DEVELOPMENT OF AN INTEGRATED, PROGRAMMABLE, NON-EMISSIVE TEXTILE DISPLAY MATERIAL

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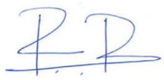
Declaration

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

 (1/8/2013)

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Abstract

Interactive textiles explore various ways and means in which textiles can become a medium of communication and expression. Researchers have begun to explore these possibilities of interactive textiles by modifying their properties or adding new properties into them through embedded electronics and materials. As such, *textile displays* are a commonly investigated topic in this field of research. Textile displays allow various display technologies to be embedded into the textile to enhance the textile to display images and animations on the textile.

This thesis explores the detailed development of a non-light-emissive displays using heat sensitive thermochromic inks. In non-light-emissive textile displays, the display is more subtle and ambient, and has a natural form of color change. Thus, to actuate the thermochromic inks, we introduce the use of Peltier semiconductor elements along with a fine tuned closed loop temperature control system. The control system accurately controls the temperature of the thermochromic ink textiles using the rapid heating and cooling capabilities of Peltier elements. Thus, the core novelty of this work lies within the robust, fast and active controllability of the color of fabric as opposed to previous research. As such, this controllability allows dynamic patterns to be displayed on the actual fabric which is presented through a wide range of prototypes of textile displays.

The thesis mainly takes an engineering perspective into the development of the display. As such, we present the detailed implementation, detailed technical analysis of the system, prototypes & applications with analysis, and further refinements to the textile display system.

Through this analysis we have identified key advantages and limitations of the system and how they can be used strategically for different usage scenarios. As such we present a design methodology for practitioners who wish to develop future non-light-emissive textile display systems.

Due to the ubiquitous and subtle nature of this textile display system, we envision that it will be able to breathe life into the textiles of the future. Hence we envision that the technology presented through this thesis would radically challenge the boundaries of current & future textile research and industry.

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Introduction

In an age where the Internet and television were non-existent, often textile mediums were used to communicate complex mythologies, ideologies, narratives and were even used for entertainment [17]. Textiles and other craft media held special roles in many civilizations for passing on knowledge and were often the center of attention in the homes of yesteryear. Since then, textiles have been through a long journey, being subjected to a thorough process of re-engineering and re-invention, and finding itself being an essential item in our daily lives.

Likewise in the field of interactive research, concepts like ubiquitous computing are attempting to re-invent the idea of a 'computer' merged into our everyday objects. The introduction of Ubiquitous Computing [75] in the early 90's has fostered a whole new era of embedding information and technologies into many different forms and factors. Moving away from the traditional desktop model, researchers have explored wrapping these technologies into more tangible forms that we can grasp and manipulate [35]. Adhering to Weiser, textiles are being focused as a common platform for ubiquitous technologies [65] to "weave themselves into the fabric of everyday life [75]". With these advancements, textiles are facing a rapid phase of experimentation rendering them to be more than just a fashion statement.

Textiles are a common form of material we interact with daily. Since its recorded uses from prehistoric times textiles have become an integral part of our daily lives in the form of our clothes, home furnishing, architecture and numerous other uses. With the introduction of new concepts and technologies researchers have begun to embed more and more electronics into textiles [15]. This field of 'electronic textiles' or 'e-textiles' has created a vast area of research and application spanning from medical applications [68] to education [16] and even to textiles becoming a medium of expression [37].

With this development, a widely explored area of research in e-textiles is textile displays. Here, researchers look into embedding various forms of visual displays in textiles. From large scale displays [6] to embedded LED (light emitting diode) displays [59], textile displays have become a common occurrence in this field of research on house-hold textiles, clothes, furniture, etc. Adding a visual display allows the textile to attain another dimension in time allowing its appearance to reconfigure to a certain extent making it a platform for a variety of uses such as social interaction, emotional expression [37], gaming [18], etc.

Currently these displays can be categorized as *emissive*, such as embedding LEDs, Electro luminescent sheets and wires, or, *non-emissive*, such as using thermally actuated inks. However, the use of emissive technologies in conjunction with textiles renders rather an obtrusive form of a display [73]. Such displays are typically used for more specific purposes to gain people's attention positively such as in advertising or specific social contexts [6].

Alternatively, this research focuses on a ubiquitous and ambient textile display on which, the technology falls to the background and lets the user interact with the actual textile itself. This minimalism is an important characteristic in designing ubiquitous interfaces where the augmentation of technologies should not obscure the highly defined interaction modalities of the textile [77]. Hence, in this context, non-emissive display technologies have become a primary technology, in which, the display does not emit any form of light. Thus, in most cases, the display is the actual fabric itself, where the animations of the display are performed as an unobtrusive and non-emissive color change of the fabric [73].

Figure 1.1: Overview of the textile display material technology

Most current such non-emissive technologies are non-animatable due to too slow color change. This is a main limitation in enhancing the textile's capabilities through a non-emissive display as it limits the display's controllability. Thus, this thesis explores the engineering of a non-emissive fast color changing textile display using thermally actuated thermochromic ink and Peltier semiconductor elements as the thermal actuators (Figure 1.1). A key goal of this research is to innovate a baseline technology that overcomes the boundaries of the current non-emissive ubiquitous displays. By extending the daily used textiles into subtly animated interactive textile displays, this research tries to blend the display technology with fabrics in its natural form.

The thesis presents the base line technology, its design, implementation and an in-depth technical review of the technology. In addition, it presents the technology's uses through the enhanced capabilities of the system as an animateable ubiquitous textile display. The prototypes detail initial try-outs of the technology such as in furniture, wearable/pixelated displays and its application in three different areas. These areas include merging the technology with the traditional textile craft of byobu; enhancing Augmented Reality markers through 'dMarkers', or, dynamic markers; and the fabrication of a new paper based temperature sensor that was developed with thermochromic inks. In addition, to enhance the interactive experience, we present the development of a new touch-sensor that slightly modifies the display technology to serve as a display *and* sensing technology. We also present the refinements to the system with the use of novel miniature Peltier elements. As such, the thesis uses iterative design processes of the technology and prototypes to optimize the presentation of the non-emissive textile display technology.

1.1 Background

Ambient and ubiquitous computing involve redistributing full or parts of computing capabilities to the environment surrounding us [5, 74]. Works in ambient and ubiquitous technologies have seen the implementation of a variety of new types of interfaces. These works try to manipulate the digital bits with the use of our intrinsic gestures in the real world. MusicBottles [34] is an early example of this where the user tries to manipulate the playing of a digital music track with interactive gestures with bottles. These works involve careful collaboration between many expertise fields in order to achieve a perfect interaction between the user and the new interface. As such, frameworks such as Tangible User Interfaces (TUI) [35] attempt to characterize the development of such interfaces between the digital world and the real world seamlessly.

