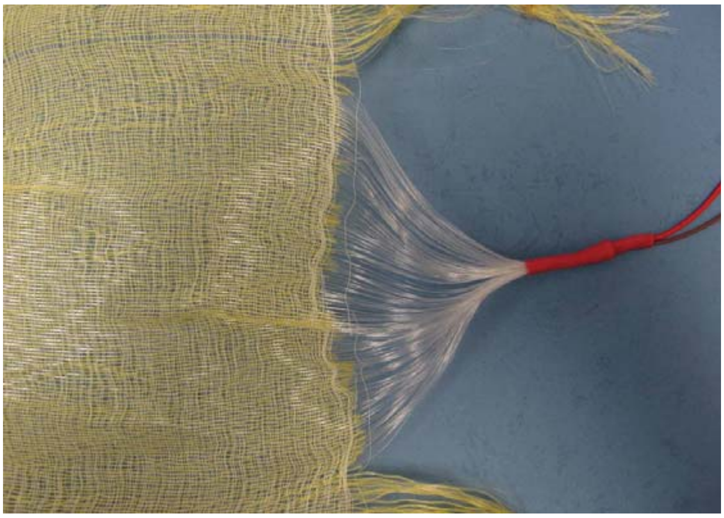
Figure 4.28 Illuminating fabric with machine embroidered pattern

4.2.5 Integration of LEDs

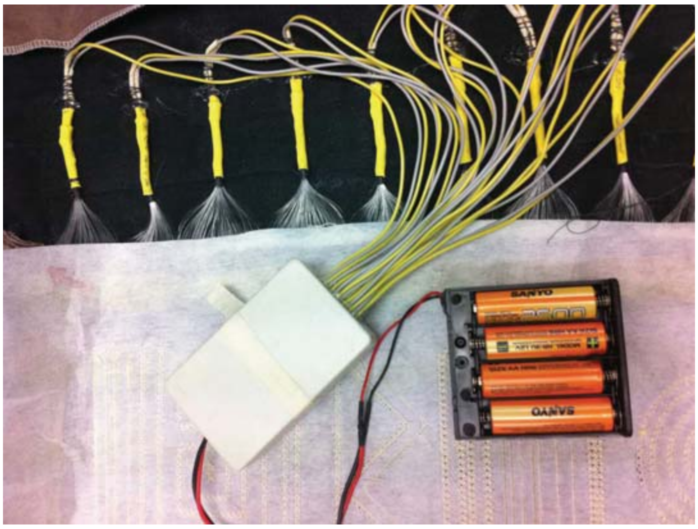
POF bundles are prepared after weaving, in order that a group of optical fibers can be connected with LEDs. Both weft yarn and warp yarn are removed at the edge of the fabric except the optical fibers (Figure 4.29).

Figure 4.29 Preparation of POF bundle

LEDs are connected to the ends of POFs as a form of light source. LEDs are chosen as the source of light due to the fact that it is lightweight and can be integrated without being intrusive to the design and usability of the final interior product. Groups of POFs are bundled together and then the ends of these POFs are coupled to LEDs by using ultraviolet bonding technique, which can maximize the light efficiency and reduce the coupling loss. NORLAND 65 optical adhesive is used as the coupling agent.



(a)



(b)

Figure 4.30 Coupling of LED and optical fibers

In Figure 4.30a, a branch of POFs is bundled together with a plastic tube at fiber ends. Then the fiber ends are attached to a LED using the optical glue. In order to solidify the optical glue, the assembly (including fiber ends, optical glue and LED) is exposed to ultraviolet radiation for several minutes. After ultraviolet exposure, fiber ends are fixed to LED. POF fabric can emit different colors when coupled with different LEDs (Figure 4.31).

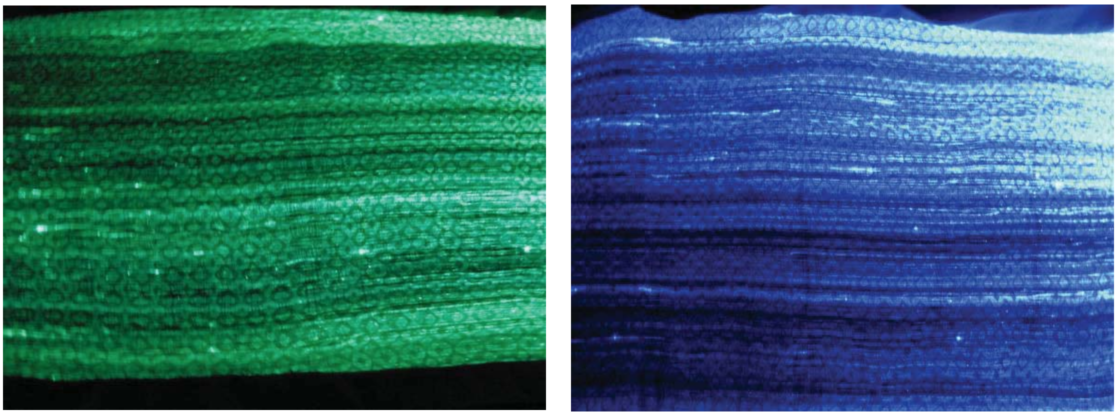


Figure 4.31 Same POF fabric emitting different colors

4.3 Results

4.3.1 Photonic textile samples

This section presents some photonic textile samples after combining dyeing/printing, weaving, laser engraving and lighting effect. Figure 4.32 shows the illustration of printing and laser-engraving patterns which are created by Photoshop® software. The design principle combines printing and laser-engraving and final lighting effect.

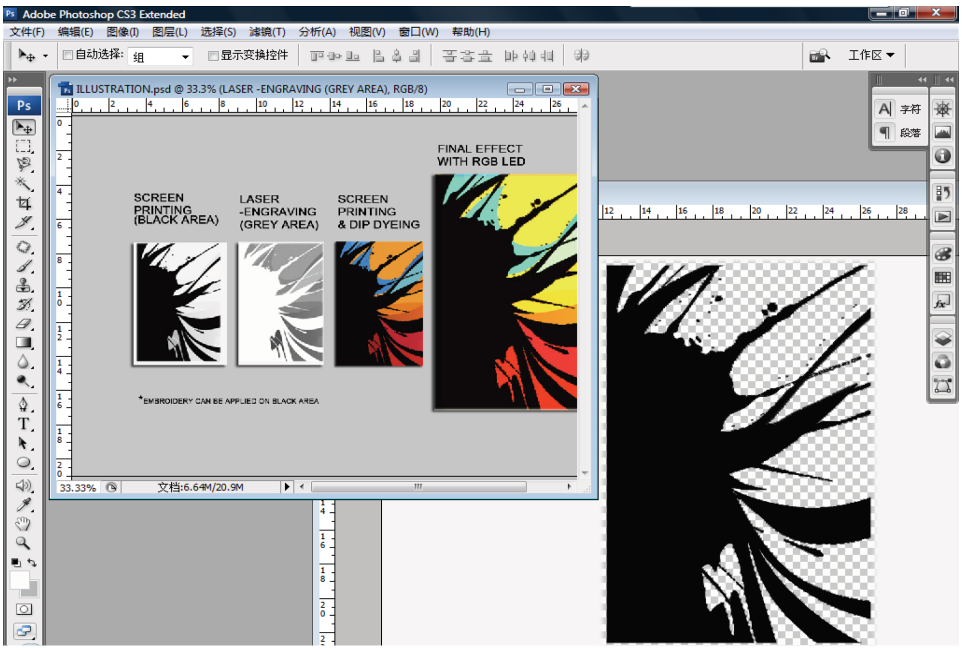


Figure 4.32 Combination of printing, laser-engraving and LEDs

Several photonic fabrics have been created for further development of photonic interior furnishing prototypes. Figure 4.33 to Figure 4.36 present the appearances of these fabrics with and without illuminating effects. All of the fabrics are treated with laser to realize the side-emission. With the integration of LEDs, photonic textile can obtain the property of decoration in both bright and dark environments. With the integration of printing, the surface design of photonic textile is enhanced. The photonic textiles provide designers with an innovative material for interior design.

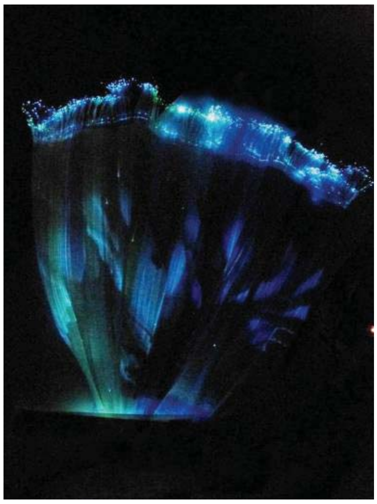
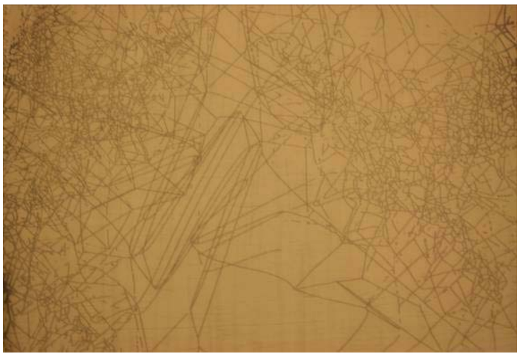


Figure 4.33 Photonic fabric 1 (left: without illumination, right: with illumination)



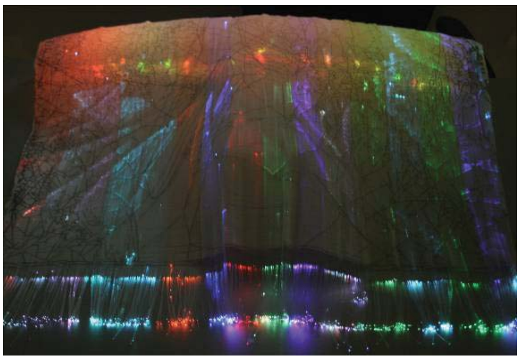


Figure 4.34 Photonic fabric 2 (left: without illumination, right: with illumination)

Figure 4.35 Photonic fabric 3 (left: without illumination, right: with illumination)

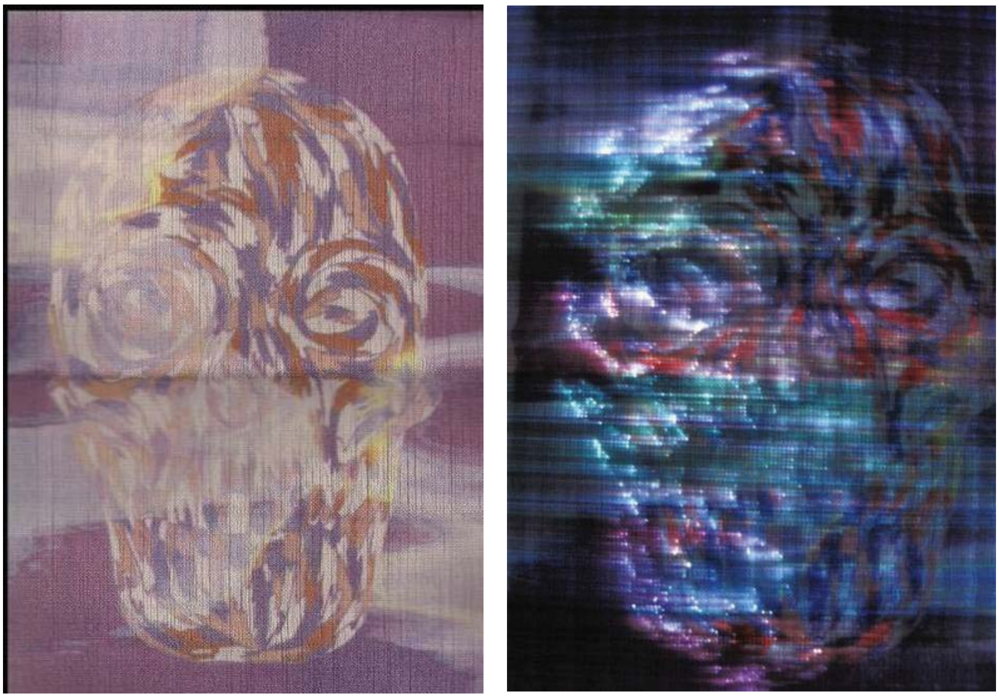


Figure 4.36 Photonic fabric 4 (left: without illumination, right: with illumination)

Figure 4.37 to Figure 4.39 show the photonic fabrics with the integration of weaving design, laser-engraving and LEDs. Photonic fabric 5 (Figure 4.37) was woven in plain weave structure with a dimension of 50 cm by 200 cm (Tan & Bai, 2011). The weft yarns at some parts of the fabric were intentionally removed during weaving to create an unique appearance. Laser-engraving was applied on the entire piece of fabric.

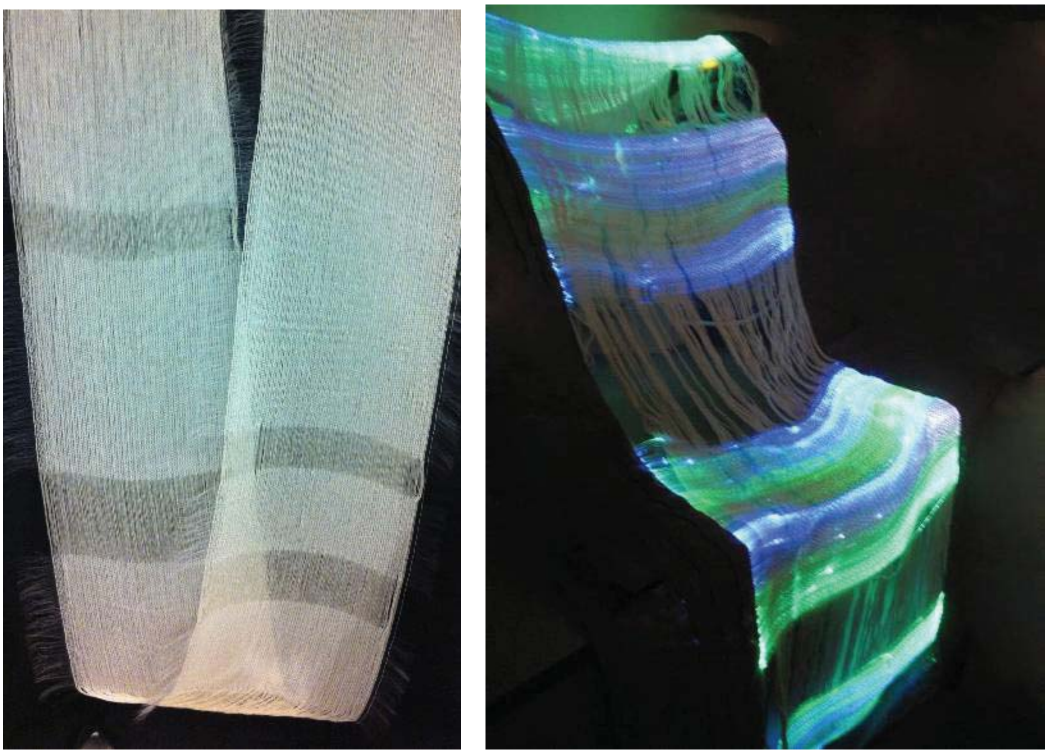


Figure 4.37 Photonic fabric 5 (left: without illumination, right: with illumination)

Photonic fabric 6 was woven in jacquard structure with a dimension of 100 cm by 200 cm (Figure 4.38). Different from the printed pattern, the circle pattern on photonic fabric was woven by jacquard loom. With the integration of red and green LEDs, the fabric shows totally different colors in both lit and non-lit environment. This fabric named “Circles 2012” was exhibited in International Shibori Design Exhibition at Fo Shan, China (Tan, Bai, & Johnston, 2012) (Figure 4.39).

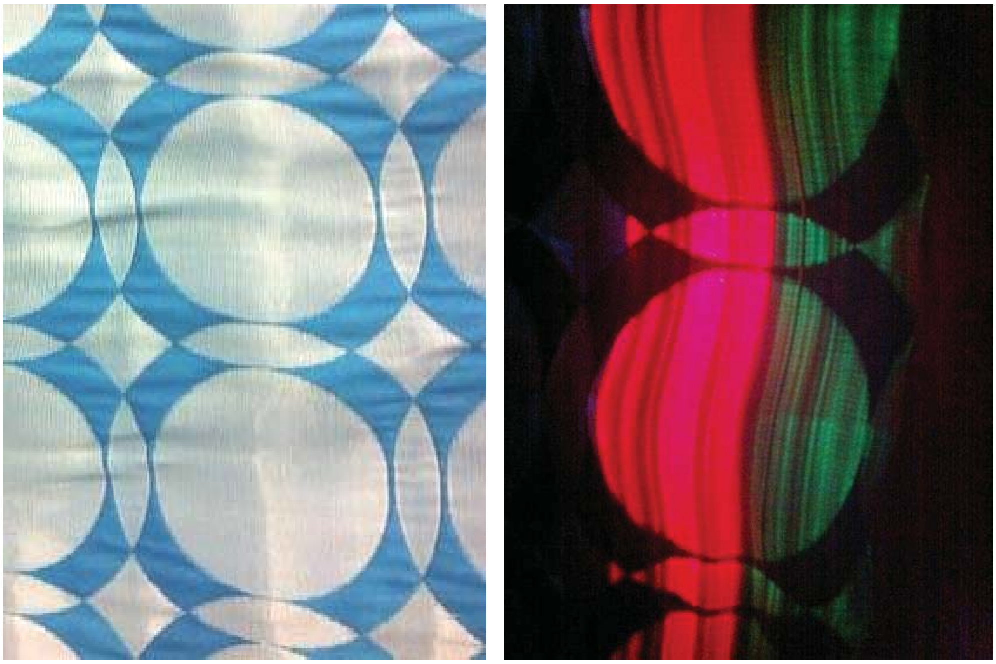


Figure 4.38 Photonic fabric 6 (left: without illumination, right: with illumination)

Figure 4.39 Photonic fabric 6 in exhibition

4.3.2 Prototypes of interior furnishings

The objective of the design is to develop photonic fabrics, and adopt these fabrics to construct a collection of interior furnishings, including cushion, wall hanging. With the illuminative effect, the furnishings can create two different interior environments during day and night (Figure 4.40). Several prototypes have been developed.

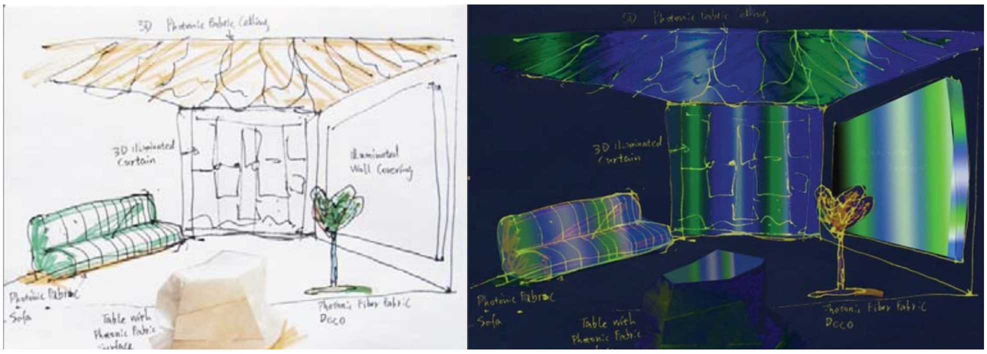


Figure 4.40 Design Sketch- Illuminating interior furnishings in different environment

4.3.2.1 *Prototype 1 – Chinois Photonics*

The creative inspiration for Chinois Photonics is derived from Neolithic Chinese earthenware and the showcased technology will feature photonic textiles (Figure 4.41). Both the design inspiration and technology are considered as parallel factors at the beginning of the process. Subsequent research on the physical shape, form, texture and surface pattern of the ancient pottery is interpreted with a contemporary perspective and introduced into the interactive textiles as the surface print, form and base material.