Likewise, the world of electronic textiles combine many different disciplines such as engineering and design. Thus, enhancing the analog properties of a textile material using a digital technology should try to create a seamless or 'analog-like' interaction between the user and the material. The 'Analog-Digital-Continuum' [40], lists out some of the key characteristics of the development of such an 'analog-like' interface. This is clearly addressed in such non-emissive textile display materials where the manipulation of the color creates a continuous link between the technology and the textile material. I.e., the technology attempts to manipulate a core property of the textile, its color, in order to achieve the display on the fabric. Thus, the interaction can be considered to be continuous as observed by the 'Analog-Digital-Continuum'.

Furthermore, Organic User Interfaces, or, OUIs also try to incorporate the properties of materials into their interactions [27]. OUI's involvement of the ergonomics of the medium into its interaction has paved way for many common materials to become interactive platforms. As such, textiles have gained wide attention transforming the traditional role of textiles to more expressive and interactive materials. Frameworks such as the ones outlined by OUIs provide new ways of looking at fabric and textiles as interface media [19]. Because OUIs stipulate that the input and output of an interface are one and the same, OUIs promote the natural and intrinsic qualities of the particular media used in the interface. This lends itself well to textile-based interfaces and makes research such as this, possible.

Hence, this research uses these frameworks as background references for the development of the non-emissive textile display.

1.2 Research Objective

Our main research objective is ***"Identifying the key development technologies for a non-emissive textile display material that can be seamlessly merged with the everyday textile objects around us"***.

Non-emissive textile displays have a potential for a wide range of applications in the world around us. If ubiquitous enough, such technologies can be applied to almost any textile based object rendering them to be a ubiquitous display. However, the current state of the art has not looked deep enough into these enabling technologies limiting most of the works to possess limited controllability of display. As such, these displays could not be actively controlled/animated displays, thereby, limiting their capabilities as an interactive display.

Therefore, through realising this research objective, the thesis presents the following key contributions.

- Presentation of the foundation technologies for a non-emissive textile display system and its usage
- In depth technical analysis of the display system
- Presentation of a wide range of prototypes and applications that displays the ubiquitous and ambient characteristics of the system
- Presentation of a novel temperature based touch sensor for non-emissive textile displays

- In depth discussion of the technical results and the prototypes of the display system
- A design methodology for constructing non-emissive textile displays

1.3 Motivation

One of the main motivations behind this project is to develop a textile display that can ubiquitously blend into everyday objects that use textile materials. Our intentions are to increase the ubiquity of the textile such that the technology can seamlessly be applied to various different applications while preserving its analog properties. We demonstrate this through a wide range of prototypes, merging with traditional textile artifacts and even extending into other areas such as Augmented Reality or Sensor Fabrication using the ubiquity of this technology to our advantage.

Next we intend to develop a non-emissive fabric display technology with relatively fast and accurate color control capability of the fabric itself. Fast and accurate color change on fabric allows many different patterns or sequences of patterns to be animated on fabric which in turn allows us to gain full controllability of the display. The non-emissivity of the display preserves the subtlety of animations displayed on the fabric allowing the display technology to blend in as a part of the fabric. This would be overcoming some of the main limiting factors of existing research on non-emissive textile display technologies.

Lastly, we intend to focus deeply on the engineering of the technology. Most of the existing research does not attempt to analyse the technology from an engineering perspective. Thus, we aim to take an in-depth engineering perspective to comprehensively develop and analyse the results whilst merging the artistic and design qualities in to the display. This would help us identify key limitations or possibilities that were undetected in earlier works to open up new avenues of application areas for textile displays while pushing the boundaries of existing research.

1.4 Approach

Figure 1.2: Thesis approach

Figure 1.2 outlines our approach to achieving these goals. Overall, we take an applied research point of view that allows us to implement the ideas and theories discussed in this research into working prototypes such that they fulfill two main factors. Firstly, implemented prototypes would prove to the readers that the ideas and theories discussed here are realistically achievable. The goal here is to present a feasible solution to the development of a non-emissive textile display and therefore it is important to affirm the practicality of the solutions presented. Secondly, we wish to ensure that the relevant communities can easily understand, design and develop non-emissive textile displays with relative ease through the guidelines discussed in this research.

In addition, this research incorporates a multidisciplinary effort to design and develop the system. Eventhough this thesis weighs more towards understanding the engineering principles of the system, the development process included collaboration with artists, designers, craftsmen and understanding and applying the artistic and traditional theories, practices into developing the prototypes and applications. As such, the development process has been subjected to many design iterations to find the optimum solutions.

Next, we outline our approach.

1.4.1 System Design

Here, our main goal was to identify the weakness of the existing research and recognize our potential solutions. Thus, one of the final solutions was the use of Peltier elements that can rapidly speed up the color change of thermochromic inks on the non-emissive textile display. However, in achieving this goal, a considerable time was spent in identifying and optimizing the system components and parameters. In the selection of thermochromic inks, the temperature sensitivity, easiness of applicability were a key parameters that were factored in. With Peltier elements there is a wide range of selection parameters such as Peltier size and performance parameters which had to be carefully identified for particular usage scenarios. This was followed by the design of the driver circuits and firmware algorithms for accurate temperature/color control and ultimately gaining full control of the animateable textile display.

1.4.2 Technical Evaluation

We provide a comprehensive technical evaluation of the designed system. This helped identify the functionality and main strengths and weaknesses of the designed system. These results were key in fine tuning the design parameters to improve the system in the next design iterations.

1.4.3 Prototypes and Applications

The development of prototypes and applications was to identify the ubiquity of the developed system. As such, we tried our technology on a wide array of prototypes and applications in order to understand the feasibility of the technology as a ubiquitous display platform. Following are the prototypes and applications that we have implemented with our technology.

- ***Initial prototypes*** - *animated wall painting, animated table cloth, pixelated displays, and wearable displays*: These were developed at an initial stage where we directly applied our platform on to the textile object. These prototypes were helpful in our iterative design and optimization of the system.

- ***Application*** - *Merging textile display technology with Byobu*: Byobu is a traditional textile craft that features textile room divider screens from Japan. With this application we were able to investigate the organic qualities of our ubiquitous technology which allowed it to be merged with a traditional textile craft.

- ***Application*** - *dMarkers : Ubiquitous dynamic markers for Augmented Reality*: This application featured merging our textile display technology with Augmented Reality (AR) technology. Without limiting to textiles, this work helped us extend our technology in to paper material that created dynamic markers for Augmented Reality applications.

- ***Application*** - *A dynamic AR marker for a paper based temperature sensor*: Based on some of the potentials identified from the previous application, this work explores the altering of the textile display technology into developing a paper based temperature sensor that can be read digitally.

1.4.4 Temperature based touch sensor

Observing some of the user interactions from our above prototypes and applications, we developed a novel temperature based touch sensor. The key innovation of this sensor is that it can be developed on top of the existing textile display technology without the need for any external hardware. By using this sensor we can convert any of our prototypes into a touch sensitive interactive textile display.

1.4.5 Refinements

Through the design process of the system and prototypes we identified some of the key areas that can be improved further. In this phase we introduce a new miniature Peltier element that enhances capabilities of the textile display technology.

1.4.6 Dissertation structure

The thesis is organized as follows

- Chapter 2 : *Related Work* : Provides an overview of the existing research relevant to the non-emissive textile display material, and we present some of the state of the art works that are relevant to different prototypes that were developed.

- Chapter 3 : *System Design of the textile display* : Provides an in-depth discussion of the system development. We detail the main elements of thermochromic inks, Peltier elements, controller circuit, firmware design and the integration.

- Chapter 4 : *Evaluation of the system* : This chapter analyses the system's performance characteristics such as colour change characteristics, temperature change characteristics, power characteristics. In addition the chapter discusses experimenting with different temperature ranges that could be useful for future design of textile displays.

- Chapter 5 : *Prototypes and applications* : Here we detail the initial prototypes that examine the system's capability as a ubiquitous display and its characteristics in different contexts. Next, we present three application areas : merging with textile craft, augmented reality and sensor fabrication, to demonstrate the textile displays diversity of being embedded all around the environment.

- Chapter 6 : *Exploring a temperature based input system for the display* : This chapter describes a novel temperature based touch sensor that can be introduced to the existing textile displays without any change to the existing hardware. The chapter details the development of this touch sensor and its performance characteristics.

- Chapter 7 : *Continuous system refinements* : This chapter examines refining the existing system with the use of miniature Peltier elements. Here we present the characteristics of the new system.

- Chapter 8 : *Discussion* : This chapter discusses the important system characteristics, prototype and application observations of the textile display. Furthermore, based on careful observations, experience and knowledge gained through the work, we present a design methodology for a new textile display system.

- Chapter 9 : *Future Work* : Here we discuss some of the possible future directions of the research. We discuss the use of micro/nano technologies, weaving technology and textile together and some possible future applications.

- Chapter 10 : *Conclusion* : Concludes the thesis.

2

Related work

This chapter attempts to identify the state of the art of textile displays in the scope of this research.

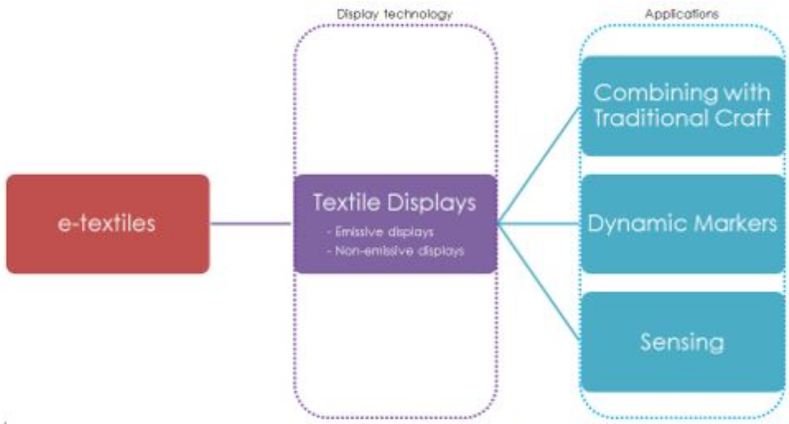


Figure 2.1: Scope of related works

Figure 2.1 illustrates the scope of the review of the related works approach of this thesis. We briefly describe an introduction to e-textiles which is followed by a detailed analysis of the current textile display technologies. These technologies are discussed under emissive and non-emissive categories. Following this discussion we move into identifying some of the key works in the work related to the applications we implemented using our technology. These applications were briefly introduced in the previous chapter. Thus, we discuss the related works pertaining to the application areas of merging traditional craft and contemporary technologies, dynamic markers for Augmented Reality applications and, development of a touch sensor for our non-emissive textile display.

2.1 Textile Displays

Works in e-textiles have been around for a period of time. With many fields of application and research explored, these works have focused on many different aspects such as embedding components from conductive elements to sensors itself. Some of the early works in the field demonstrate the embroidery of conductive metallic fabric to form a keyboard [53]. Since then e-textiles have come a long way in enabling to integrate sensors and even switches as integrated fabrics [58] [15]. In line with these technologies, as mentioned above, fabric displays are mainly categorized as emissive and non emissive display.

There has been plenty of work done in the emissive fabric displays field. Lumalive by PHILIPS [59] uses LED to implement the fabric display. Here they embed multi-color LED's into the fabric to form the display. Lumalive has been used with further interactions such as through proximity sensing [18]. Electro-luminescent wires and sheets too have been used in many occasions due to its flexibility and ease of integration [67] [47]. In addition Lumigram [64] displays the use of fiber optics woven in fabric as a display. In more recent works, Berzowska et.al.[12] use photonic band gap (PBG) fibers woven in a computer controlled

Jacquard loom during the fabrication process. In 'The History Tablecloth' [22] the authors use flexible substrate screen-printed with electroluminescent material forming a grid of lace-like elements. Thus, once the objects are kept on the table a halo effect is formed on the cloth which is retained for hours indicating the flow of the objects over the table cloth. However, the materials discussed here such as LEDs, BGFs, and electroluminescent materials are regarded as 'emissive materials' due to their emission of light [73]. However, due to the nature of obtrusiveness of emissive displays they are more useful for purposes of gaining attention. This is a clear case in Adwalker [6] where a complete display itself is embedded into the fabric.

For a more ambient and subtle approach, non-light-emissive materials such as e-inks, photochromic inks, and thermochromic inks have been used. Most of these works use these specialized inks which are actuated by an external trigger such as temperature, UV light or force. One of the key recent non-emissive display developments include EInk. There is work being done which attempt to merge this technology as a flexible display [3]. However, the display here features a transparent electrode layer. In addition, the display itself if attached to the flexible by placing it on top the material thus the interaction is not with the actual textile material. In the works of 'Information Curtain' [49], the authors use photochromic inks which actuate based on ultraviolet light. They use computer controlled ultra violet lights to interact with the textile. These lights create various patterns on the textile which lasts for several minutes upon removal of the light.

Further to these materials, thermochromic inks have been used as a popular material to fabricate non-emissive textile displays. Thermochromic inks too which change the color due to temperature changes, are widely adopted due to their ease of use for non-light-emissive displays. In ‘Shimmering Flower’ [9] Bersowska uses thermochromic inks with conductive yarn woven through a Jacquard loom to construct her textile display. When powered up, the conductive yarn heats up and in turn actuates the thermochromic inks to change the color. Hence, this display animates slowly to reveal various colors and patterns on the textile. Bullseye [52] too, uses thermochromic inks which are actuated by conductive yarn that is woven into the fabric. In ‘SMOKS’ [11] the jacket is printed with thermochromic ink shoulder pads which, when touched, change the color. This change gradually changes back, thus, keeping the memory of the touch for a certain time. In ‘Reach’ [38] , Jacob’s et. al. uses thermochromic inks printed scarfs, hats, etc. which change the color based on physical contact. Thus, the ‘SMOKS’ [11] and ‘Reach’ works use the body temperature to change the color of the thermochromic inks. In contrast, Yamada et.al. uses infrared LED’s to actuate the thermochromic inks [78]. Here, they use thermochromic inks to digitally change the color of paintings. In the works of, ‘Pure Play’ of ‘Memory Rich Clothing’ [10] use Peltier semiconductor elements to present fast changing non-light-emissive animations on textiles. Similarly, Mosaic Textile [73] uses liquid crystal inks, which changes color due to temperature. This uses sewn conductive yarn to actuate the display. Here they construct fabric elements of ‘Fabcells’ which contain this technology. These Fabcells are then used as pixels in groups to form the display on the textile.