Figure 4.41 Design theme, mood and color-board for artwork “Chinois Photonics”

“Chinois Photonics” (Figure 4.42 and Figure 4.43) is a collection of furnishings using POF fabrics. The collection has been exhibited at the Future Photonics exhibition (Bai, et al., 2011a). This collection includes life-sized cushions and wall hangings which are made from innovative illuminating textiles.

Figure 4.42 “Chinois Photonics” cushions in the daytime

Figure 4.43 “Chinois Photonics” with illuminating effects

In contrast to the unchangeable nature of traditional interior textiles, the innovative photonic textiles can present two different colors during the day and night. During the day, they show the original color of the textiles with printing (Figure 4.42). The earth tone color palette represents the ancient pottery in a harmonious and cohesive manner, showing a return-to-the-original-nature style. During the night, strong block colors are illuminated from the textiles, providing a stark contrast to the other version (Figure 4.43). Meanwhile, POFs, LEDs and other textile techniques are integrated into the design to enrich the color and pattern of the interior textiles.

4.3.2.2 ***Prototype 2 – Sculpting Light***

The creation "Sculpting Light" is inspired by the bodiless nature of light (Figure 4.44). The artwork is made of luminous fabric with screen printing (Figure 4.45), and this work has been presented at Fiber Society 2011 Spring Conference (Bai, et al., 2011b). Literally, light is fickle and elusive. In the collection "Sculpting Light", light is emitted from the curved fabric surface as well as the fabric sides. Light appears to be "sculpted" into a tangible body, and is given texture and shape. The printing on the photonic fabric presents special visual effects in both bright and dark environments.

Figure 4.44 Design theme, mood and illustration for artwork “Sculpting Light”

Figure 4.45 Sculpting Light: Printed optical fiber fabric art work

4.3.2.3 *Prototype 3 – The glowing object 2012*

Prototype 3 is inspired by the traditional Chinese antique with the aim of merging the antique furniture with the photonic textiles, not only to generate a new look for the contemporary furniture design, but also to create new functions for the existing object (Figure 4.46). The final artwork is named “The Glowing Object”, which is a wooden chair with a POF fabric and a laser-cut acrylic seat as shown in Figure 4.47. This artwork has been exhibited in Interstoff Asia Essentials, HKCEC (Tan, Bai, Johnston, et al., 2012).

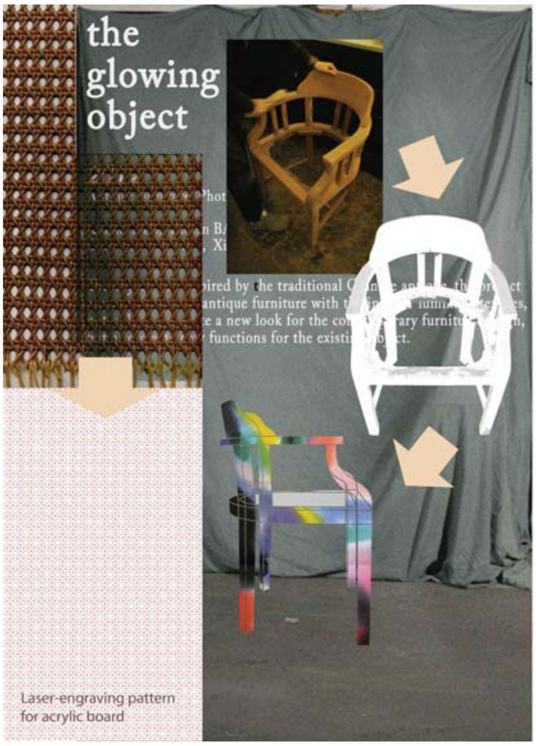


Figure 4.46 Inspiration and development process of “the glowing object”

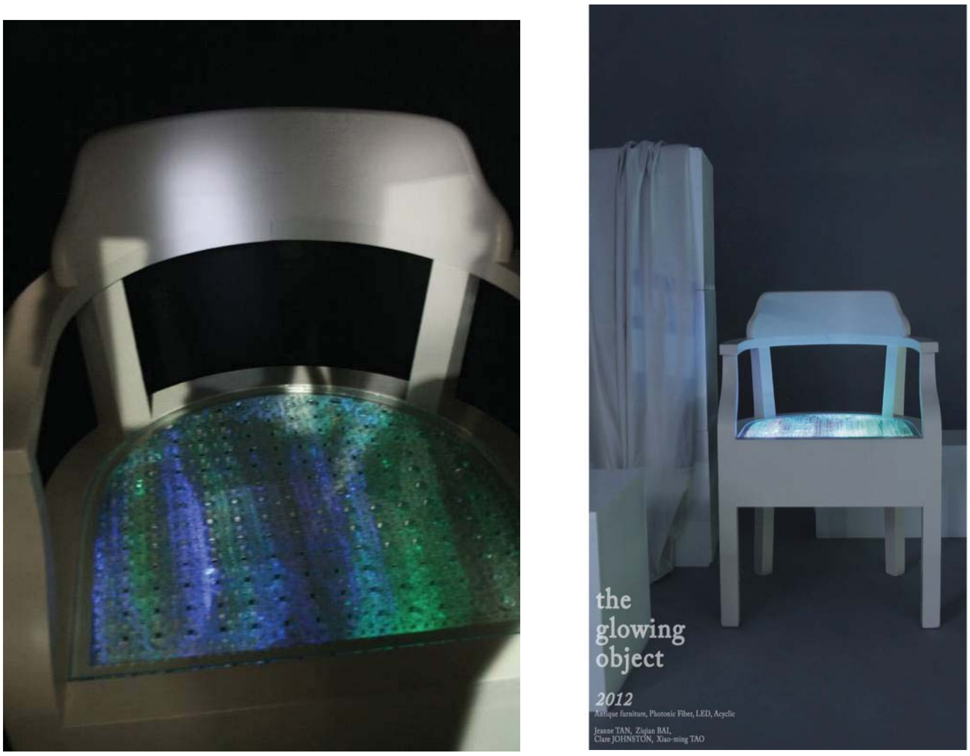


Figure 4.47 The glowing object

4.3.2.4 *Prototype 4 – The White Blossom*

Prototype 4 is inspired by Chinese traditional carving of the window (Figure 4.48). The wood carving of Chinese traditional window is delicate and sophisticated. A photonic decoration named "The White Blossom" is created, which is a 190 cm high by 80 cm wide photonic wall hanging (Figure 4.50). In the design and development process, both design and technology parts are considered. The 3D flowers in this art work are made from pure white synthetic leather carved by laser-engraving machine (Figure 4.49). The optical fibers are woven together with cotton yarn to create a piece of fabric with positive hand feeling and good draping ability. More than 40 LEDs with green, blue and white color are embedded.

Figure 4.48 Inspirations of "The white blossom"

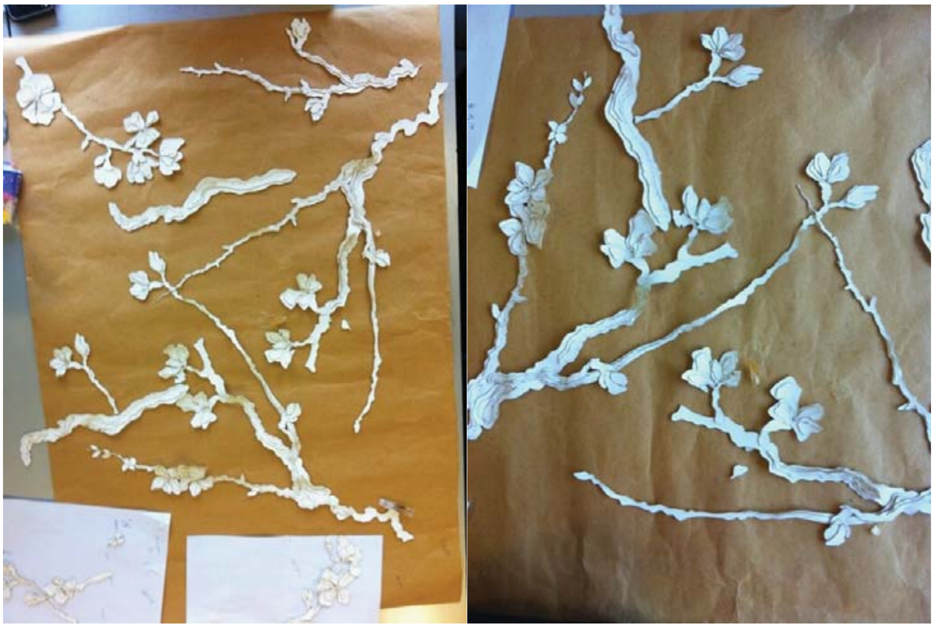


Figure 4.49 Laser-cut pieces of flowers

Figure 4.50 The white blossom in non-lit and lit conditions

4.3.3 Survey

In order to assess the usability of the photonic soft furnishing, a questionnaire was conducted to analyze the user's experience with the prototypes. Fifty subjects took part in this questionnaire. They are 20 to 25 years old college students who are from fashion design discipline. Among them, 17 subjects are male, and the other 33 subjects are female. "Chinois Photonics" (Bai, et al., 2011a), a collection of soft photonic furnishing was evaluated (Figure 4.51).

Figure 4.51 Photonic cushion

"Chinois Photonics" was inspired by ancient Chinese pottery. The design attempts to interpret the colors and patterns of ancient painted pottery from a contemporary perspective. A series of earth-tone cotton fabrics and yarns were selected. Printing and embroidery on the surface of photonic cushion can enhance the aesthetic attractiveness as well as the hand feel. The rechargeable batteries were hidden inside the foam of cushion, so that the cushion is movable. Users can hug, sit against and play with the photonic cushion just like the cushion in daily life. In the dark, strong block colors are illuminated from the textiles, providing a stark contrast to the daytime version.

Before the questionnaire, the basic knowledge of photonic textiles and the design method of final product were introduced to each subject (Figure 4.52). The investigator observed the subject's behavior while they were using the product. After that, a questionnaire was carried out on each subject.

Figure 4.52 User experience investigation

The questionnaire consists two parts. In the first part, the subjects were asked to rate the performance of the prototype according to a seven-point scale. As color, appearance and hand feel 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 original color of fabric, color of photonic fabric, appearance of printing, appearance of embroidery, shape, hand feel and illumination (Table 4.9).

Table 4.9 Assessment system of the performance

	Unsatisfactory						Very Satisfactory
Original color of fabric	1	2	3	4	5	6	7
Color of POF fabric	1	2	3	4	5	6	7
Printing appearance	1	2	3	4	5	6	7
Shape/silhouette	1	2	3	4	5	6	7
Hand feel	1	2	3	4	5	6	7
Illumination (lighting)	1	2	3	4	5	6	7

Each performance is 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 second part of the questionnaire includes a series of questions, such as " Do you agree the photonic cushion can enhance interior environment?", "Is it convenient to use photonic cushion?", etc. These questions are designed to evaluate the performance of photonic cushion from both technological and aesthetical aspects.

In the first part of the questionnaire, a quantitative analysis was performed, and the average grades of all items are listed in Table 4.10.

Table 4.10 Overall grade of performance

Performance	**Overall rating**
Original color of fabric	4.28
Color of photonic fabric	4.3
Printing appearance	4.26
Shape/silhouette	4.32
Hand feel	4.06
Illumination (lighting)	4.6

Table 4.10 shows that the overall grades of all performances are above four, which indicates that the overall performance of photonic cushion is satisfactory. It is also observed that the grade of hand feel is slightly lower than the others. Due to the rigid nature of polymeric optical fibers, it is understandable that the hand feel of the photonic fabric is a little worse when optical fibers are integrated. Experiments with different materials will be carried out in future to improve the hand feel of POF fabrics.

When is asked “Do you agree the photonic cushion can enhance interior environment”, 54% users agree and 24% users strongly agree that photonic cushion can enhance interior environment (Figure 4.53). This result indicates that photonic soft furnishing can definitely enhance the interior ambience with its unique function and appearance.

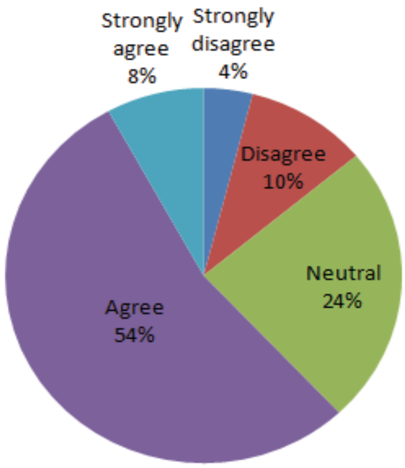


Figure 4.53 Result of question- “Do you agree the photonic cushion can enhance interior environment?”

It is very important that a hi-tech product is easy to operate by end-users who have little technical background. In the second part of the questionnaire, the ease of use of the prototype is assessed. The subject is asked to rate on "Is it convenient to use the photonic cushions?", and 12% users chose “convenient”, 54% users chose “acceptable”, while around 20% use recognize that it is not convenient because the batteries need to be recharged or replaced (Figure 4.54). The power supply seems to be still a big challenge to the development of photonic furnishing.

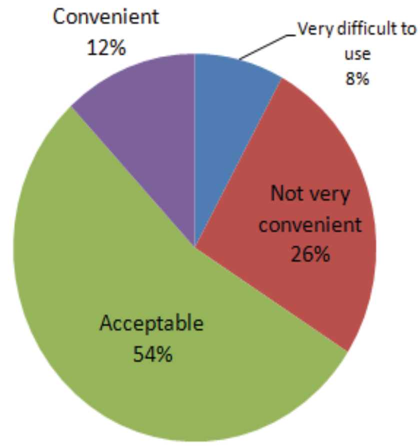


Figure 4.54 Result of question- “Is it convenient to use photonic cushion?”

The photonic cushion has the property of illumination, while tradition interior textiles do not have. Figure 4.55 shows that totally 78% users appreciate this novel technology of illuminating, and consider that this new property of photonic interior textile is more attractive than the general properties of traditional textiles, such as color, material and hand feel. This result indicates that the photonic property by integration of POF can improve the attractiveness and function of interior textiles.

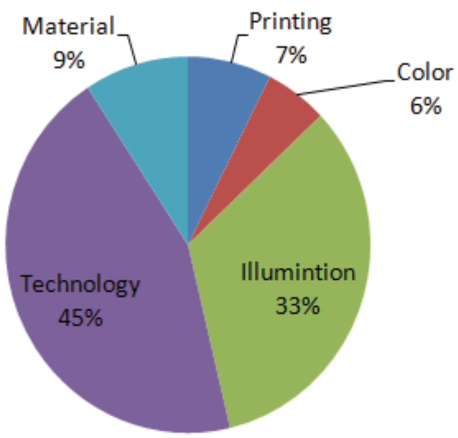


Figure 4.55 Result of question- “Which one is the most attractive to you for Photonic cushion?”

The survey results indicate that the overall performance of the prototypes is satisfactory, and photonic furnishings are considered to be able to enhance the interior environment. The result of questionnaire also reveals that with the integration of POF, the functionality of traditional interior textiles can be improved. The subjects suggest that power source needs to be improved. Different light sources will be examined in future experiments in order to improve the illumination effect of POF fabrics.

4.4 New design process model

Using the author’s own design practice as a case study, a model of the design process for photonic textiles and interactive interiors was developed. A new design model based on action research for the design of photonic soft furnishing was proposed (Figure 4.56).

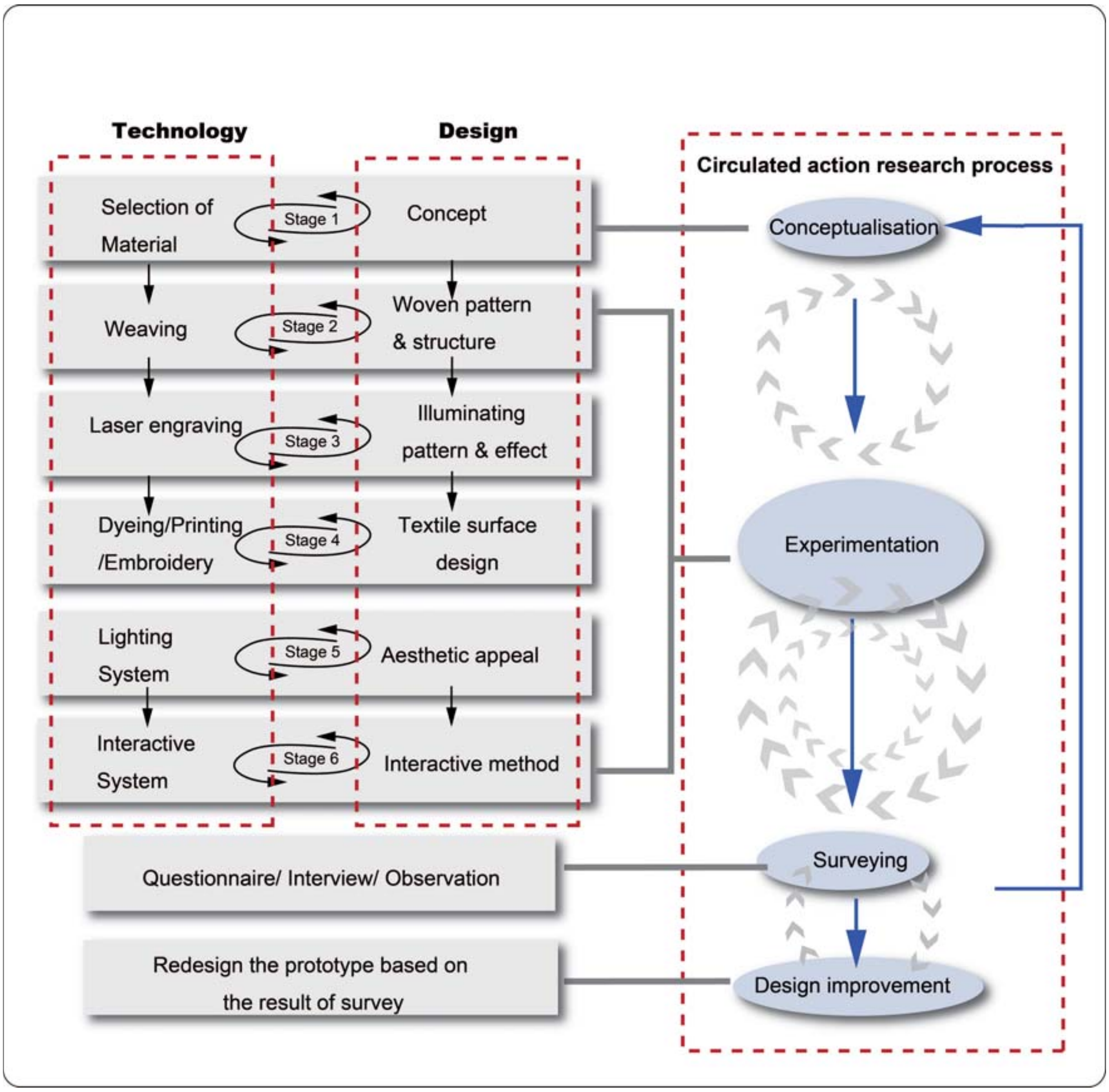


Figure 4.56 Proposed design process model

Fashion design methods and textile technology are used in combination with modern technologies throughout the entire process of development. In the new proposed design framework, every stage is an interactive process between technology and design. The development of one part simultaneously affects its counterpart, and therefore the development at every stage is a continuous process. For instance, in stage one, the selection of material should express the design concept, and the design concept should also consider the characteristics of the selected materials, such as the features of optical fibers. In stage two, traditional weaving should follow the weaving pattern and structural design, while the design of the woven pattern and structure should consider the technical issues of weaving optical fibers into a piece of fabric. It is important to utilize the weaving technique to create an aesthetic design yet taking account of the fragile and brittle nature of polymeric optical fibers. Design work needs to be continuously revised in accordance with experiments on the prototypes. In stage three, the side-illumination of optical fiber fabric is achieved by laser-engraving technology. Laser engraving fabricates physical damage on the surface of the polymeric optical fiber to create minute cracks which allow light to be emitted. The technical and design aspects should work very closely to successively improve the illuminating effects. In stage four, the design of printing pattern should take the printing technology into account. The fifth and sixth 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. Development of interactive system and design of interactive method should be based on the study of user's needs; therefore, the survey will provide the feedback of end users for further study of user's experiences.