Almost all of the above non-emissive displays have been used in an omni-directional manner. That is, these works only use a heating source such as body heat or conductive yarn without any cooling method. Due to this reason the absolute controllability thus the ability to animate the display is not profound.

Overcoming the above mentioned limitations, the goal of this research is to present a comprehensive ubiquitous display technology that is embedded on fabrics. We use thermochromic inks as our display medium to achieve a non-emissive display to preserve the ambient and ubiquitous characteristics of the fabrics. In addition the Peltier semiconductor modules used here allow the rapid heating and cooling of the fabric which allows this technology to be embedded as a ubiquitous animated display technology.

2.2 Merging traditional craft with contemporary technology

We experimented the ubiquity of our technology by trying to merge the display with the traditional textile craft of byobu. As such, this section details the works that are related to merging technology and traditional craft.

Work on Neo Craft [69] uncovers the need for traditional crafts people to embrace and incorporate new technologies into their process in order to survive and influence the coming onslaught of mass homogenization in our everyday objects. Our work puts these theories into action. By attempting to augment the traditional art form of byobu, without interrupting the tranquil function of the represented paintings, our technology enables traditional crafts people to incorporate interactive, digital technology but still retain the qualities of painted fabrics. This way of merging digital and the real world allows us to explore this work as a new ambient media that combines digital technology and traditional craft [45].

There are numerous examples of ubiquitous technology in the household and beyond. Media furniture projects such as CREATUREs - Designing of Interactive Interior Lamps by Ueki et al. discuss interactive decor such as lighting, and how technology can be incorporated into the home [71].

Other works discuss the improvement of functionality and affection in the home. Works like The Pet Plant: Developing an Inanimate Emotionally Interactive Tool for the Elderly by McCalley and Mertens [48] look to improve various situations in the home. Our work with byobu looks to address the disparity between tradition and modernization by providing an application that marries both successfully. Thus this work looks to improve the aestheticism of technology and functionality of traditional craft art forms.

2.3 Dynamic Markers

Dynamic markers or 'dMarkers' is an attempt to combine our technology with Augmented Reality markers to add time dimension to the augmented reality marker. Using the same technology, but on paper, dMarkers animate markers to morph into different markers based on external stimuli. This section identifies the works related to the dynamic markers for Augmented Reality applications.

Most work related to Augmented reality, so far, has adhered to using static markers. However, there are few works that address the requirement of dynamic markers. In [46], the authors present a system to paint real objects in a virtual environment using AR. Here, for the interaction they use two different types of markers, physical and virtual. While the physical markers are used as usual AR markers to grasp and manipulate virtual objects, the virtual markers are used to enable changing of the size. A back projection system on an interactive table top system is used where the physical markers are placed. The virtual markers are projected on to the surface and thus are re-sizable virtually. However, they address the main issue of these 'projected' virtual markers as being unable to grasp and manipulate as normal AR marker.

Often, dynamic content is displayed on most AR markers. As pointed out in [54], some applications use AR markers to display various dynamic content on the AR marker based on various states [13]. Similarly, in [31] authors use a single marker to interact with different content with the application. The marker is used mainly to identify the position of the paper on which the marker is printed. As there is no particular way to change the marker physically, the content displayed on the marker is changed dynamically by the AR application.

In terms of the dynamic markers, some works use displays as the platform for changing the marker. In MagicMeeting [61] authors use a personal digital assitant that can display markers on its screen. In [39] the authors use a computer monitor to display different markers.

However, the use of such visual displays prevents the true ubiquity of these markers. Instead, here our main objective is to identify a dynamic marker technology that can actually allow the material itself to become the dynamic marker similar to the conventional paper based marker. Thus through the concept of dMarkers, such would be possible as the marker itself can be changed to suit various states based on the external stimuli.

2.4 Sensing

This section addresses the works related to developing a temperature based touch sensor. Thus, the presented work draws upon literature from textile displays, interactive textiles, and thermal sensing systems.

Most of these textile displays are limited in their interactivity and are limited to fixed animations. 'SMOKS' uses the user's hand temperature to trigger the color change naturally when touched. But, there is no active detection of touch but more of a passively triggered response by the thermochromic inks. A similar pattern is seen in Mosaic Textile where the touch changes the color on the textile due to the body heat. However, 'Emotional Wardrobe' [66] uses various sensors embedded on the textile to detect various emotional states of the user as the form of interaction. These sensors monitor various physiological data of the user and communicate with a central server. Next, they use various electroluminesence panels embedded in the clothing as the display. 'Cloth Displays' [43], where the display is projected on to the textile, use gesture interactions such as pinching, draping, stretching, etc. with the textile as the input. However, this work required seperate display and tracking equipment to be setup to interact with the textile. On similar grounds, Paper Windows [29] explore the use of projection and tracking method to implement computing on flexible materials such as paper. In 'Memory Rich Clothing' [10], the authors present the use of soft circuits that detect groping, touching, etc. Thus, on a series of LED indicators the information on how long and how hard these actions were performed are displays. Even though not a textile display, to detect touch input on textile, PocketTouch [63] presents a through-fabric capacitive touch input mechanism which interacts with mobile phones without having to remove them from the pocket. However, most of these methods require adding additional hardware on to the cloths display. Thus, next we discuss some works which use temperature as an input interface.

In [36], the authors use thermo infrared cameras setup behind a sensing surface to detect the finger temepratures to detect input. Similarly, HeatWare [41] uses digital thermal imaging cameras to detect, track, and support user interaction on arbitrary surfaces. However, the main limitations of both these works is the requirement of external equipment set up which is not suitable for our application. In ThinSight [26] the authors use an array of retroreflective IR to detect the touch on an LCD panel. However this too requires adding more hardware on to the surface of the textile which is not suitable for our context since the thermal actuators need to be in good contact with the thermochromic ink textile.

Depending on the contexts, most of these mechanisms require additional hardware to integrate sensing mechanisms. Since we focus on thermochromic ink based non-emissive textile displays, our main motivation is to extend the existing technology to facilitate the sensing through the same textile interface. Thus, in this thesis, as our contribution, we present a mechanism that uses the existing hardware of a thermochromic ink based textile display to detect touch input to add interactivity. This would allow the display and the sensing through the same textile interface depicting a low fidelity touch sensitive screen.

2.5 Summary

This chapter details the related works in the scope of textile displays, relevant attempts of merging technology and craft, dynamic augment reality marker technologies and ubiquitous touch sensor systems. As such, we identify key limitations in these areas and propose this textile display technology and its applications to overcome these limitations. We attempt this by, firstly, identifying the key technologies for this textile displays and implementing a wide range of prototypes and technologies that demonstrate the ubiquity of this technology. Therefore, our key contributions over the previous technologies can be summarised as follows.

- This thesis presents a comprehensive ubiquitous display technology that is embedded on fabrics using thermochromic inks as our display medium and Peltier semiconductor modules

- We combine the textile display technology with byobu to address the disparity between tradition and modernization by improving the aestheticism of technology and functionality of traditional craft art forms.

- We identify a dynamic marker technology that can actually allow the material itself to become the dynamic marker similar to the conventional paper based marker.

- We present a mechanism that uses the existing hardware of a thermochromic ink based textile display to detect touch input such that the display and the sensing occurs through the same textile interface depicting a low fidelity touch sensitive screen.

3

System design of the textile display

This chapter discusses the core implementation of the textile display technology. The section presents the choice of components and the detailed implementation methodology.

3.1 System Description

The overall system is depicted in Figure 3.1. The textile display system uses a combination of Peltier semiconductor modules and thermochromic leuco dye ink technologies to achieve a fast color changing display. These two technologies are combined together using a closed loop control system employing a PID (proportional, integral, derivative) controller in order to accurately control the Peltier temperature and thereby control the color. Next we describe in detail the workings of each main component of the system.

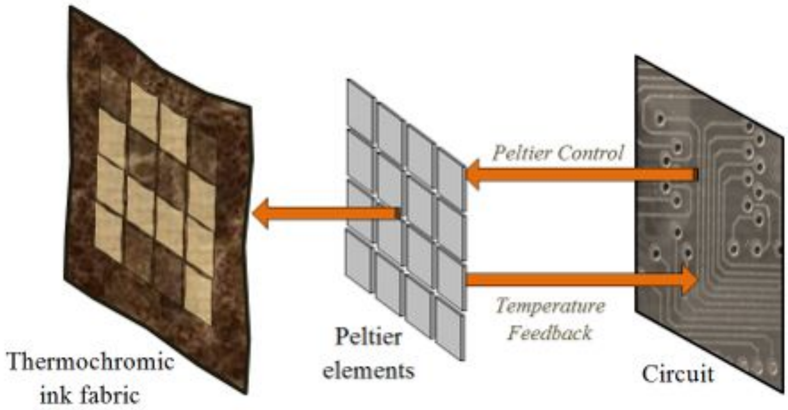


Figure 3.1: Overall system

3.1.1 Component Selection

3.1.1.1 Thermochromic inks

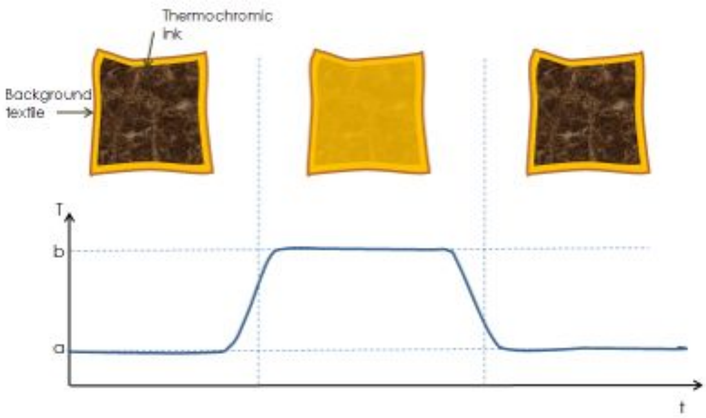


Figure 3.2: Thermochromic inks of actuation temperature range a^{0}C-b^{0}C: When temperature is higher than b^{0}C the ink becomes colorless. When temperature is lower than a^{0}C, the original color is achieved.

The textile display system uses thermochromic leuco dye inks as the display method due to its ease of implementation and high robustness. These inks work on the basic principle that, when their temperature is raised beyond their 'actuation temperature range', the inks become colorless. When the temperature is brought below the 'actuation temperature range' the ink regains its original color. Figure 3.2 illustrates this concept. For example, the ink we regularly used in our experiments is of 24^0C to 32^0C actuation temperature. It becomes completely colorless at 32^0C and regains the original color approximately around 24^0C. In between are gradual shades of the original color based on the temperature. However the color of these inks and the actuation temperature ranges can be customized for any specific requirements.

For scope of this work, we have experimented with off the shelf inks which are of 15^0C, 27^0C and 32^0C actuation temperatures and of colors such as red, blue, green, black and dark brown color. These inks are then combined with textile binder and screen-printed, making the fabrics more robust for everyday use. Even though most of the prototypes feature single color elements, we performed some multicolor experiments which are briefly discussed later in the Section 4.1.3.

3.1.1.2 Semiconductor Peltier Elements

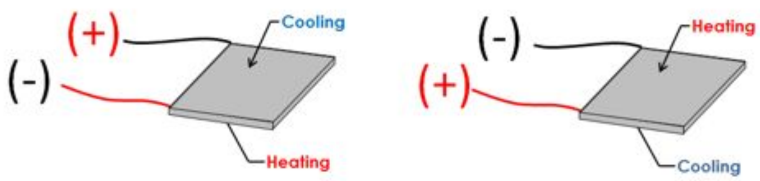


Figure 3.3: Reversing of supply voltage to reverse the heating/cooling function of Peltiers

As thermochromic inks are thermally actuated, we chose the Peltier semiconductor modules due to its rapid thermal actuation capabilities within a wide range of temperatures. Peltier semiconductors use the thermoelectric effect, i.e.

it creates a temperature difference across the module when a voltage is applied. Conversely, the temperature difference is reversed when the voltage is reversed. That is, when the voltage is reversed, the heating surface becomes the cooling surface as illustrated in Figure 3.3. This is a very useful feature in our work as it eliminates the requirement for bulky cooling systems as the heating and cooling occurs on the same surface of the module. Therefore we use Peltier elements as one of our main core technologies due to its ability to rapidly heat and cool the inks with minimal space constraints.

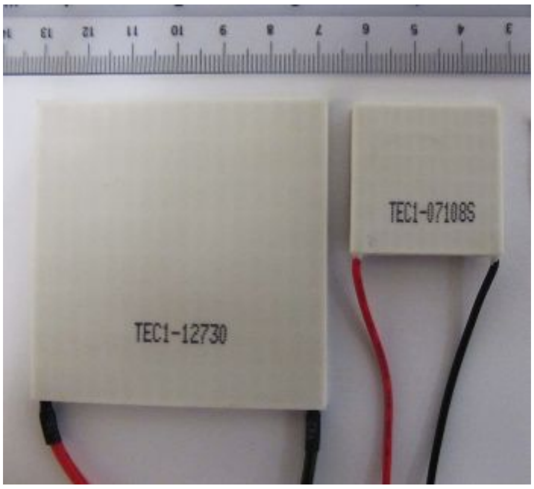


Figure 3.4: Different Peltier modules

Peltier elements come in various sizes which usually feature different operational characteristics. For the workscope of this thesis we have utilized Peltier elements of sizes, 60mmX60mm, 30mmX30mm and 15mmX15mm based on the context of the application. The Figure 3.4 show some of the used Peltier modules. The Table 3.3 describe the maximum specified characteristics of each Peltier element.