Feedback from the experiments and survey have also been reflected in the development of the new design process. Experimental results suggest that the fabrication of POF fabrics should be in an order of weaving, laser engraving, embellishment, integration of electronics. Dyeing and printing should be carried out after laser engraving otherwise the laser treatment cannot be precisely controlled, and laser treatment on dyestuffs may possibly produce toxic gases. Since the fabric can only be dyed and printed without all the electronic components, all electronics should be integrated into the fabric at the last stage.

The design process is also a reflective circulation involving continuous improvement of developed prototypes (right part of Figure 4.56). Concept, experiments and survey are three integral processes, and development in each process is reflected to other processes. In this fashion, the whole design process is a continuous improvement process until the final prototypes meet all predetermined requirements.

4.5 Summary

This chapter introduces design process of POF prototpes. Experiment and implimentations were conducted in both technology and design aspects. Priliminary prototypes of photonic soft furnishings were developed. A survey was conducted to evaluate the prototypes. A design modle was built up for the development of photonic product. The main achivement of this stage can be concluted in six points:

1) POFs can be successfully woven with traditional yarns into different structures. By inserting POFs as weft yarns and varying the weaving pattern, different constructions can be achieved and eventually different illuminating effects can be realized.
2) From the laser engraving experiments, we find that laser engraving technology can be readily applied to photonic textile and enable light to emit from specific areas in a predetermined pattern. The illuminating pattern can be well controlled and customized according to the designer to suit different needs. The SEM observations indicate that in order to establish an appropriate removal of cladding of POFs to secure an optimal illumination from the fabric surface, the suitable parameters for laser engraving should be set as 20 dpi in resolution, 130 μs in pixel time, and the laser-engraving should be repeated for 7-9 times.
3) Different embellishments can be applied onto POF fabric to enhance the tactile quality and the aesthetic, such as screen printing, digital printing and embroidery.

4) The method used in this chapter to couple light source (LEDs) with POFs is in a way that a bundle of POFs are grouped together, and then all ends of this bundle of POFs are attached to a LED by optical glue. In order to solidify and fix the attachment, the optical glue must be exposed to ultraviolet for a period of time. This process is time-consuming. A more efficient coupling method needs to be explored, and this will be discussed in next chapter.

5) The survey implies that the overall performance of the developed photonic furnishing prototypes is acceptable. The illumination from fabric surface adds new feature to traditional home textile, and therefore enhances the interior environments. However, the interaction between the user and the photonic furnishing has not been fulfilled. This requires a more complicated design of an intelligent system to control all electronics and a comprehensive interface between textiles and electronic components, and all these will be further investigated in next chapter.

6) A new design process model for development of photonic textile product is developed, which bases on author's own design practice. Both design and technology parts are considered in the whole reflective design process. This symmetrical design model format the whole design process and provides guides to further research and design practice of interactive photonic furnishing.

Chapter 5. **Developed results**

5.1 Introduction

As discussed in last chapter, there are still several drawbacks for the photonic prototypes, for instance, coupling of POFs to LEDs is time-consuming, the brightness of the illumination is unsatisfactory, and the interaction between user and photonic prototypes has not been fulfilled. In this chapter, these issues are addressed. A novel technique to couple POFs to LEDs light source is proposed. Different LED light sources are adopted, and corresponding control system is developed. Both user-prototype interaction and user-user interaction through photonic prototypes are realized. Several creations, from 2D to 3D forms, including interior designs as well as fashion items, are created. New expressional and functional properties of textiles are explored. Both objective and subjective evaluations are performed to assess the developed prototypes.

5.2 Improvement of design

On the basis of the findings in the last chapter, the following issues have been identified which are addressed in this chapter:

- The interactive function of photonic prototypes is lacking.
- The luminance of POF fabric is not sufficient.
- The usability of photonic prototypes needs to be improved. An efficient coupling method to connect POF ends to LEDs light source needs to be explored.

Design and development of interactive photonic textiles require knowledge from multiple areas. During this multi-disciplinary design practice, the designer should understand the knowledge of technical parts. How to communicate with technical experts and engineers is a big challenge to designers, since the language the designer uses is very different from the language the engineer uses. Discussions should be carried out during the whole design process between different parties (Figure 5.1). The prototypes are continuously revised until the final prototypes meet the preset requirements from both functional and aesthetic points of view.

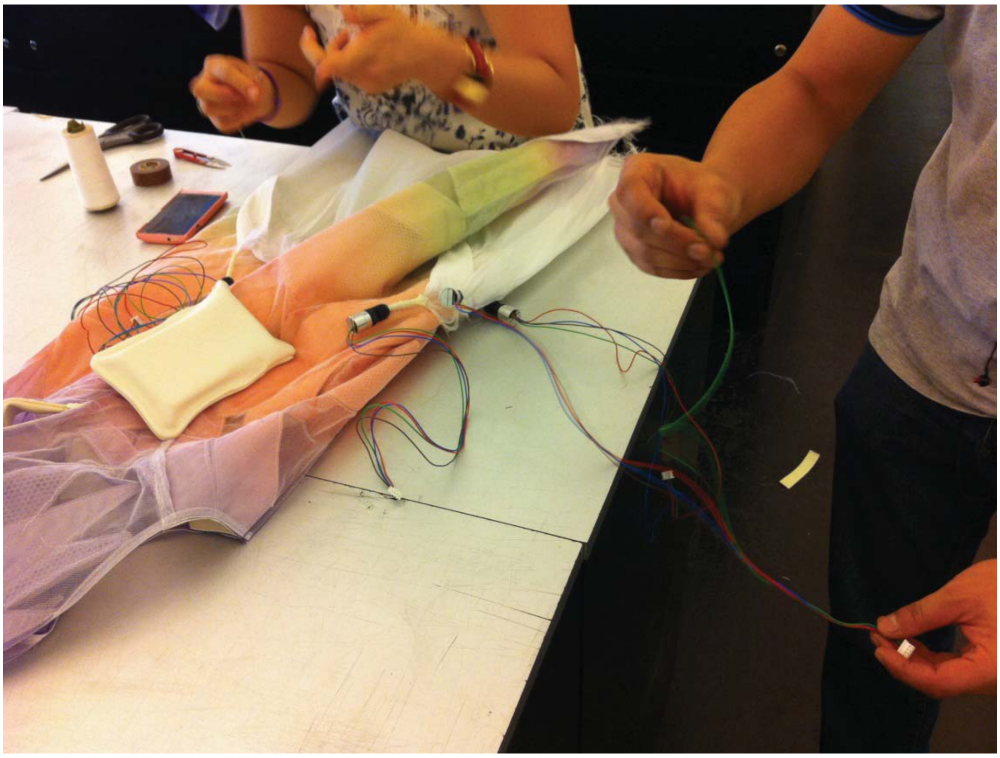


Figure 5.1 Discussion between designer and engineer during the design process

5.2.1 Interactive function development

In order to further develop the interactive function of POF textile, sensors are embedded into textiles and an interactive POF textile system is built up. The function of sensors is to transfer physical phenomena into processable electrical signals, while the function of actuators is to transfer electrical signal into physical phenomena (Nørstebø, 2003). In this research, electrical sensors, which can transfer touch and motion into electrical signals, are embedded into photonic textile to realize the interactive function of final prototype. The photonic fabric acts as an actuator that can transfer the electrical signals into physical phenomena - changing of light. The changing of light affects the atmosphere of the interior environment where the user is located. Therefore, people can interact with other users and their living environment by creating meaning and emotion together through photonic products. The design of the interactive system is illustrated in Figure 5.2.

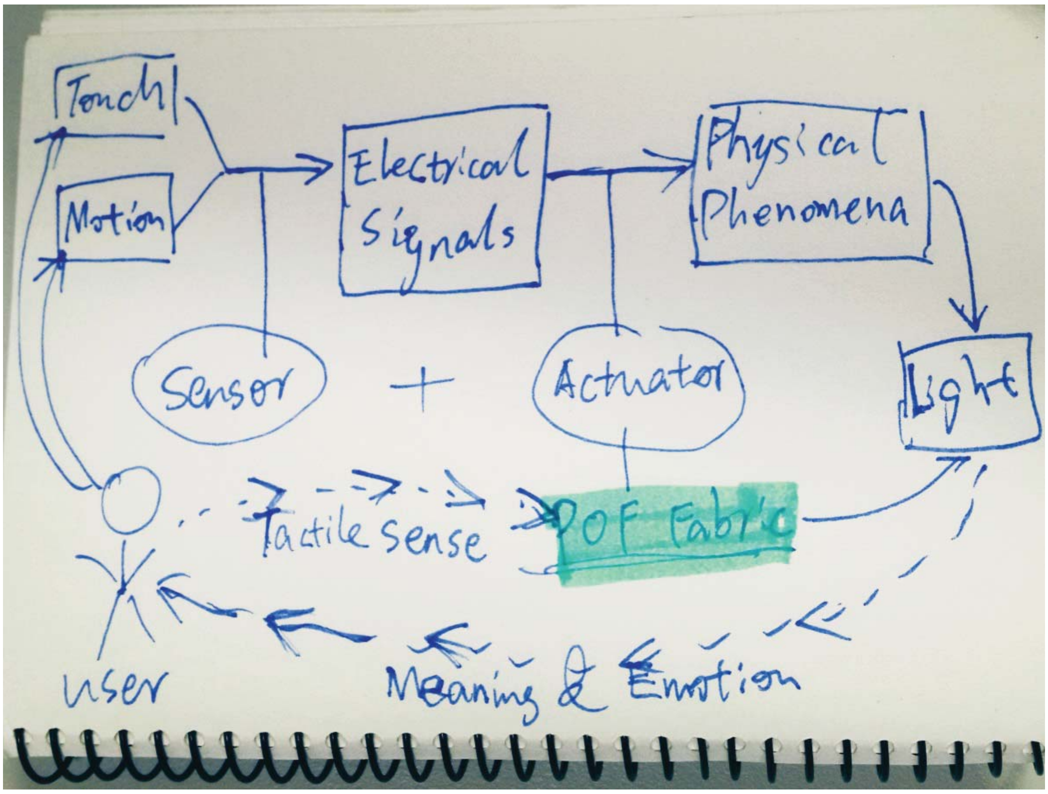


Figure 5.2 Design of interactive system – individual experience

When the interactive function is designed, users' experience needs to be considered. People now can easily share the experience with others via social networks like Facebook. Shared experiences allow a range of interpretations by others, from the expected and agreeable to the unusual or even deviant. For example, one may reciprocate, reject or ignore an experience. This kind of experience is classified as "co-experience" for interaction design (Forlizzi & Battarbee, 2004). In this research, both individual experience and co-experience are examined. A short-range communication network is built up between a group of POF textile prototypes to achieve the interaction between multiple users. Bluetooth and ZigBee devices are adopted to facilitate the communication between POF textile prototypes. When two or more users interact with photonic prototypes, the sensors in corresponding prototypes can detect the stimuli from the users and respond. Individual experience involves interaction between individual user and prototypes. Different from individual experience, co-experience involves not only user-prototype individual experience but also co-experience among users via photonic prototypes, and the illumination of photonic textiles appear group lighting effect. Each user can get unique experience from the multiple changes of lightings which are created by other users and themselves. As illustrated in Figure 5.3 and Figure 5.4, the interactions among user-prototype (individual experience) and user-user (co-experience) can be realized. Both individual experience and co-experience are examined and explained in Section 5.3.

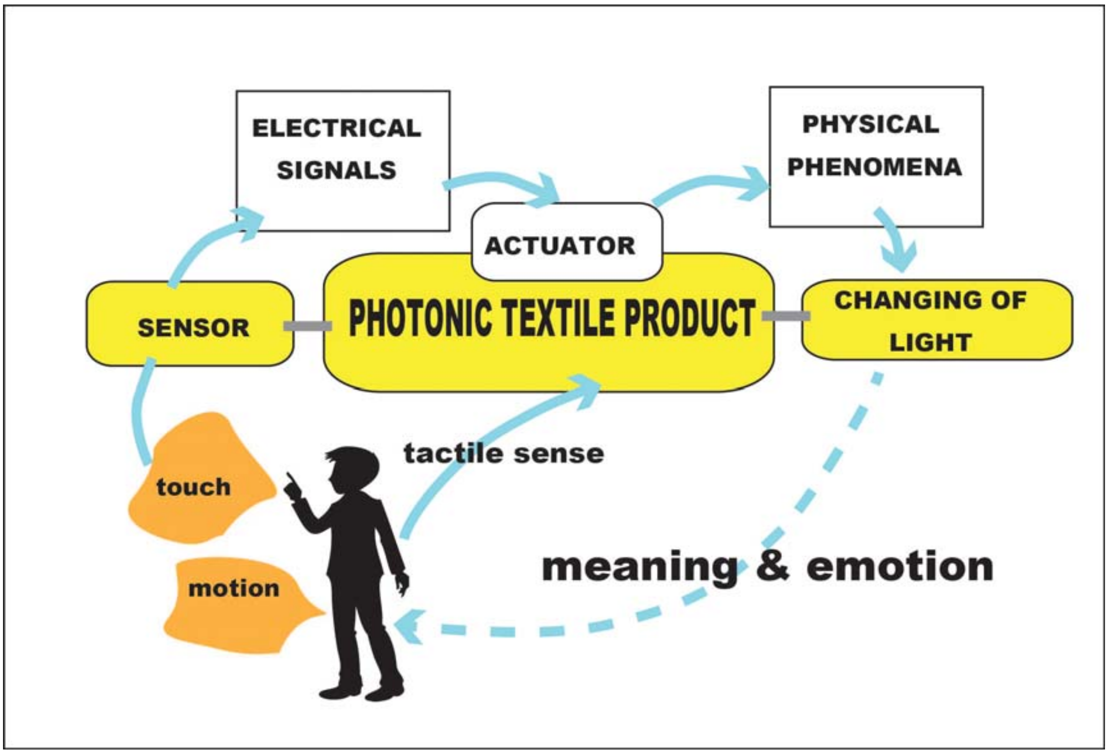


Figure 5.3 Individual experience

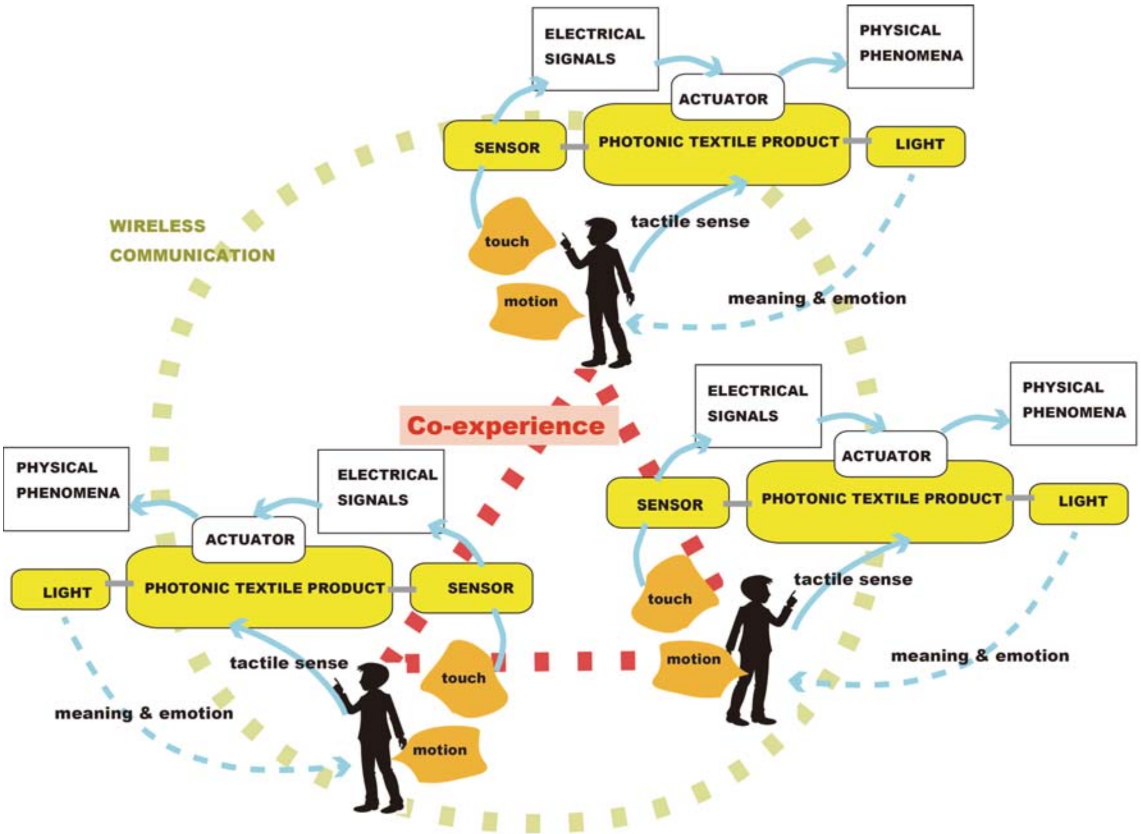


Figure 5.4 Co-experience

5.2.2 Improvement of textile design

Cotton and polyester yarns with POFs of 0.25 mm in diameter are successfully woven together to create photonic textiles. In order to suit various purposes of photonic products, different yarns are woven with POFs to create POF textile with sophisticated appearance and texture. In Figure 5.5 and Figure 5.6, the metallic fluorescent yarns are inserted as weft yarns with POFs to create a unique look. Due to the different tensions of yarns and POFs, the fabric can show a pleated appearance without ironing and sewing. The advantage of this pleated fabric is that the POFs will not be damaged during sewing and ironing process. This fabric is suitable for making garment with pleated looks.