Peltier	Temperature Rate	Power
60mmX60mm	3^0CS^{-1}	20W
30mmX30mm	3^0CS^{-1}	10W
15mmX15mm	3^0CS^{-1}	5W

Table 3.1: Maximum characteristics of Peltier elements

3.1.1.3 Controller circuit

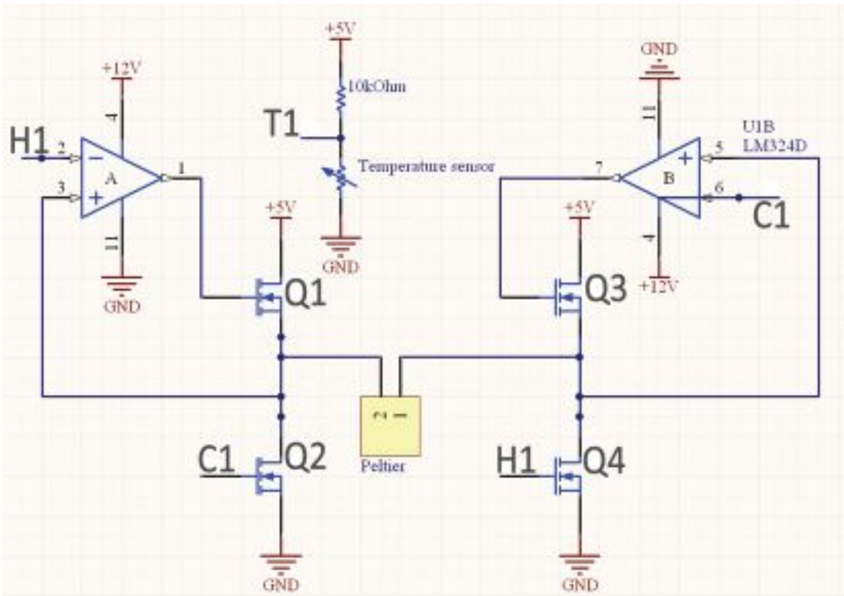
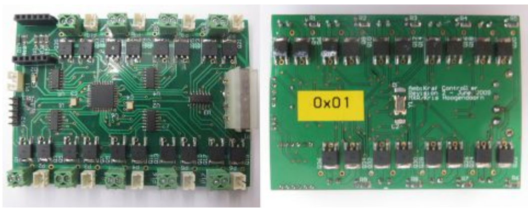
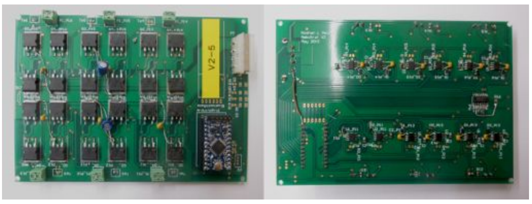


Figure 3.5: Controller circuit schematic

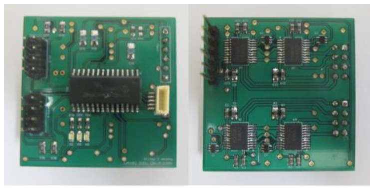
The basic controller circuit for one color changing pixel is shown in Figure 3.5. An H-bridge circuit was employed to achieve the change of direction of voltage applied on the Peltier element (Figure 3.5). The voltage direction can be changed in the forward or reversed directions by switching on the Q1 & Q4 while Q2 & Q3 are switched off or switching on Q2 & Q3 while Q1 & Q4 are switched off respectively. The switching on is done by a 100Hz pulse width modulated (PWM) signal, whose pulse width is controlled by the PID controller, in order to control the current through the Peltier element. U1, U2, U3 and U4 are MOSFETS



(a) Circuit 1 : 12cmx8cm circuit to drive 9 Peltier modules



(b) Circuit 2 : 15cmx10cm circuit to drive 6 Peltier modules



(c) Circuit 3 : 2.5cmx2.5cm cascadable circuit to drive 4 Peltier modules each

Figure 3.6: Front and back views of implemented circuits

(metal-oxide-semiconductor field-effect transistor) which have been selected based on the maximum current that is required by the Peltier module. Based on the prototype application, MOSFETs of different specifications have been used to match the specifications of the prototype's Peltier element. The MOSFETs are selected according to the maximum current required by each Peltier element.

To control the temperature of the Peltier element a temperature sensor is placed on the surface of the element. This closed loop feedback allows the controller to implement a fine tuned PID controller. In Figure 3.5, the labels H1, C1 and T1 are connected to the microcontroller. H1 and C1 are switched to control the Peltier element using PWM as mentioned above, the T1 is the temperature feedback from the NTC (negative temperature coefficient) temperature sensor that is read by the microcontroller. The temperature sensor used in here is Murata NTSA0XV103FE1B0 NTC 10kOHM thermistor.

As we use different Peltier elements for different applications, we have implemented different versions of the controller circuit, but with the same setup discussed above. The Figure 3.6 show different versions of implemented circuits (with different specifications) using the same described basic driver module. (For circuit schematics and PCB layouts please refer to the Appendix). The Table 3.2 describes useful specifications of each circuit.

Circuit	Microcontroller	No. of Peltiers	Maximum Peltier size
1	PIC18F4620	9	30mmX30mm
2	Arduino Pro Mini	6	60mmX60mm
3	PIC18F2620	4	15mmX15mm

Table 3.2: Circuit specifications

3.1.1.4 Firmware

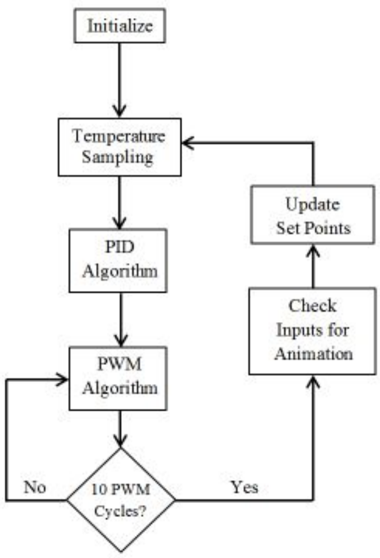


Figure 3.7: Overview of the firmware algorithm

The overall firmware algorithm flow is illustrated in Figure 3.7. The algorithm mainly consists of the PWM algorithm with dead time, PID algorithm with temperature sampling and animation controls. Next, we briefly describe each of these steps.

PWM Algorithm : We use two PWM pins for each Peltier module as described in the Section 3.1.1.3. PWM is calculated to an integer value between -100 and +100 where negative values indicate cooling and positive values are for heating. Since most microntrollers do not have multiple in-built PWM output pins, we use our own technique to produce multiple PWM signals. This is achieved by using internal timers and timer interrupts of the microcontroller. We set the internal timer interrupts to occur every milisecond. Next, with every timer interrupt we increment a counter variable and check the PWM value for each element. If the counter value is less than the absolute PWM value the relevant cooling/heating pin is set high and if else, it is set low. For example, if the PWM value is -40 and the counter variable is 32, the cooling pin for the relevant Peltier is set high while the heating pin is set high. This is illustrated in Figure 3.8. Once the counter passes 40, the cooling pin is set low. Once the counter variable reaches 100, it is reset to 0 and would have completed one full PWM duty cycle. With few such cycles, we read the temperatures and calculate and update the PWM values. This is done for all the Peltiers allowing us to use any digital output pin as a PWM pin.

Dead Time : By default, when the above counter variable is set to 0 upon reaching 100, all pins would be set high since each absolute PWM value is more likely to be greater than 0. This would cause all Peltiers to be turned on (heat or cool) causing a high current to be drawn instantaneously to the circuit possibly causing damage to the circuit. To avoid this, we implement a few milisecond

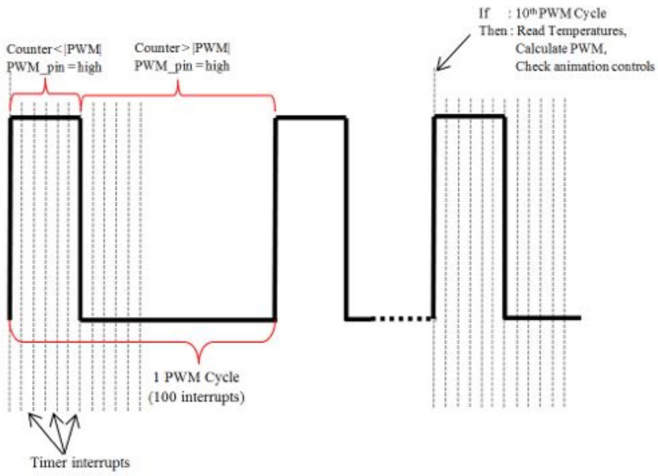


Figure 3.8: PWM Algorithm concept

delay between the PWM cycle starting point for each Peltier element as seen in Figure 3.9. This would result in a step wise increment in the drawn current instead of a instantaneous high current protecting the circuit and its components.

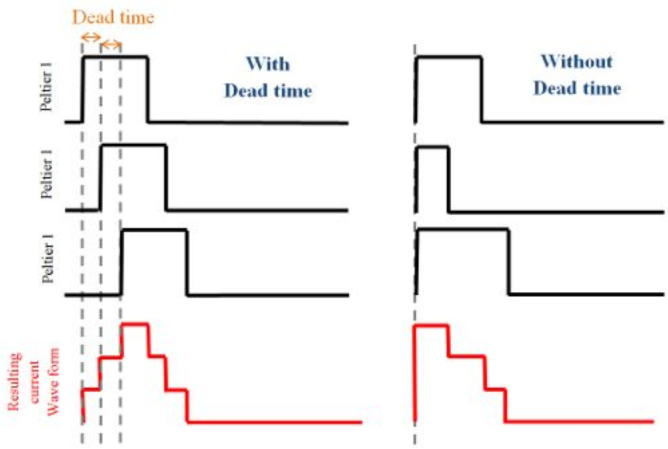


Figure 3.9: Dead time

PID Algorithm : With the completion of few duty cycles the algorithm reads temperatures of all modules. Each time all the readings are done, the controller calculates the proportional (P), integral (I) and derivative (D) terms for each of the modules using the following algorithm.

$$
\begin{aligned}
e &= sp - temperature \\
P &= k_p \times e \\
I &= I + (k_i \times e \times dt) \\
D &= k_p \times (e - p_e)/dt \\
p_e &= e
\end{aligned} \tag{3.1}
$$

where, e - error, sp - set point, dt - sampling time (time interval between two samples), P_e-previous error, k_p - proportional constant, k_i - integral constant, k_d - derivative constant.

By changing the value of the set point of a certain Peltier element the pixel can change color to become colorless or regain the original color. For example, if the thermochromic ink with a 24^0C to 32^0C is used, the set point can be changed to 33^0C to make the pixel colorless or 23^0C to make the pixel the original thermochromic ink color.

Animation controls : Animation controls are used to program the output animation of each pixel. This programmability defines the animation of each pixel of the display by selectively setting the set points of each pixel to change color based on the application context. For example for a constant animation, firmware can change the set points of each Peltier module in a sequence or for interactive animation, an input from an external sensor (eg.proximity sensor) can be used to trigger the animations. Some experimental results of this animation programmability in implemented prototypes are discussed in Chapter 5.

3.1.1.5 Tuning the PID controller

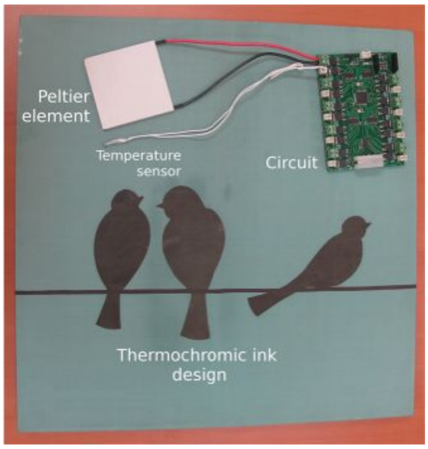
It is essential to tune the PID controller to achieve the best desired results for the system. Here, our goal was to minimize the rise time and fall time for the controller to achieve high speed temperature change in order to achieve high speed color change of the thermochromic ink. In addition, this process helps us to optimize the power usage of the system where once the required temperature is reached, the system draws only a minimal amount of current to maintain the temperature at the required temperature. These results are discussed in Chapter 4. To tune the PID controller we used a heuristic method named the Ziegler-Nichols method [72]. With this method, we first increase the k_p value until it reaches k_u where the system reaches an oscillating state while having the k_i and k_d values at zero. Once we achieve this state, the k_p, k_i and k_d values are set as follows (p is the oscillation period).

Controller	k_p	k_i	k_d
PID	$0.6k_u$	$2k_p/P$	$k_pP/8$

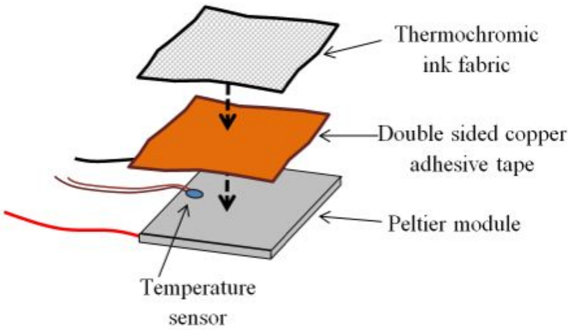
Table 3.3: Ziegler-Nichols tuning method for PID controllers

3.1.1.6 Integration

To construct a color changing pixel, the system contains few different elements that need to be carefully put together. The main basic elements of the system are shown in Figure 3.10(a). To integrate the system together, we initially mounted the temperature sensor on the Peltier element using a copper adhesive tape (Figure 3.10(b)). The copper adhesive tape allows efficient heat transfer between the Peltier element, temperature senor and the fabric in that area. The Peltier ele-



(a) Main elements of the system (one Peltier element and temperature sensor connected to the circuit)



(b) Setup of a single pixel of the system

Figure 3.10: Integration of the system

ments are attached to the fabric by a thermally conductive adhesive which allows efficient heat transfer between the fabric and the element (Figure 3.10(b)). We have tested this implementation setup on several different types of fabric ranging from silk to cotton which produce similar results. This is the most common technique that has been utilized for the prototypes discussed in the next chapter.