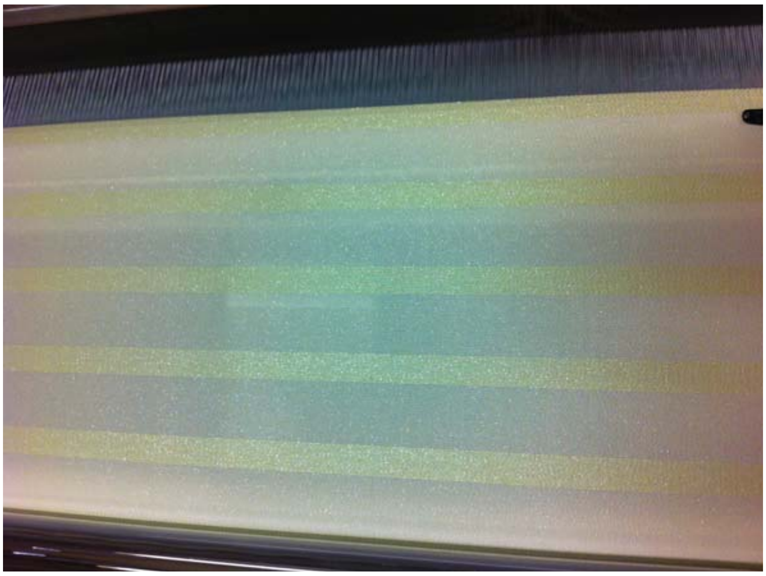


Figure 5.5 Metallic yarn integrated POF fabric on the weaving loom

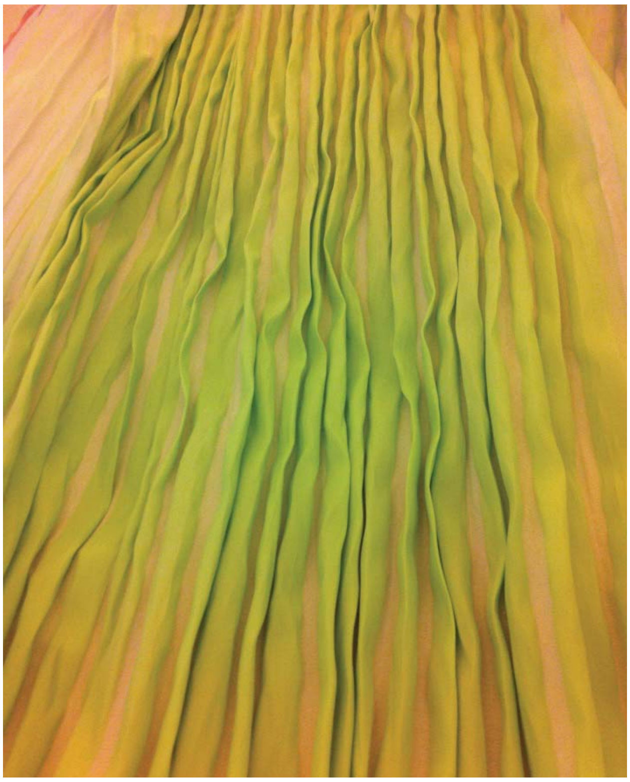


Figure 5.6 Pleated POF fabric with metallic fluorescent yarns

Meters of POF fabrics for large-scale installation are manufactured by large weaving loom

(Figure 5.7). The POFs are woven with white polyester yarns in pain weave structure. The density of POF in weft direction is 45 picks/ inch. With this high density of POFs, the overall illumination is strong.

Figure 5.7 POF fabric for large-scale purpose

5.2.3 New coupling method to connect POFs to LEDs

One of the main challenges in development of photonic textiles is the integration of electronics. At the beginning phase of this project, the connection of LEDs and the POF bundles is a time-consuming and labor-cost process, which was introduced in section 4.2.5. For instance, a POF bundle is formed in every 5cm fabric length, which is defined by the diameter of the LED. Every LED is coupled with a bundle of POFs by using optical glue. Each LED is then connected to a mother board through two wires by hand welding. For a one meter long POF fabric, there are totally 20 LEDs with 40 wires that need to be connected to the POFs and the mother board. Meanwhile, all of the electronics are placed in a customized box, which is heavy and bulky (Figure 5.8).

Figure 5.8 Old coupling process to connect LEDs to fabric

In order to improve the connecting method and enhance the luminance of POF fabric, a new type of LED, the Moonstone™ Tri-Color Power LED, is selected (Figure 5.9). Three LEDs with different colors, namely red, green and blue are combined together into integrated one. With the control of Printed Circuit Board (PCB), the LED can emit numerous colors by mixing the three primary colors. These energy-efficient LED can stand for higher driving current and emit less heat comparing to conventional LEDs.

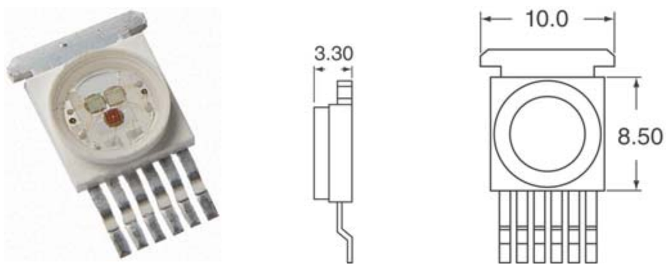


Figure 5.9 Moonstone® Tri-Color Power LED Light Source (the unit of dimension is mm)

A customized coupler based on cable gland is developed as shown in Figure 5.10.

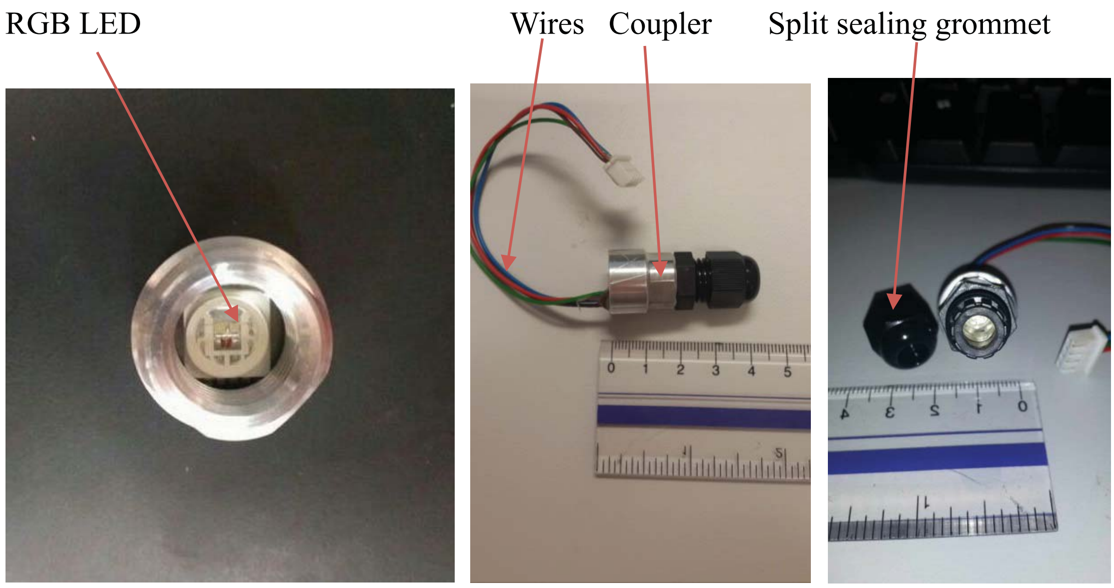


Figure 5.10 New coupler for connection of LED and POFs

A Tri-color LED is fixed inside the coupler, and is connected with PCB via wires. A bundle of POFs is inserted into the coupler, and then is fastened by the sealing grommet. The advantages of adoption of super bright LEDs and the new coupler are:

- Numbers of LEDs and wires used are reduced, and total weight of the whole prototype is greatly reduced.
- The super bright LED is much brighter than small LED. The overall brightness of POF fabric is improved.
- The process of connection of POF bundle with LED is more efficient. It only takes minutes to connect POF bundles to LEDs.
- The whole electronic part can be easily detached from the POF fabric, which greatly enhances the possibility of cleaning the surface of textile without electronic part.

Figure 5.11 shows the difference between the previous and the new connecting method of electronics and POFs. In the previous prototype (left), there are amount of LEDs and wires which are connected with POF fabric. It is challenging for the cutting and sewing of the fabric. After using the new generation of LEDs and couplers, both the number of LEDs and the weight of electronic part are greatly reduced.

Figure 5.11 Improvement of connecting method (left: old model, right: new model)

5.3 Creations

The final collection of creations investigates the interactions between user-product and user-user. Light, darkness, light density, hue and duration are new design variables, which create new meanings and emotions to users. Final creations, such as photonic interior soft furnishing, art installation to fashion design are introduced. Technologies of communication, LEDs, sensors and remote controls are utilized, which enable users to interactively customize their garments and environment via the changes of emitted colors, patterns and emission frequency. Interactive photonic textiles can also be used as an effective communication platform between users, viewers and their surroundings.

5.3.1 Interactive POF soft furnishing – ConneXion

Since the interactive function has not been developed in "Chinois Photonics" (introduced in Section 4.2.2.1), a new generation of photonic soft furnishing named "ConneXion" based on “Chinois Photonics” are developed with touch sensing function. Individual user or multi-users can change the color of cushions with touching the surface of a group of POF textiles under different interactive modes. This collection of soft furnishing includes three cushions in different sizes. The design concept is illustrated in Figure 5.12.

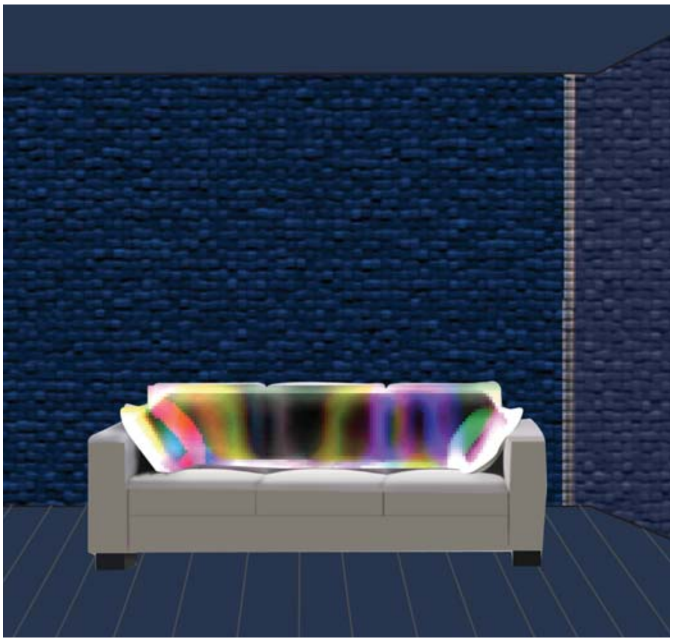


Figure 5.12 Illustration of ConneXion with lighting effect

The POF fabric with circle patterns is cut and sewed into square shape for the surface of cushion (Figure 5.13). The POF bundles are finished at one side of the square. There are two layers on POF fabric at the edge of the cushion, namely lighting layer and sewing layer. The design of sewing layer is to protect the POFs of lighting layer from sewing.

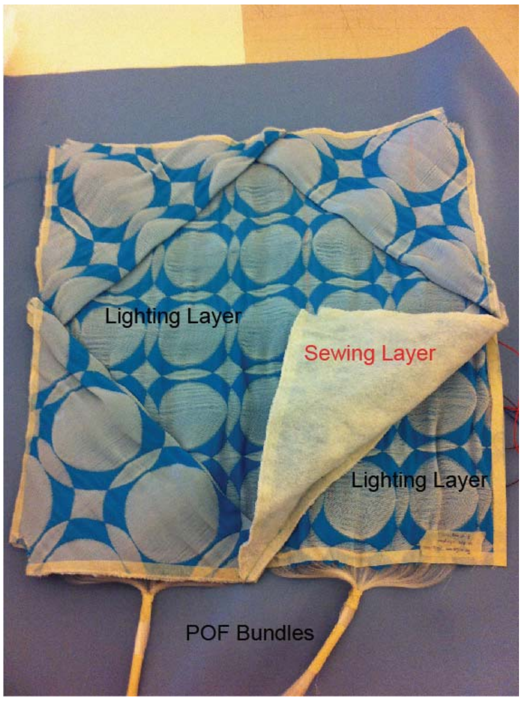


Figure 5.13 POF fabric system

In order to achieve the interaction between user and prototype, as well as interaction between different users through the prototypes, an intelligent POF fabric system is developed as shown in Figure 5.14.

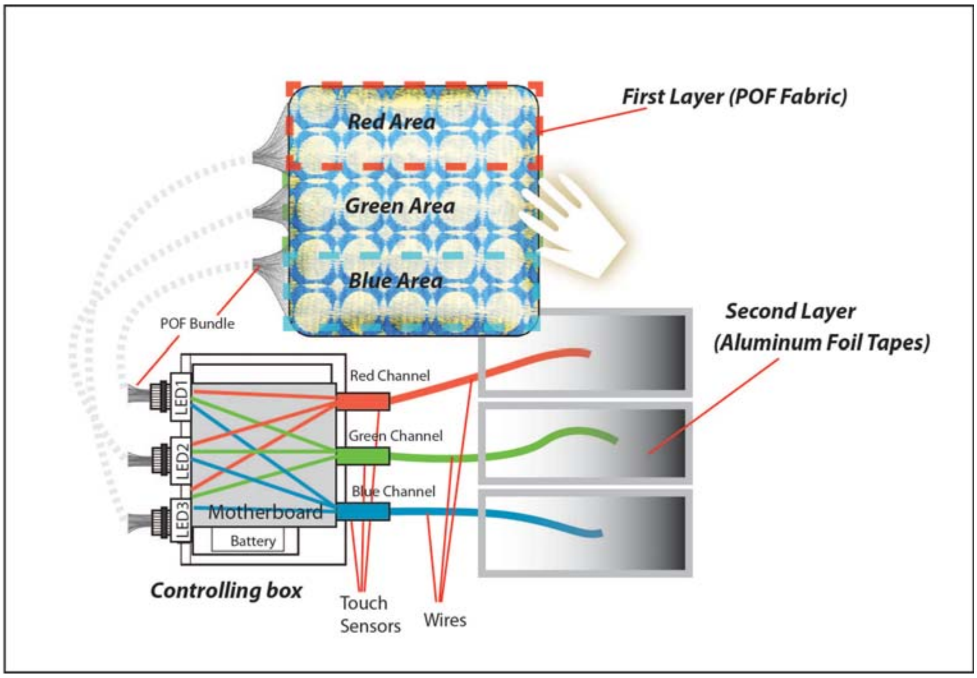


Figure 5.14 Intelligent POF fabric system

Bundles of POFs are connected to LEDs, which are packaged in a 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 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 (PCB) packaged in a controlling box. The colors of the LEDs are controlled by sensing the 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 5.15). When both red and blue areas are touched, the cushion presents a mixed color between red and blue (Figure 5.16).

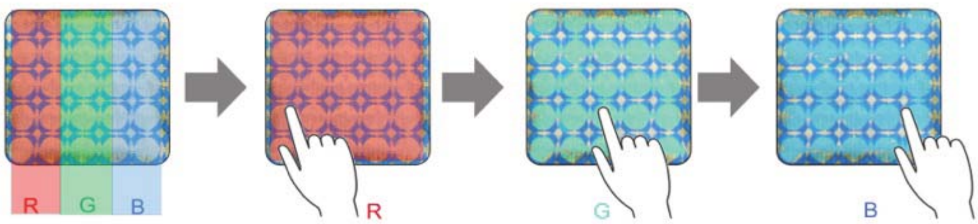


Figure 5.15 Color of cushion when different area (Red, Green or Blue) is touched

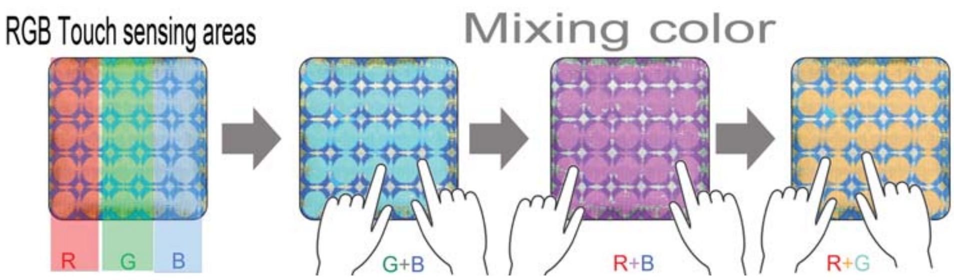


Figure 5.16 Color of cushion when more than one area are touched

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-cast 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. synchronize mode and flash mode. Under the synchronize mode, when any cushion is touched and a color is trigged, all other two cushions present the same color (Figure 5.17). Under the flash mode, when one cushion is touched, the other two cushions flash in different colors (Figure 5.18).

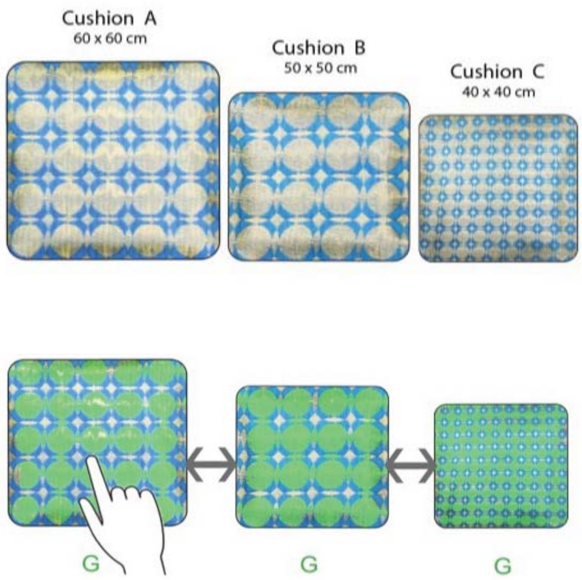


Figure 5.17 Synchronize mode

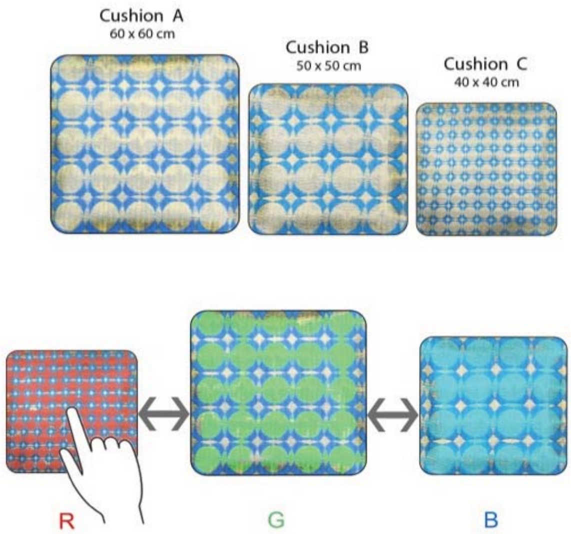


Figure 5.18 Flash mode

In order to control all the electronics to realize the designed interaction for individual cushion, a controlling system for cushions 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 5.19.

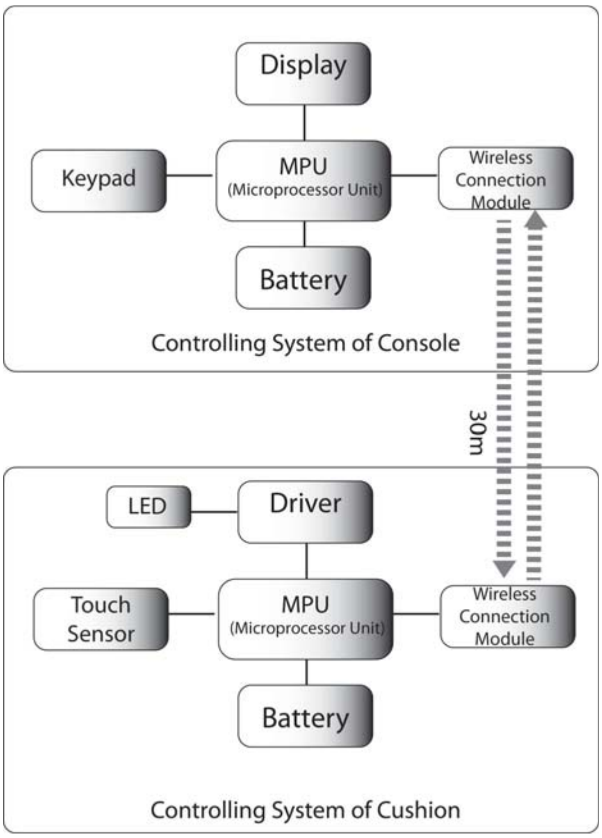


Figure 5.19 Controlling system design

A collection of interactive photonic cushions with different sizes in 60/60cm, 50/50cm and 40/40cm is created. Cushions of different sizes are designed in order to examine the different illuminating effects. 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 the laser-engraving treatment (Figure 5.21).

Figure 5.20 Photonic cushions prototypes

Figure 5.21 presents the inside structure of interactive photonic cushions. Optical fibers are bundled and connected to LEDs by the coupler (cable gland). All the electronic components including LEDs, microprocessor unit (MPU), battery, driver, communication module are packaged in a detachable plastic box. GB 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.

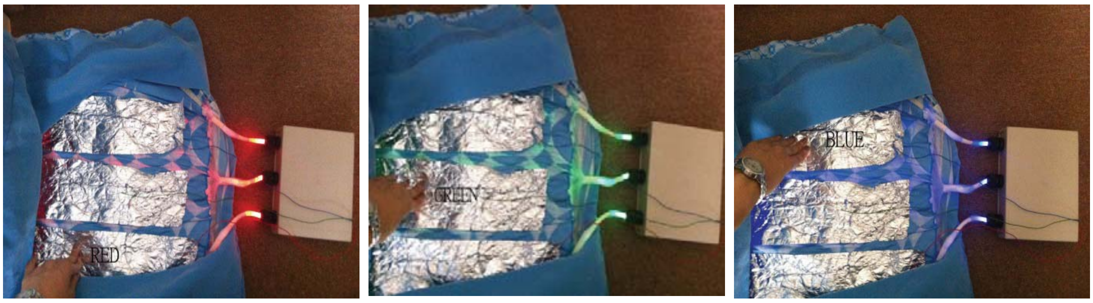


Figure 5.21 Inside structure of the cushion. When different areas are touched, different colors are triggered

By touching different areas on cushions, 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 5.22).

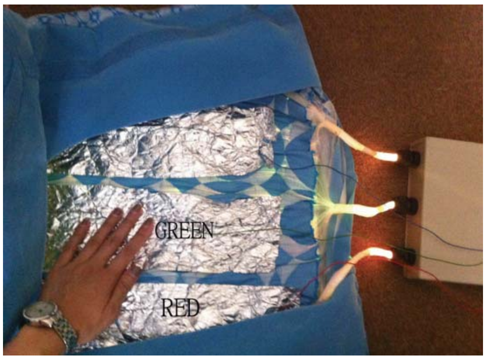


Figure 5.22 When green and red areas are touched at the same time, yellow color is illuminated

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 5.23). The console is easy to control.

Figure 5.23 Console

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 (Figure 5.23). Under the individual mode, users can change the color of each cushion by touching the surface of the POF fabric. Under the interactive function, the short-distance communicative function is turned on. Two interactive modes are developed, i.e. synchronize mode and flash mode. Under the synchronize mode, when one cushion is touched, the other two cushions show the same color at the same time (Figure 5.24 and Figure 5.25). Under the flash mode, when one cushion is touched, the other two cushion flash in different colors (Figure 5.26).

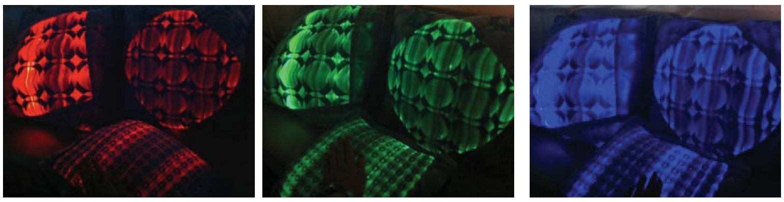


Figure 5.24 Synchronize mode - when only one area is touched

Figure 5.25 Synchronize mode - color is mixed when more than one area are touched

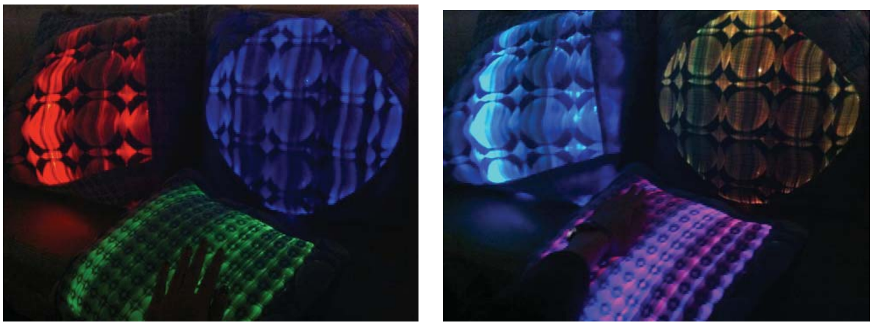


Figure 5.26 Flash mode

ConneXion 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. Users can also have co-experiences with other users via using ConneXion. The interior soft furnishings are no longer unresponsive to people, but can react to them, adapt to their behaviours, 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.

5.3.2 Interactive POF installation - Ephemeral

This artwork explores how POF textiles can be used as an adaptive media to transfer the ambience of interior spaces to suit different users and purposes. The original design of Ephemeral is inspired by the traditional Chinese painting and calligraphy (Figure 5.27).

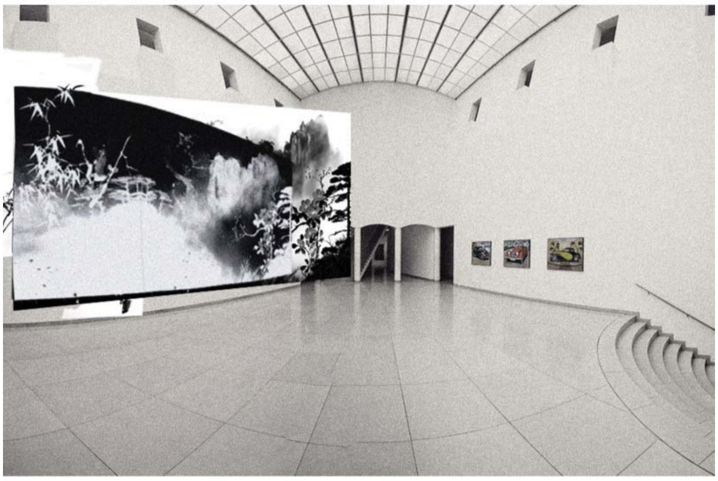


Figure 5.27 Illustration of POF fabric installation

An illuminating installation based on POF textile with interactive function is designed. The upper part of the illumination graphic is Chinese calligraphy (Figure 5.28), while the lower part graphic is Chinese motifs (Figure 5.29).

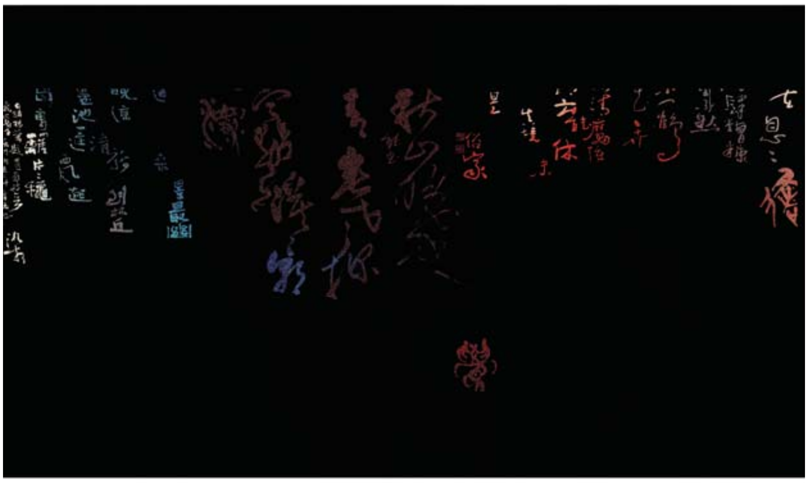


Figure 5.28 Upper part of illuminating pattern design - Chinese calligraphy

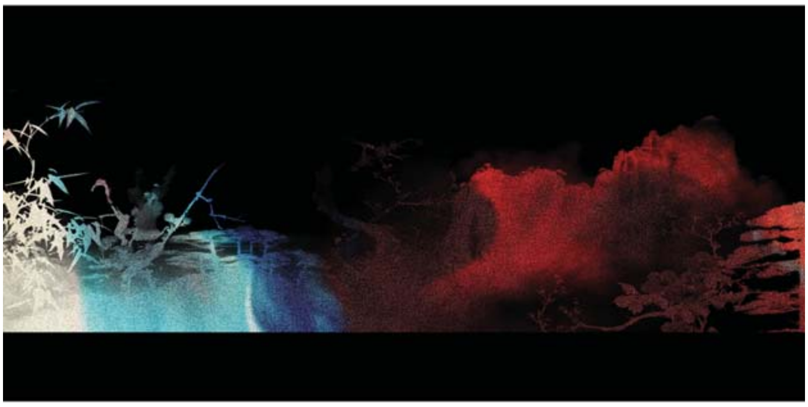


Figure 5.29 Lower part of illuminating pattern design - Chinese motifs

After several rounds of discussions between designers and engineers, the final design is revised into three frames to further develop the interactive functions. The POF textiles are mounted onto metal frames with POFs coupled onto the cable glands attached to the frames. The schematic diagram is illustrated in Figure 5.30. As this creation is intended to be installed within an interior environment, Ephemeral is not connected to low power sources (batteries), but is designed with a conventional power plug connected to a typical Alternating Current (AC) power supply. LEDs with RGB colors are coupled with optical fiber bundles as light source, which are controlled by a MPU (Micro Processor Union) on a PCB. Radar and Ultrasonic sensors are placed on the frames, in order to examine how sensors can be embedded into the interior textiles to detect and respond to the stimuli from the user, and therefore promote interaction between textiles and user. The function of radar is to detect if there is a subject (human body) entering the sensing range. Once people come into the area that radar can sense, the radar will send a signal to the controlling board, and then the corresponding LEDs will be lightened. The function of ultrasonic sensor is similar to that of radar. Different from radar, ultrasonic sensors use ultrasonic to detect the accurate distance between the subject and the frame.

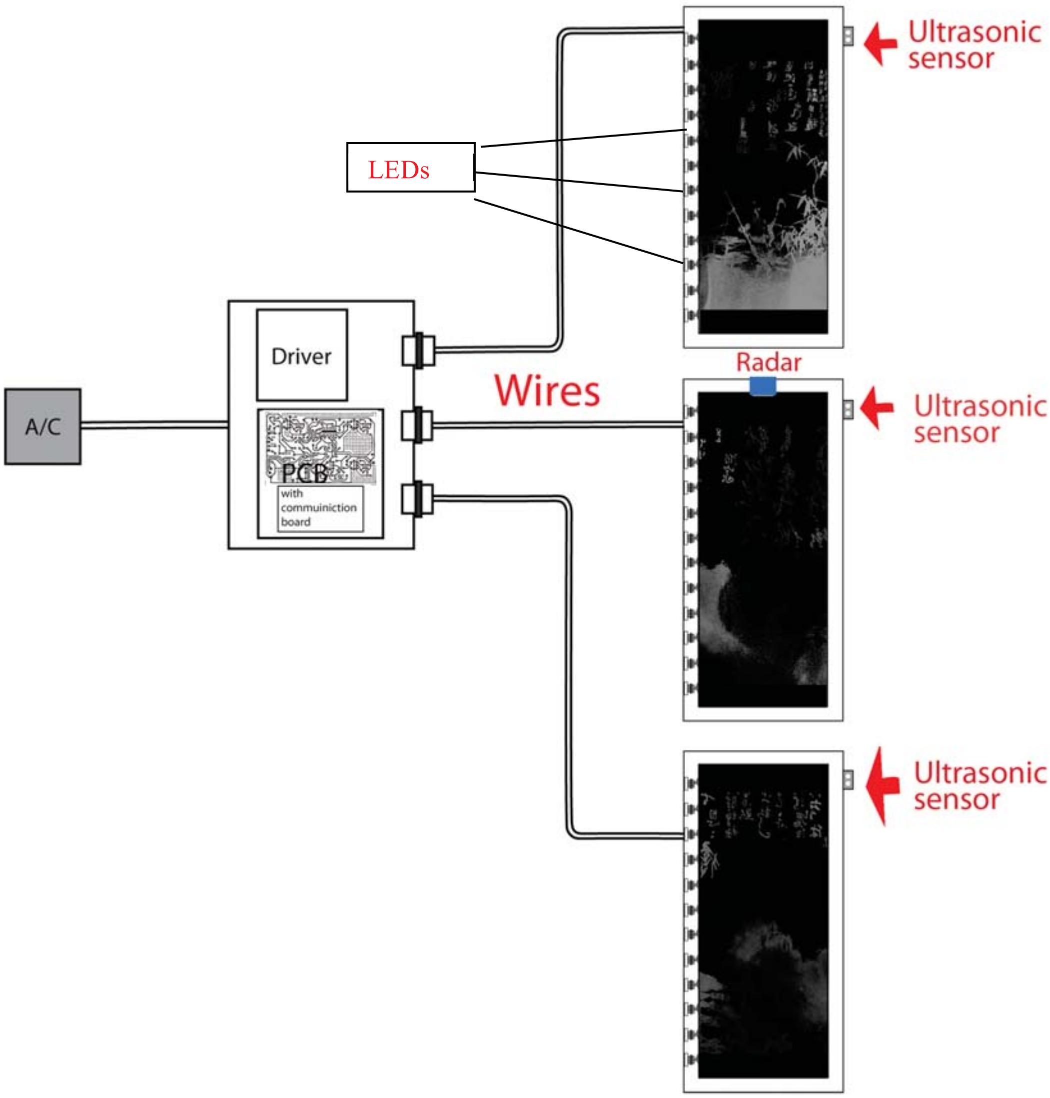


Figure 5.30 Schematic diagram of Ephemeral

Three interactive modes are designed to examine the interactive function of Ephemeral, and they are:

Mode 1: Up and Down Mode

Mode 2: Individual Mode

Mode 3: Dynamic Mode

Under Mode 1 (Up and Down Mode, Figure 5.31), when the ultrasonic sensor on the frame detects that there is movement of object within 2 meters' distance to the frame, the lower part of that frame will be lightened, and the illuminating Chinese motifs will appear; when the person comes closer to a range within 1 meter's distance to the frame, the upper part of that frame will be lightened, and the illuminating Chinese calligraphy will appear.

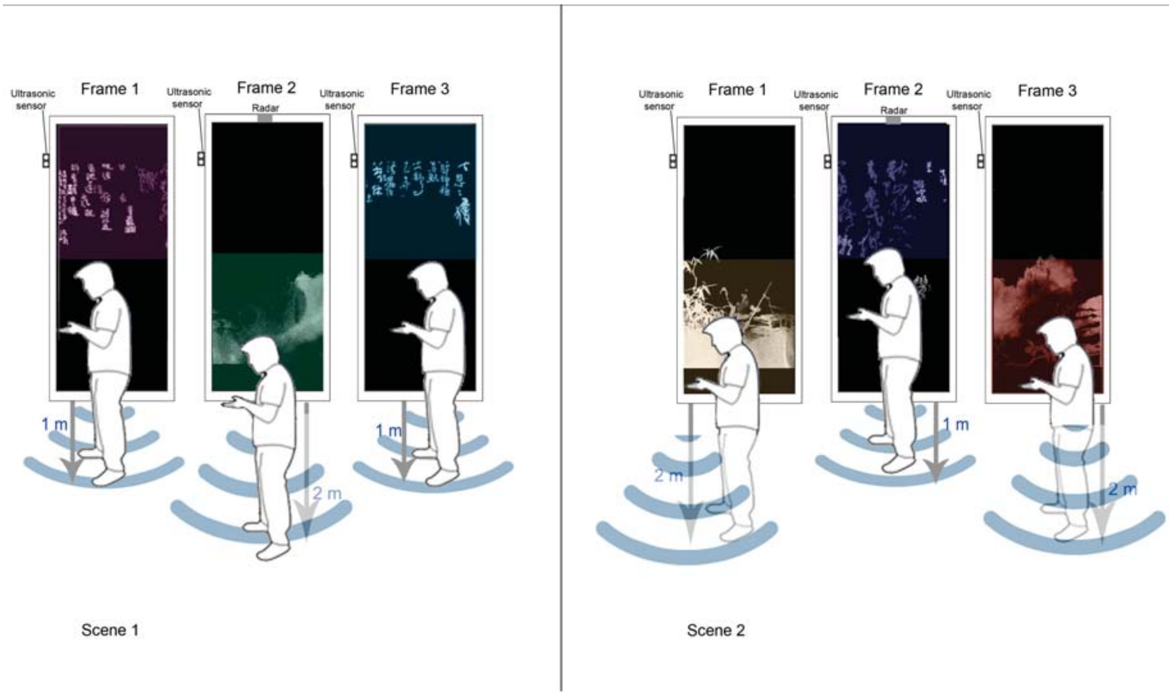


Figure 5.31 Illustration of Mode 1 - Up and Down Mode

Under Mode 2 (Individual Mode), when a person enters the sensing range of 2 meters' distance to the frame detected by the ultrasonic sensor, the corresponding frame will illuminate (both upper and lower parts) as illustrated in Figure 5.32. Under the dynamic mode, once the radar detects the movement of object within 6 meters, all the three frames will show the illuminating patterns with dynamic colors.

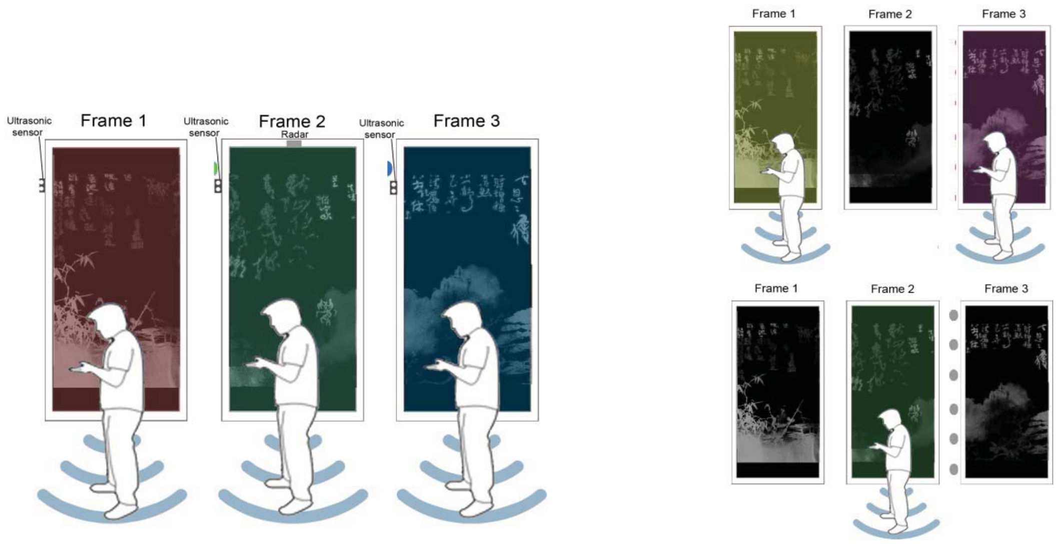


Figure 5.32 Illustration of Mode 2 – Individual Mode

The laser-engraved POF fabric is mounted on a metal frame whose measurement is 150cm in height by 60cm in width. 10 LED couplers are fixed on the back and along one vertical side of the frame, where they are connected with the optical fiber bundles. 5 LEDs are designed into a group, and therefore the upper part and lower part present different colors of illumination as shown in Figure 5.33.

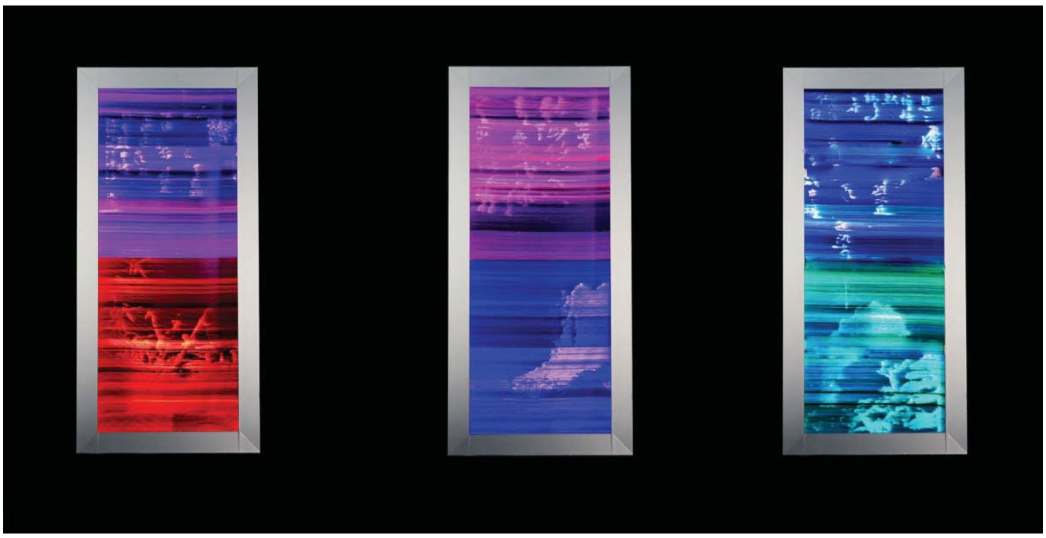


Figure 5.33 Illumination effect of Ephemeral

As shown in Figure 5.34, under Mode 1 – Up and Down Mode, when one person enters the sensing range of the ultrasonic sensor, up or lower part of the corresponding frame is turned on with dynamic colors. When nobody is within the sensing range, the light is turned off. Under the Individual Mode, when one particular frame senses the movement of people within 2 meters, the whole frame will be lightened with dynamic colors (Figure 5.35). The lights are turned off when there is no person nearby. Under the Dynamic Mode, all three frames are turned on and show different illuminations once the people come close into 6 meters' range (Figure 5.36).

Figure 5.34 Mode 1 - Up and Down Mode

Figure 5.35 Mode 2- Individual Mode

Figure 5.36 Mode 3 - Dynamic Mode

Generally speaking, Modes 1 and 2 realize the interactive function of user-user and user-product. Users can experience co-experiences during the interactive activities with Ephemeral. Mode 3 shows the overall lighting effect, and creates a unique atmosphere which is different from the traditional interior lighting. The controlling of on/off of light, and the duration of lights can be determined by the movement of user. People can engage with their interior environment and gain a new experience via Ephemeral.

5.3.3 Interactive POF fashion - Neo-Neon

A garment forms the intimate environment around human body. Although the main focus of this project is to investigate POF-based interactive textiles for interior furnishing, another objective of my research is to explore the feasibility to apply interactive photonic textiles to fashion items. The POF fabric is designed into interactive fashion to create a prototype named Neo-Neon which utilizes fashion as a medium to explore the movement of time. It is inspired by the subtle relationship between light and time (Figure 5.37). The illustration is presented in Figure 5.38.

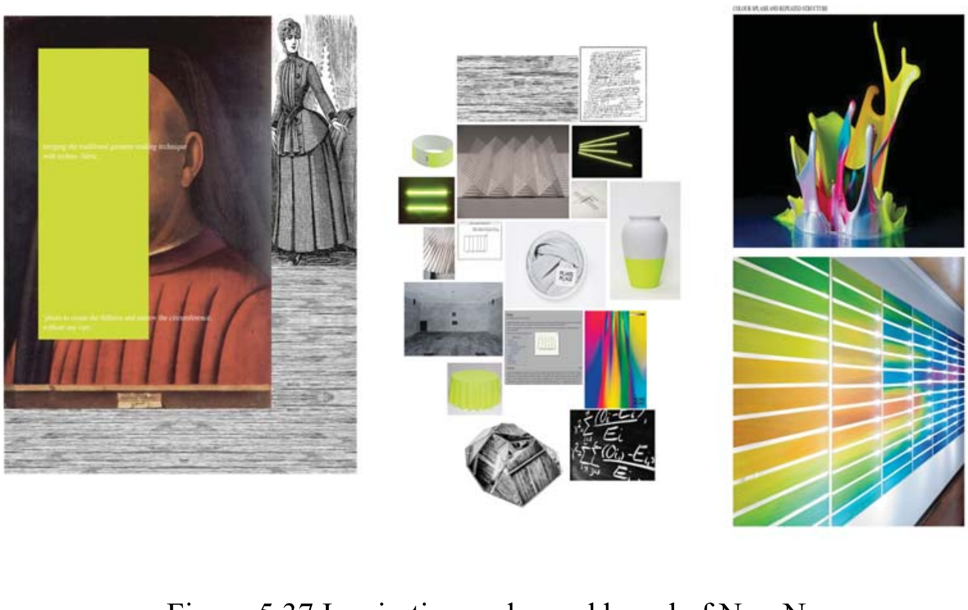


Figure 5.37 Inspiration and mood board of Neo-Neon

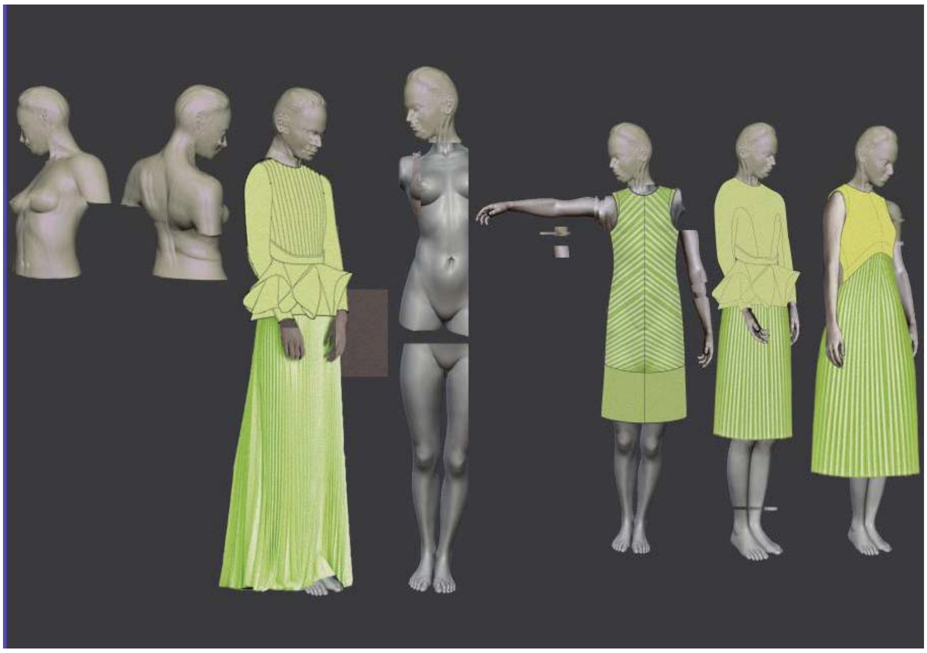


Figure 5.38 Fashion illustration of Neo-Neon collection

This prototype combines neon green neoprene fabric with photonic textiles to create an outfit. The skirt is woven using the Jacquard loom to create three dimensional pleats which emits irregular rays of light thus exploring the movement theme of this creative work. The skirt can emit up to six different colors to adapt to the wearer’s requirements. The color emission of the skirt can also be predetermined to allow gradual color changes thus allowing the wearer to evoke different emotive expressions over time.

Comparing to interior furnishings, clothing necessitates a higher requirement due to the concern in safety, comfort and drape. The placement of LEDs, motherboard and the batteries should be considered according to the ergonomics of body. At the beginning stage of fashion design and during the pattern making processes, how to cut the POF fabric and how to place the electronics are considered. In the process of developing, experiments are conducted to examine the feasibility of the original design. Figure 5.39 shows the discussion and corporation between the designer and the engineer. Samples of garments are developed, and then continuously revised as based on an action research approach until the final prototype meets the users' requirements in both functional and aesthetic considerations.

Figure 5.39 Discussion between designer and engineer during sample making of photonic garment

Two pieces of garments are designed, namely a long dress and a front panel of top. The LEDs are connected with POF bundles at the waist of the garment. A weave-shape decoration is designed to avoid exposure of LEDs at waist line. The structures of garments are illustrated in Figure 5.40.

Figure 5.40 Sketches and illustration of Neo-Neon

The entire POF fabric is engraved by laser to achieve an overall illuminating effect. At the upper part of the dress, a horizontal line is intentionally treated with higher power of laser to create a brighter line, which signs for the fractured pigment of time (Figure 5.41).

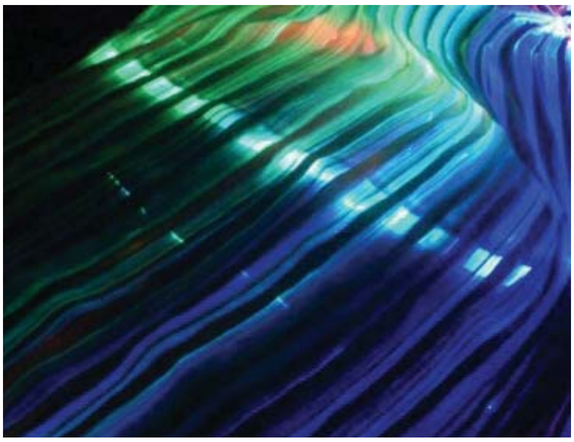


Figure 5.41 Lighting design of Neo-Neon

There are two patterns of color changing. One is continuous color-looping (Figure 5.41). The other is that one single color fades in, holds for a while, and then fade out. After that another color fades in gradually, holds for a while, and then fade out (Figure 5.42).

Figure 5.42 Color-changing method- fade in and fade out

LEDs are connected to POFs at waist of the garment, since uncomfortable feeling of wearer can be minimized during movement. A piece of weaving-shape decoration on waist is specially designed to avoid the exposure of LEDs. Both A/C and D/C power sources are adopted for static exhibition and fashion show. A commercial power bank can be used as a power source of LEDs and PCB (Figure 5.43). People can easily use their own power bank, which are usually for mobile phones, for the photonic dress.

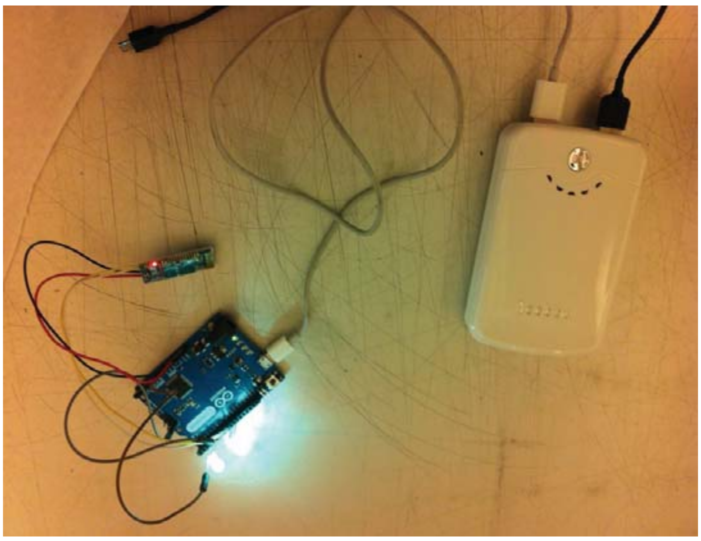


Figure 5.43 Power bank as power source of PCB and LEDs

Neo-neon (Figure 5.44) has been exhibited in “Neophotonic” Exhibition, and is selected as permanent collection by China Silk Museum.

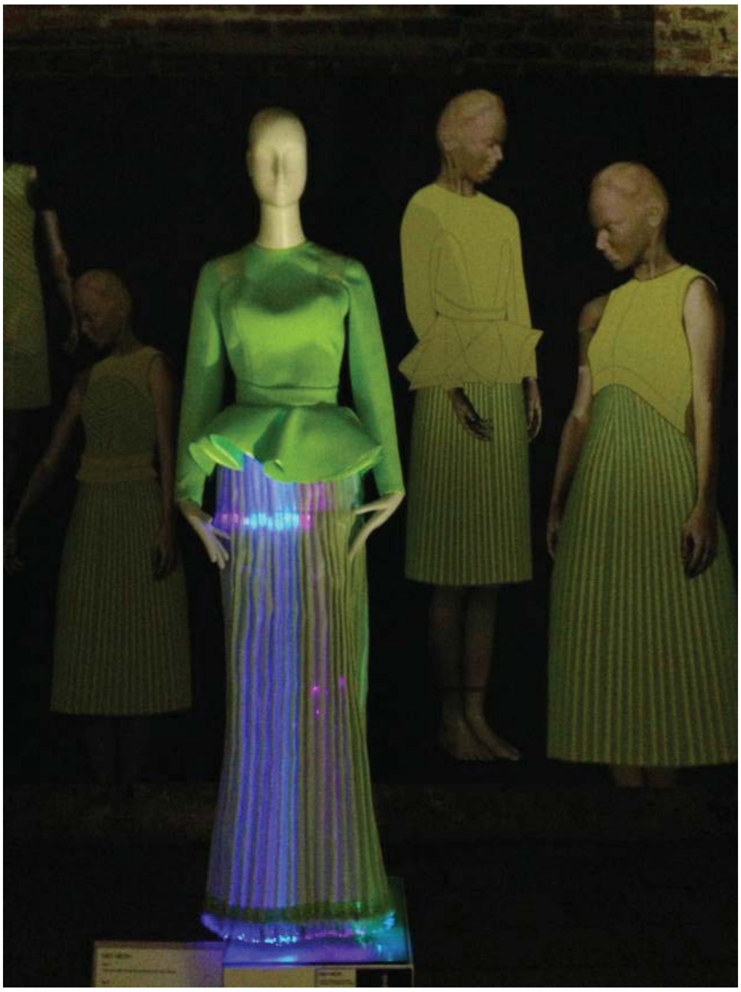


Figure 5.44 Neo-neon creation

5.4 Objective evaluation

As illumination is one of the main highlights of the prototype, an luminance meter (Figure 5.45) is adopted to test the luminance of photonic cushions.

Figure 5.45 Illuminance meter

The illuminance was measured in a darkroom. The measurement is performed at 10 different locations selected randomly on the surface of the cushion for each RGB colors. The results are presented in Table 5.1.

Table 5.1 Illuminance for different colors (lm/ft^2)

	Lowest	Highest	Average	Standard Deviation
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

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 appearance under darkness. It is also founded that the illuminate 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 5.2).

Table 5.2 LED luminous flux specification

	Luminous Flux (lm)		
Color	**Min.**	**Typical**	**Max.**
Red	33	40	56
Green	43	55	95
Blue	9	13	19.5

Table 5.1 indicates that for all three colors, the variation of illuminance measured at different locations is quite significant. Due to the flexible and uneven 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.

5.5 Subjective evaluation

Surveys are conducted to evaluate the usability of photonic creations. The purpose of the survey is to obtain the preferences of end-users and then provide suggestions to improve the design in the future work. The background of subjects we interviewed is very diverse, including financial manager, doctor, housewife, company owner, hotel manager, fashion designer, interior designer, students in different levels, tourist, retiree, etc. The subjects are firstly given an introduction of the exhibition and the products, and then the questionnaire is finished by each subject (Figure 5.46). Totally 90 peoples are invited to participate this survey. All subjects are 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: 35-45 years (16 peoples), Group 4: above 45 years (13 peoples).

Figure 5.46 Survey with subjects

5.5.1 Survey result – performance assessment

In the first part of the questionnaire, the subject was asked to rank the performance of photonic creations 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 is 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 is given a numerical grade from 1 (very unsatisfactory) to 7 (very satisfactory). The overall grade is obtained by taking the average of the grades from all subjects. The attributes assessed are listed as below:

----Design Concept

----Aesthetic

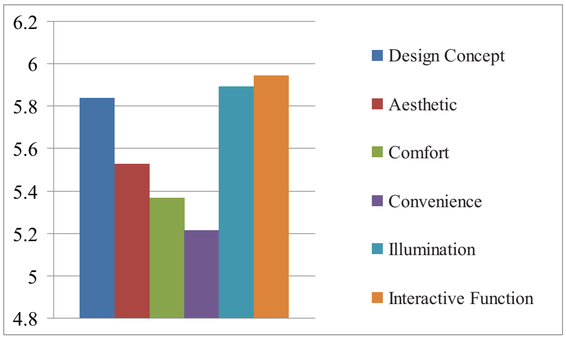
----Comfort

----Convenience

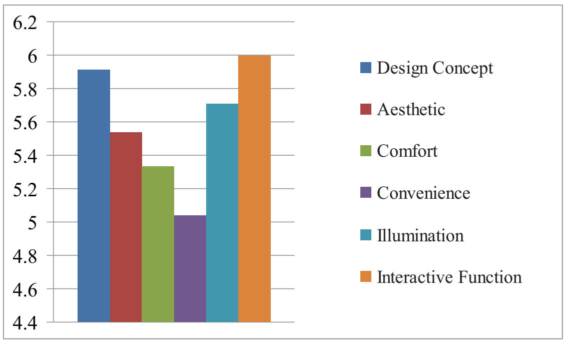
----Illumination

----Interactive Function

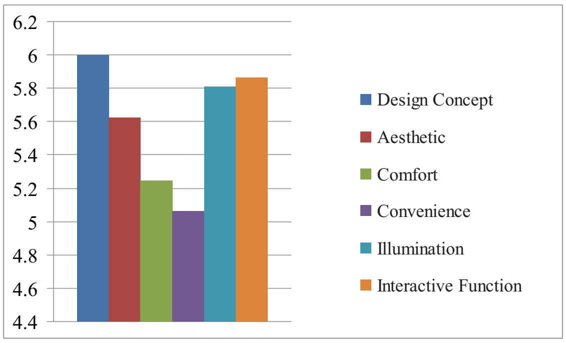
Figure 5.47 presents the results of performance assessment for ConneXion.



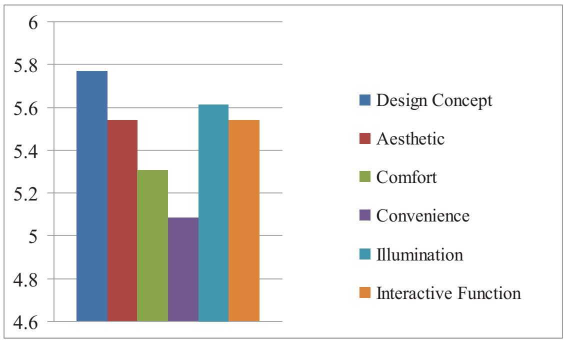
Group 1: Under 25 years



Group 2: 25-34 years



Group 3: 35-45 years

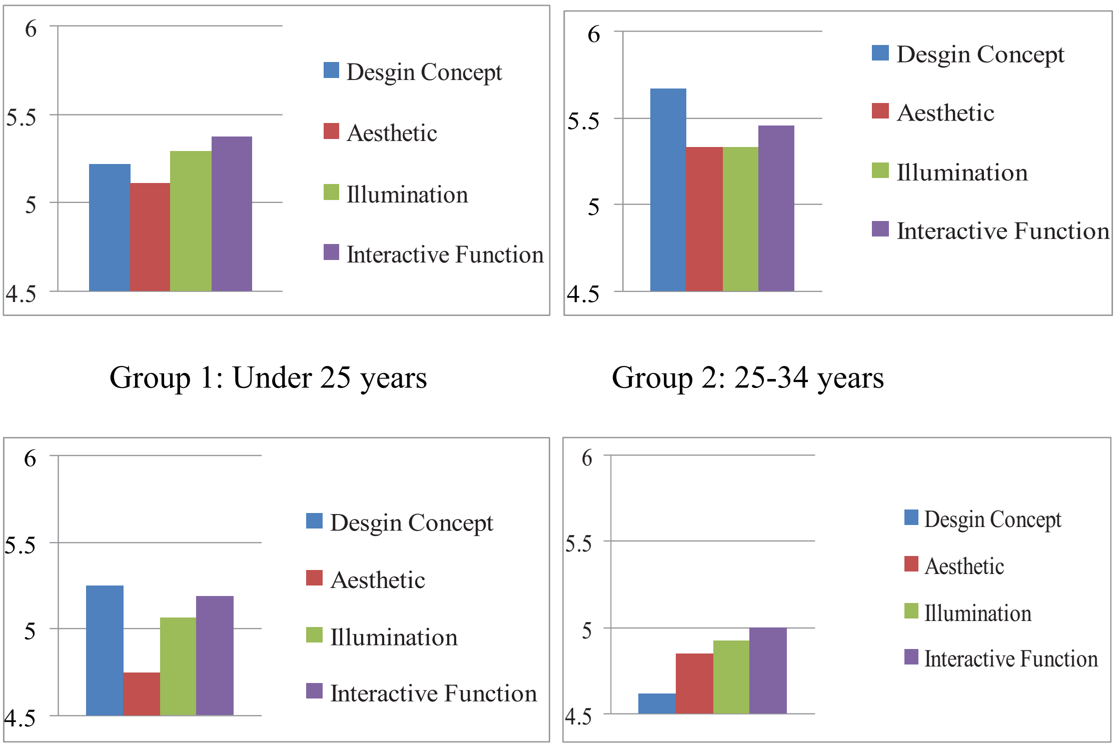


Group 4: above 45 years

Figure 5.47 ConneXion - Numerical grades of different attributes for different age groups

The 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, 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. However, the grade of hand feel is much higher than the grade of prototype “Chinois Photonics” discussed in last chapter, whose hand feel is rated at 4.06. This indicates that by using different textile materials and different woven structures, the hand feel has been improved. In order to further improve the hand feel of POF fabric, more study is needed to experiment with different materials and different textile design. 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 favourable due to its mobility and flexibility.

Figure 5.48 illustrates the survey results of Ephemeral.



Group 1: Under 25 years

Group 2: 25-34 years

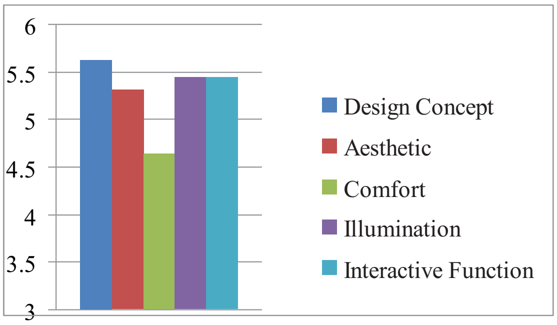
Group 3: 35-45 years

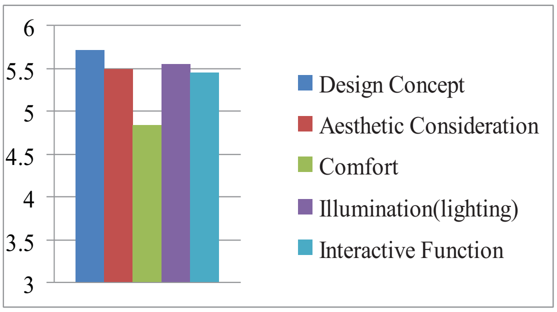
Group 4: above 45 years

Figure 5.48 Ephemeral - Numerical grades of different attributes in different age groups

As the creation Ephemeral is fixed to the wall, and the user is not supposed to physically touch the fabric, the performance of Comfort and Convenience are not assessed. Generally speaking, for all age groups the grades of Ephemeral are a little lower than ConneXion for all parameters. This is possibly because the interaction of ConneXion is more sophisticated involving in user-prototype interaction as well as user-user interaction through the prototypes, which enhances the overall image the prototypes. It is also observed from the histograms that basically the grades rated by subjects above 45 years old are lower than the grades rated by other age groups. It appears that Ephemeral is less acceptable by senior citizens.

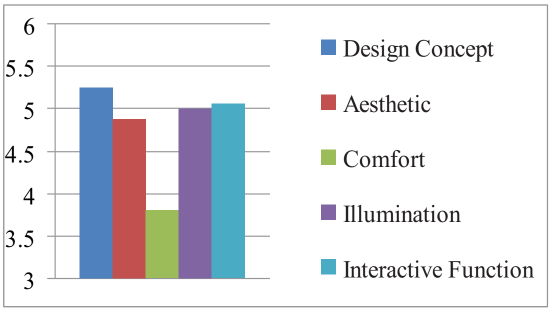
The assessment results of Neo-neon is presented in Figure 5.49.

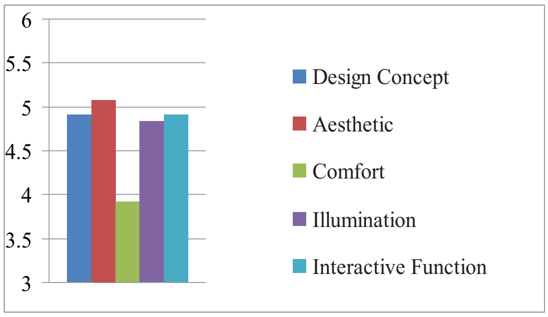




Groups 1: Under 25 years

Group 2: 25-34 years





Group 3: 35-45 years

Group 4: above 45 years

Figure 5.49 Neo-Neon - Numerical grades of different attributes in different age groups

It is found that, for all age groups, the grades of Design Concept, Aesthetic, Illumination and Interactive Function are satisfactory, while the grades of Comfort is still the lowest. This observation is consistent with previous discussion. It is noted that the grades of

Comfort in Groups 3 and 4 are lower than that in Groups 1 and 2. This reveals that older people (above 35 years old) have more concern about the comfort of clothing, whilst younger people (below 35 years old) are more attracted by high technologies.

5.5.2 Survey results – closed questions

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

Question 1: Which interactive mode do you like the most?

Question 2: Do you agree that the prototype can enhance interior environment?

Question 3: Would you like to use this kind of product in your home if it is available in the mass market?

Question 4: Which property is most attractive to you?

----Appearance

----Pattern

----Illumination

----Technology

Question 5: Which property needs to be improved?

----Appearance

----Usability

----Durability

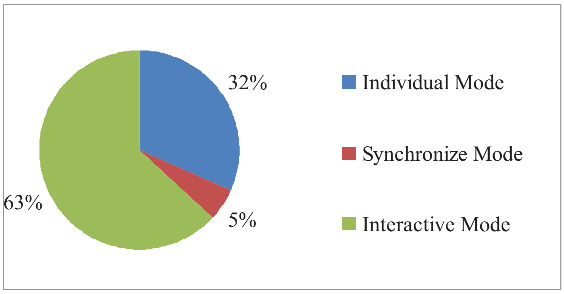
----Change of color

----Interaction with user

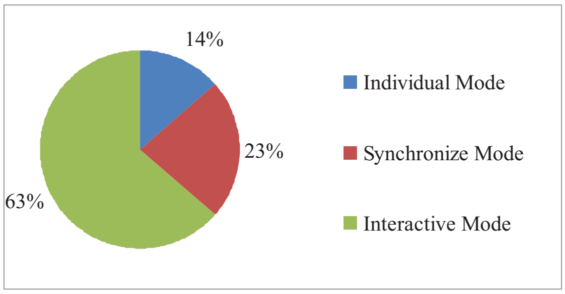
----None

5.5.2.1 *Question 1 - Which interactive mode do you like the most?*

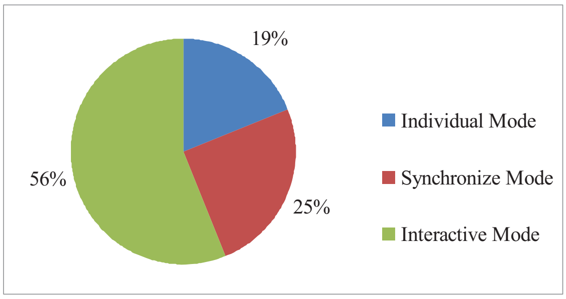
Multiple interaction modes are designed for ConneXion and Ephermeral, and only one interaction mode is designed for Neo-neon. Only the results of ConneXion and Ephemeral are discussed. The responses to Question 1 for ConneXion are summarized in Figure 5.50.



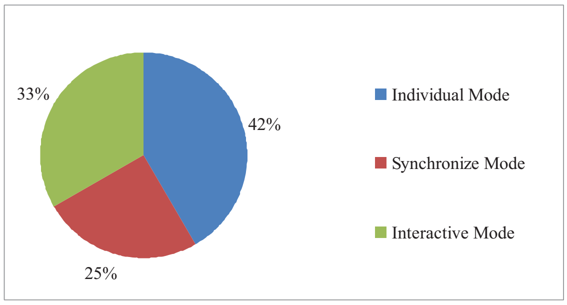
Groups 1: Under 25 years



Group 2: 25-34 years



Group 3: 35-45 years

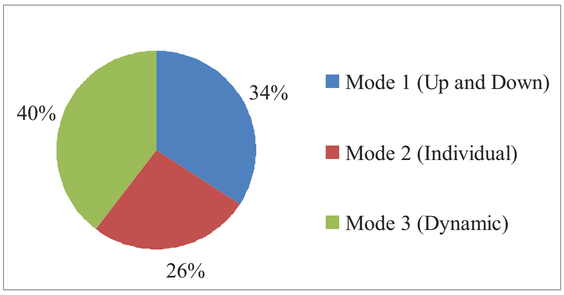


Group 4: above 45 years

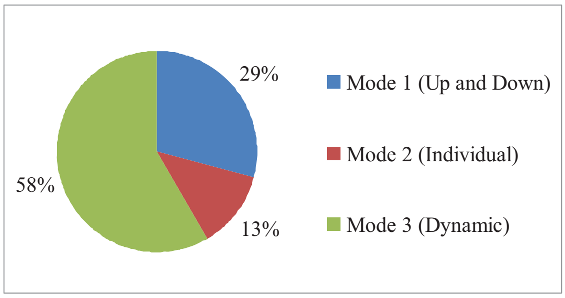
Figure 5.50 ConneXion - Responses to Question 1 - Which interactive mode do you like the most?

It is illustrated in Figure 5.50 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, the elderly prefer the low frequency flash lights.

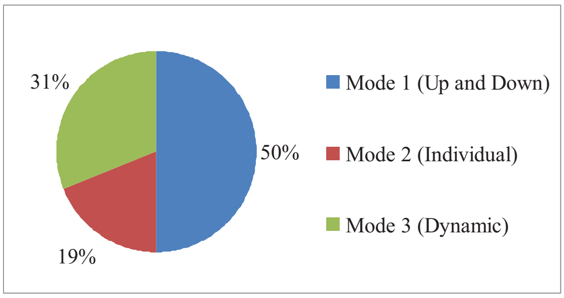
Figure 5.51 shows the responses to Question 1 for Ephemeral.



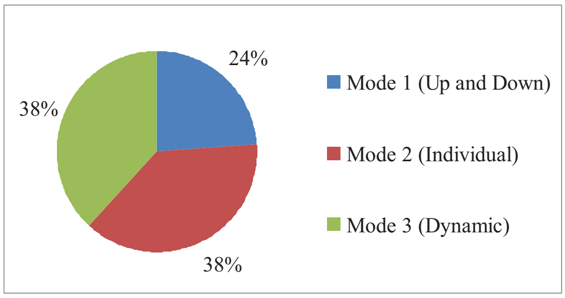
Group 1: Under 25 years



Group 2: 25-34 years



Group 3: 35-45 years



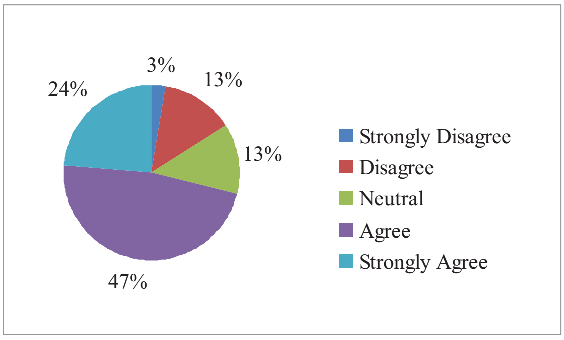
Group 4: above 45 years

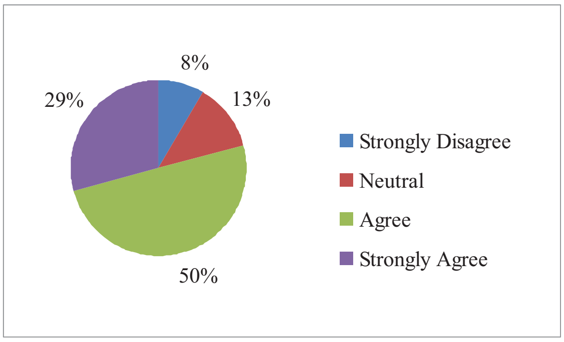
Figure 5.51 Ephemeral - Responses to Question 1 - Which interactive mode do you like the most?

The subjects in Group 1 and 2 show more interests in Mode 3 (Dynamic Mode), while the subjects in Group 3 prefer Mode 1 (Up and Down). The grades of Mode 2 and Mode 3 are very close for Group 4. Generally speaking, there is no common trend or pattern for all age groups.

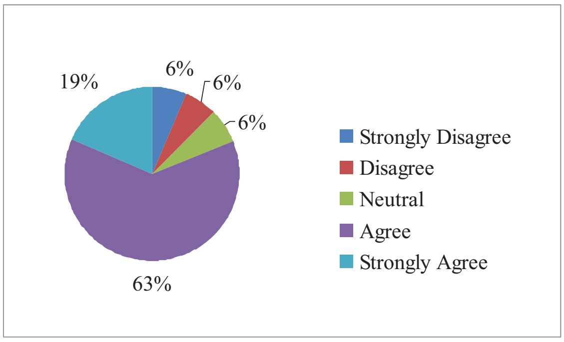
5.5.2.2 *Question 2 - Do you agree that the prototype can enhance interior environment?*

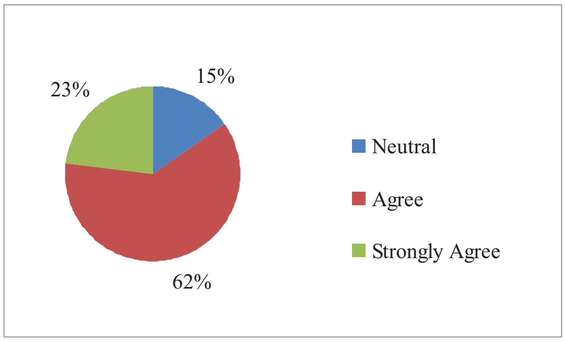
Collection Neo-neon is designed for fashion application. Therefore, Question 2 is not included in the survey for Neo-Neon. The results of Question 2 for ConneXion and Ephemeral are displayed in Figure 5.52 and Figure 5.53 respectively. As shown in Figure 5.52 and Figure 5.53, Most subjects agree or strongly agree that the prototype can enhance the interior environment. It is evidenced that the interactive photonic soft furnishings can be multi-functional and can greatly enhance the interior environment via changeable and tunable illumiescence.





Groups 1: Under 25 years Group 2: 25-34 years





Group 3: 35-45 years Group 4: above 45 years

Figure 5.52 Responses to Question 2 - Do you agree that ConneXion can enhance interior environment?

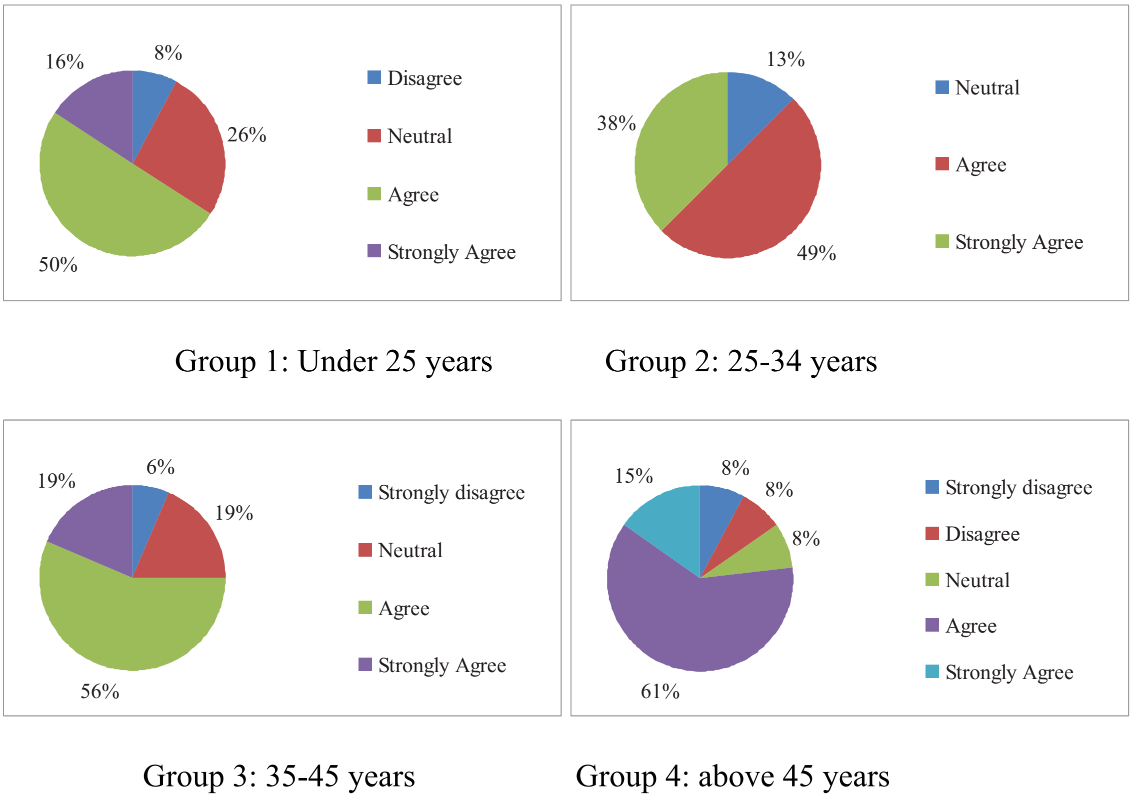
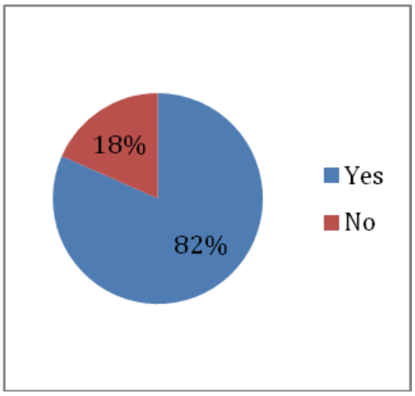


Figure 5.53 Responses to Question 2 - Do you agree that Ephemeral can enhance interior environment?

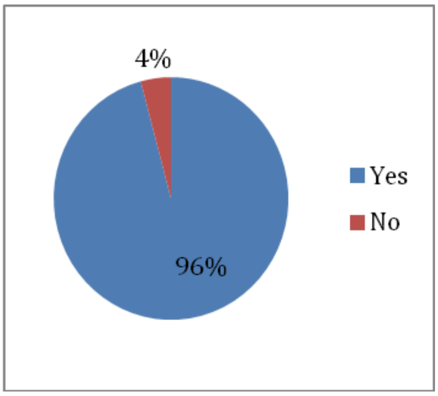
5.5.2.3 *Question 3 - Would you like to use this kind of product in your home if it is available in the mass market?*

Question 3 is designed to obtain an insight into the marketability and the potential to transfer the prototypes developed in this research to commercial products. This survey is conducted on ConneXion.

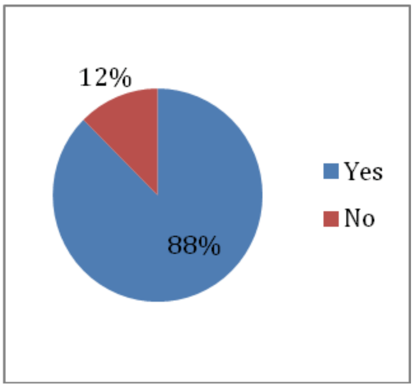
The responses to Question 3 are shown in Figure 5.54. Most subjects preferred to use this kind of product at their home, and these products seem to be more attractive to people below 45 years old. This kind of product seems to be less attractive to people above 45 years old. This finding is consistent with the observation discussed in previous sections, and it implies that elder people have less interests in hi-tech products. Generally, 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.



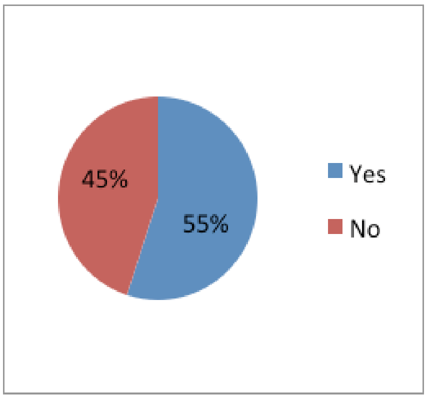
Groups 1: Under 25 years



Group 2: 25-34 years



Group 3: 35-45 years

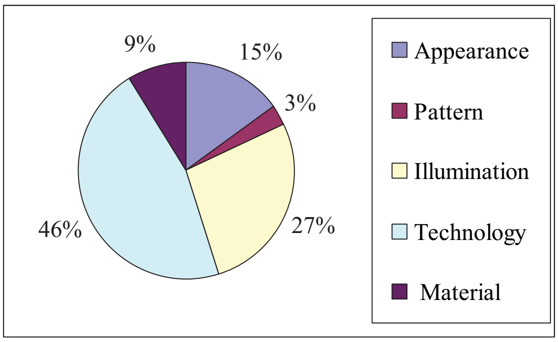


Group 4: above 45 years

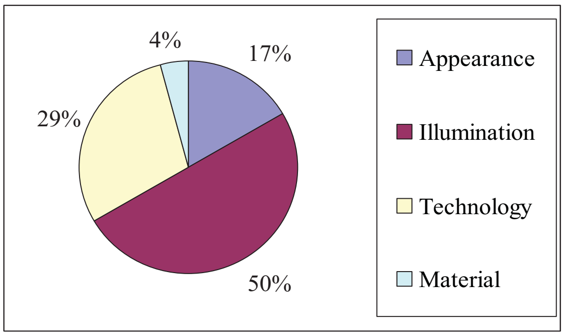
Figure 5.54 ConneXion - Responses to Question 3 - Would you like to use this kind of product in your home if it is available in the mass market?

5.5.2.4 *Question 4 - Which property is most attractive to you*

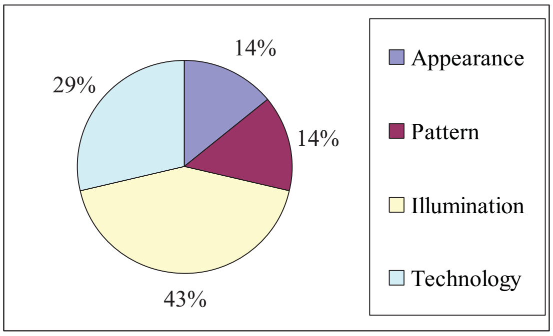
The response to Question 4 for ConneXion, Ephemeral and Neo-Neon are listed in Figure 5.55, Figure 5.56, and Figure 5.57 respectively. Generally speaking, Technology and Illumination are regarded as the most attractive elements of photonic prototypes. As an attempt to integrate cutting-edge technologies into textiles and add new features to conventional textiles, this research successfully develops interactive luminous textiles. The survey results demonstrate that the subjects are impressed by the illumination and hi-tech of final prototypes.



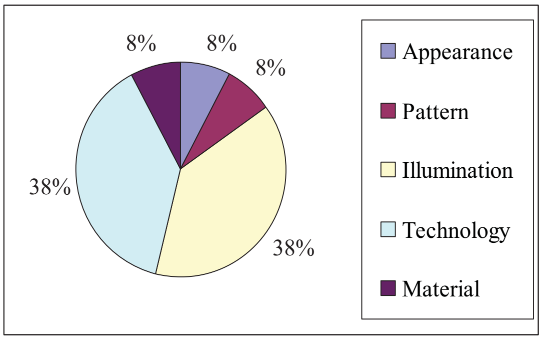
Groups 1: Under 25 years



Group 2: 25-34 years

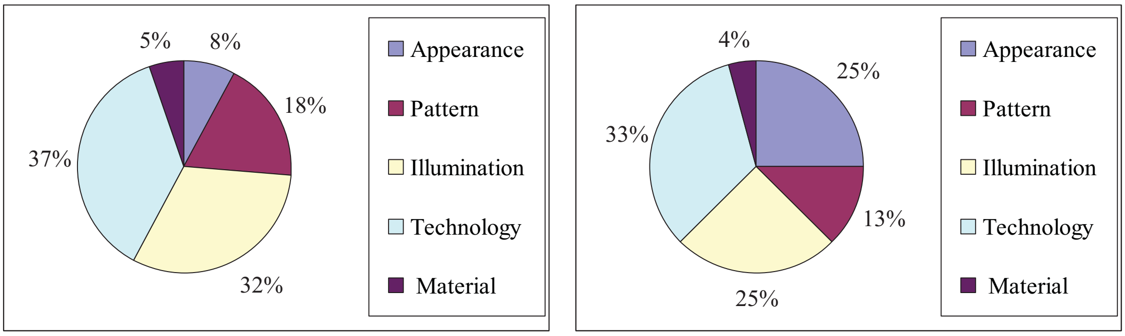


Group 3: 35-45 years

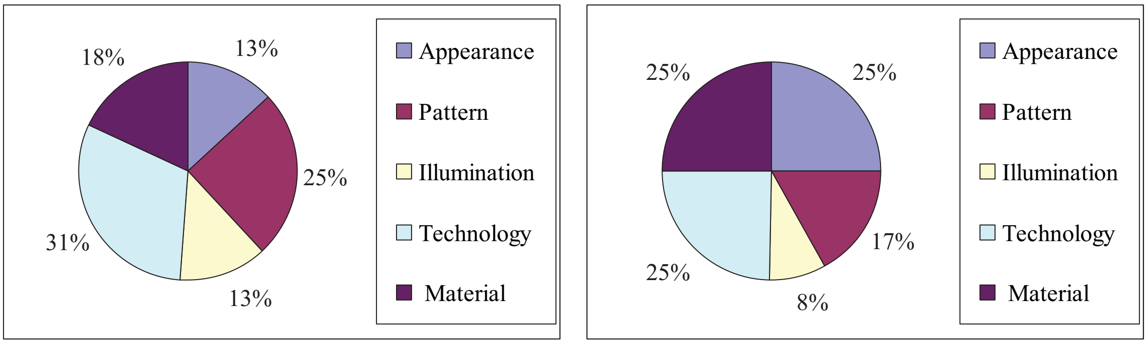


Group 4: above 45 years

Figure 5.55 ConneXion - Responses to Question 4 – Which property is most attractive to you



Groups 1: Under 25 years Group 2: 25-34 years



Group 3: 35-45 years Group 4: above 45 years

Figure 5.56 Ephemeral - Responses to Question 4 – Which property is most attractive to you

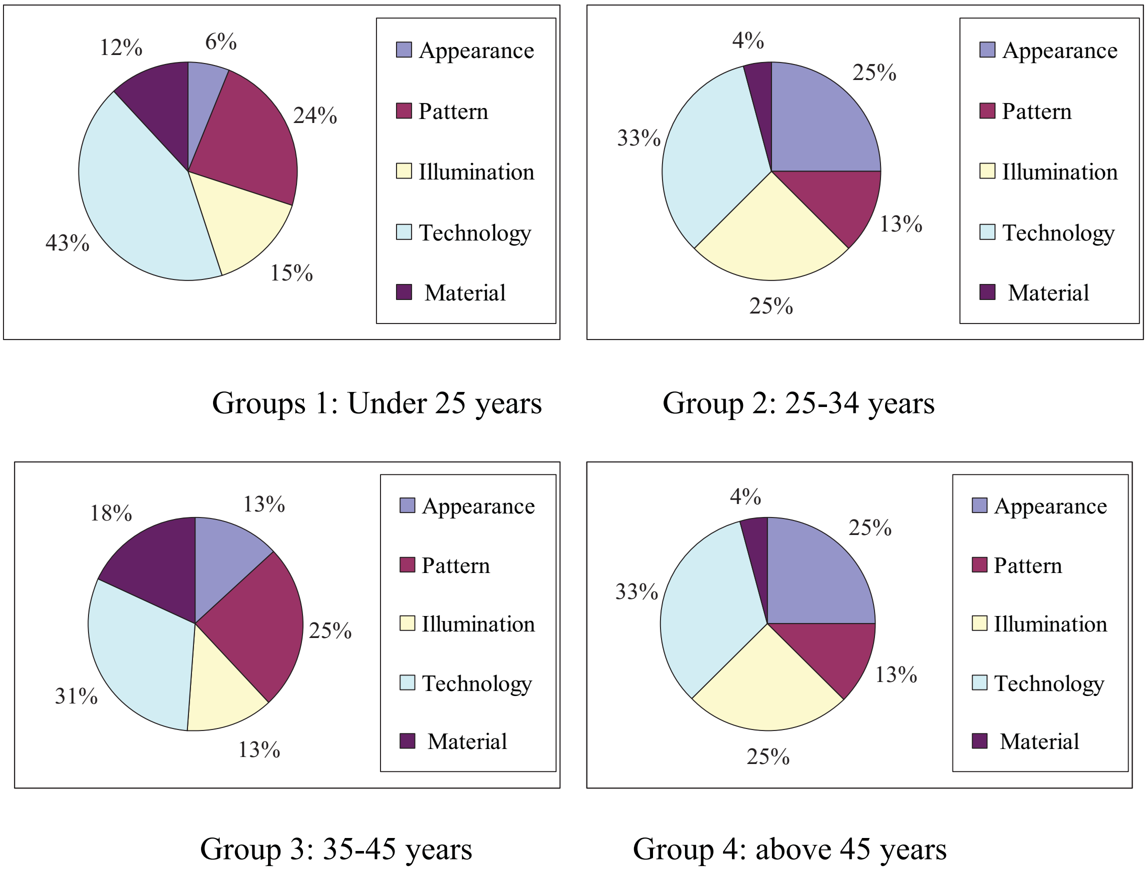


Figure 5.57 Neo-Neon - Responses to Question 4 – Which property is most attractive to you

5.6 Summary

The main findings of this chapter are summarized as below:

1) Interactive photonic creations in different forms have been developed. Sophisticated interactions, including user-textile interaction as well as user-user interaction through luminous textiles, are realized. Interactive photonic textiles can therefore be used as an effective communication platform between users, viewers and their surroundings.
2) Through design improvement, the usability of interactive photonic prototypes is improved. By using unobtrusive electronics, powerful LEDs, rechargeable batteries, and sensors, enhanced illumination with sophisticated interactive functions are fulfilled.
3) Objective evaluations indicate that the illumination of the developed photonic

furnishing is acceptable under dark environment.

4) A series of survey have been conducted to assess the performance of the prototypes, and also to examine the marketability of the prototypes and the potential to commercialize the prototypes. It is demonstrated that the feedback from the subjects is quite positive. This research not only enriches the knowledge on design and development of interactive photonic textiles, but also creates prototypes with great potential to be transferred to commercial products.

Chapter 6. **Conclusions and suggestions for future work**

This project is undertaken to study on innovative photonic textiles by investigation and development of POF integrated textiles. This chapter summarizes the research completed in this project. The main findings of this project are highlighted, and the limitations are discussed. Topics which are deserved to be further studied in subsequent research are also suggested.

6.1 Main findings

6.1.1 Cases

The design variables of photonic textiles include both tangible element (tactility, structure, color, material, form), and intangible elements (lights, darkness, light intensity, hue, duration). It is challenging for textile and fashion designers to obtain the knowledge of intangible elements design. As discussed before, design and development of interactive photonic textiles demands a multi-disciplinary knowledge from different domains. This study bridges the gap between different disciplines by design practice. The main achievements in development of interactive photonic textiles are summarized as below.

1) By introducing sensors and electronic components into photonic textiles, real-time interaction in multiple modes between users and the prototypes is achieved. An intelligent control system to regulate the interaction is engineered. Users can customize their environment by changing the light color of photonic soft furnishings according to their personal preferences. Photonic textiles prototypes with sophisticated interactions between users and the prototypes similar to the prototypes presented in this project are rare. The prototypes developed in this research fill in the gap in the field of interactive photonic textiles for interior furnishings.

2) Investigation on POF textile design in this project brings new knowledge, insights and understanding to textile design. The end-users can explore new experiences, emotions and meanings through the interaction between textiles and user as well as interaction between different users. A series of interactive photonic textiles prototypes have been created covering a range from soft furnishings, artworks to fashion apparel. Detailed design themes, moods and inspirations are depicted. All the creations demonstrate and evidence the successful implementation of the experimental development. Some of the prototypes may have great potential in commercial market. Some of the artworks have been showcased at peer reviewed exhibitions and international events.
3) POFs have been successfully woven with conventional yarns into different fabric constructions by automatic weaving loom. As the foundation to develop photonic textiles, weaving techniques are well manipulated taking the rigid nature of POFs into account to create diverse structures without significant sacrifice of drapability and hand feel.
4) Laser engraving is demonstrated to be successfully used to treat POF fabrics to cause side-emission from fabric surface. Comparing to conventional mechanical, chemical or thermal treatments, laser engraving has competitive advantages in terms of precision, ease of control, sophistication of illuminating pattern design, etc. This enables designers to design more complex and creative surface patterns and illuminating effects with more aesthetic appeal and attractiveness, which definitely add more values to the prototypes and eventually increase the marketability of the potential commercial products.
5) Conventional textile embellishments are applied onto photonic textiles in order to enhance the tactile quality and aesthetic, including dip dyeing, screen printing, digital printing and embroidery. Although it is important to embrace the cutting-edge technologies from other areas and incorporate them into textiles to create innovative

and smart textiles, as textile essentials the function of embellishments to reinforce the aesthetic of textiles should never be underestimated. With various embellishments, the surface and appearance of photonic textiles can be dramatically improved.

6) A novel technique to couple POFs ends to LEDs is developed. Although this technique has been adopted in electronics sector, this technology has hardly been applied to textile field. By embracing appropriate LEDs, this coupling technique can not only transfer the conventional time-consuming coupling process into a quick and simple task, but also remarkably enhance the side-illumination of final photonic prototypes.
7) Several surveys were conducted in order to evaluate the performance of the prototypes, and also to identify the demerits of the prototypes which should be improved to refine the design. It is elaborated in the data analysis that the subjects are impressed by the illumination, color, interactive function of the prototypes and the technologies involved. This indicates that the research conducted in this project is not only of theoretical importance, but also of practical significance regarding the high possibility of the developed prototypes to be transferred to commercial products with multiple applications under various circumstances.

6.1.2 Model

Conventional one-direction design models cannot reflect the complicated and iterative characteristics of the process to develop interactive photonic textiles. In order to address this problem, a comprehensive design process model based on author's own design practice to characterize and standardize the whole process is proposed.

Generally speaking, the new design process is a circulated action research process involving continuous improvement of prototypes. Within this process, concept development, experiments, surveys and design improvements are not isolated steps, but an integrated entity. Development in each step could possibly have an impact on another step, and therefore the results in each step can be reflected to another step in order to further refine the design. By this means, the design can be continuously improved until the final prototypes meet all predetermined specifications. The design process is hence not a simple one-way step-by-step procedure, but a highly reflective and iterative process with continuous and progressive improvement.

When the entire process is examined in details, the whole process can be segmented into two streams – one is technology and the other one is design. Throughout the entire process of development, fashion and textile design methods must be considered in conjunction with modern technologies from various areas in order to achieve innovative prototypes with technical advantages as well as aesthetic acceptance. Each step involves an interactional collaboration between technology and design.

6.2 Limitations and suggestions for future work

In this research, innovative photonic textiles with tangible interactions have been developed. Despite the achievements of this project, there are still several limitations, and some of them deserve further investigations:

1) Subjective evaluations and surveys imply that the illumination and interaction function of the developed prototypes in this project are quite satisfactory, however, the hand feel and comfort is still inadequate. More experiments with different POFs need to be conducted in order to improve the hand feel of photonic textiles with integrated POFs.
2) Plain weave and jacquard weave structures are used to develop photonic textiles in this

study due to the fact that these two structures are the most common weaves and easy to handle. Different weaving structures and techniques can be tried in future work to create fabrics with different pattern and texture. It is also desirable to integrate emerging technologies in dyeing and embellishing to photonic textiles to enhance the aesthetic.

3) Laser engraving has been successfully used in this research to realize side-illumination from fabric surface. However, due to the fluctuant nature of fabric surface, even engraving on POFs remains challenging. It is observed that at some spots more light emits, while at some other places less light emits. To ensure an even engraving on POFs and therefore an even illumination from fabric surface, more investigation is needed.
4) The color of the prototypes developed in this project is changeable and tunable. However, the color spectrum is not sufficiently broad. Photonic textiles can present mixed color tones by exploitation of various LEDs and further development of control system.
5) Sophisticated interactions between user and photonic textiles were accomplished in this research. However, the interaction is still limited to several modes. Refinement on the design of interaction and development of relevant control system are needed.

This project demonstrated the application of emerging technologies as an innovation opportunity for textile design. New development in material science, textile processing, LEDs, sensors to respond to different stimuli, surface treatment, etc. can be well leveraged and integrated into textiles to create innovative and novel artworks. New technologies in other domains continuously drive the innovations in textiles and push the boundary to another level. However, how to seamlessly incorporate these new technologies from other industry into textiles with consideration of textile essentials to develop user-friendly products still remains a big challenge to a designer. Development of smart textiles merely from a technological point of view tends to neglect the aesthetic appeal of textiles, which makes the user experience of the developed prototypes always unsatisfactory. A bridge needs to be built to fill the gap between technological development and aesthetic consideration.

The prototypes developed in this project have a broad potential market. Comparing to conventional textiles, interactive photonic textiles can emit light, present different colors, change the surface pattern and can interact with users. They are particularly suitable for decorative purpose. Home furniture is one possible application. With attractive illumination and color effect, the photonic textiles can also be used in hotels, exhibition halls, restaurants and many other circumstances to enhance the interior environment. Fashion is another area where photonic textiles can be applied. Fashion items, such as clothing, shoes, and bags, with integrated photonic textiles can present a shining and colorful look.

As electrical appliances are becoming more and more smart than ever before, smart devices which can be integrated our daily life to enhance our lifestyle and wellbeing have attracted extensive interests in both academic and industrial community. Smart phone is an example of such smart devices which have been driven by various technologies. Smart home is possibly the next area where smart devices can find wide applications. As an important component of interior environment, interior textiles are readily to embrace various emerging technologies to create a smart interior environment. With the advancement of diverse cutting-edge technologies, future smart textiles may be completely beyond our imagination.

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