3.2 Summary

This Chapter presents the implementation details of the textile display system. Here, we have detailed the main elements of the system: thermochromic inks, Semiconductor Peltier elements, implementation of the control system, firmware algorithms with tuning the controller and the integration methodology. Thus, through this Chapter, we intend to identify the basic and key technology elements of the textile display system and that can be customized and refined as per different usage scenarios.

4

Evaluation of the system

In this chapter we focus on the technical results of the system. The technical results were focused to observe the system's performance in terms of the temperature controller, color controllability and power consumption.

4.1 Technical Analysis

The temperature and color results of the system were observed with the use of one of the temperature sensors of the circuit and an external industrial color sensor. As the color changing fabric, a prototype of a wall hanging art that was printed with thermochromic ink was used. The system testing setup is shown in Figure 4.1. The following are the main characteristics of the tested system

- The thermochromic ink used here has an actuation temperature range of 24^0C to 32^0C. In addition most of the results focus only on single color display. A brief study into a multicolor display is addressed in a later subsection.

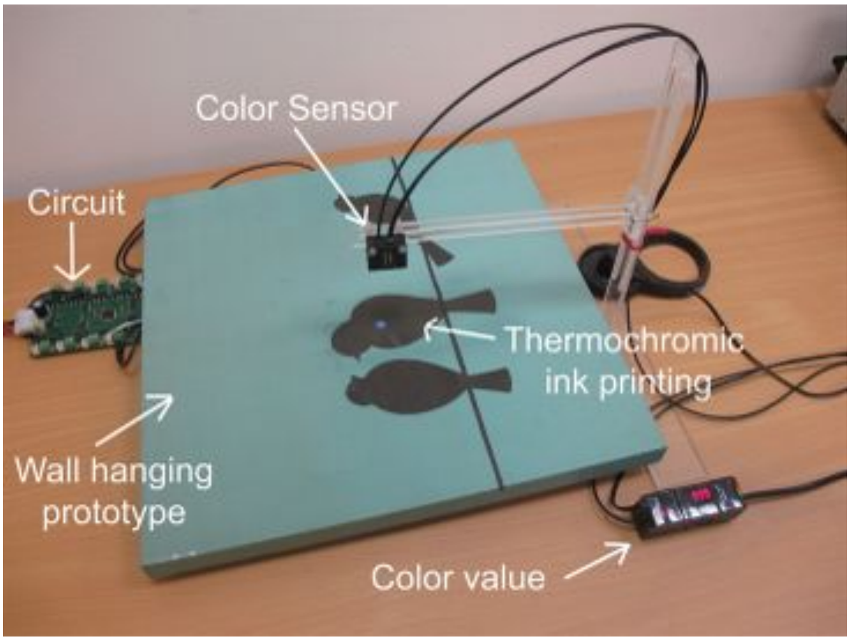


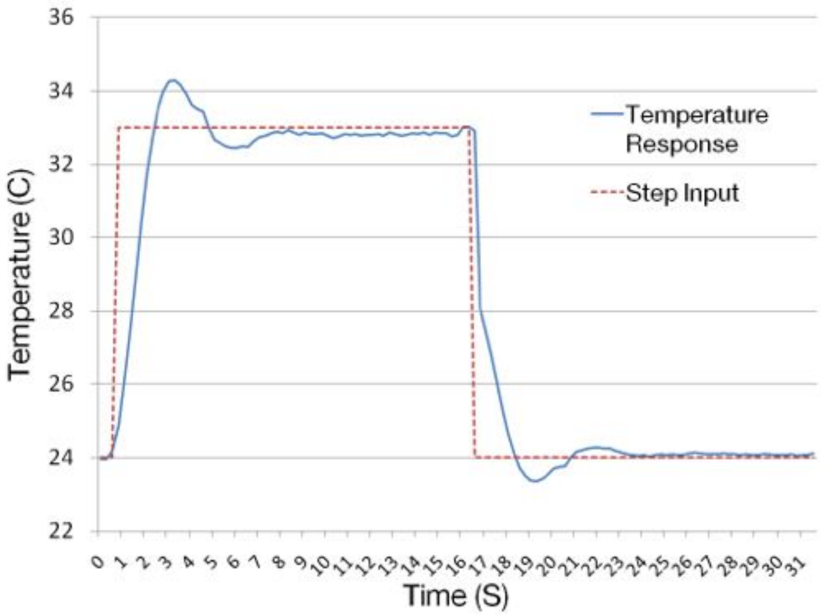
Figure 4.1: Setup of the system for testing using a wall hanging prototype

- The fabric used in this analysis is the common taffeta silk fabric and the ink was screen printed on to the fabric. (The birds have been printed in brown color thermochromic ink on the light blue fabric).

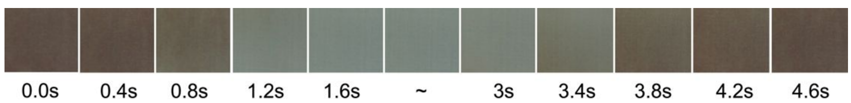
- The Peltier modules used in this case is of 60mmX60mm, 30mmX30mm and 15mmX15mm size. The results have been averaged, since all Peltier elements show similar results for the Temperature and Color Controllability Results. However, we have compared each Peltier module individually for the Power Characteristics Analysis.

It should be noted that all the experiments carried out are focused on the current implementation of the system. That is, the temperature ranges of the system are essentially to match the actuation temperatures of the thermochromic ink that is commonly used in most of our prototypes, thus, approximately between

20^0C to 35^0C.



(a) Temperature transient response of the system



(b) Resulting color change of the (when triggered from ‘color’ to ‘colorless’ state and back)

Figure 4.2: Color transient response of the system

4.1.1 Temperature controllability

The transient response of the implemented PID controller is shown in Figure 4.2(a). As observed, the rise time of the system is approximately 2s (to reach from ambient temperature of 24^0C to 32^0C). In addition, the fall time of the system too approximates to 2s which is an important characteristic. This ability of the system to rapidly cool-down the fabric allows the thermochromic ink to rapidly regain the original color hence allow subtle bidirectional animations on fabric. Figure 4.2(b) indicates the color change during this process.

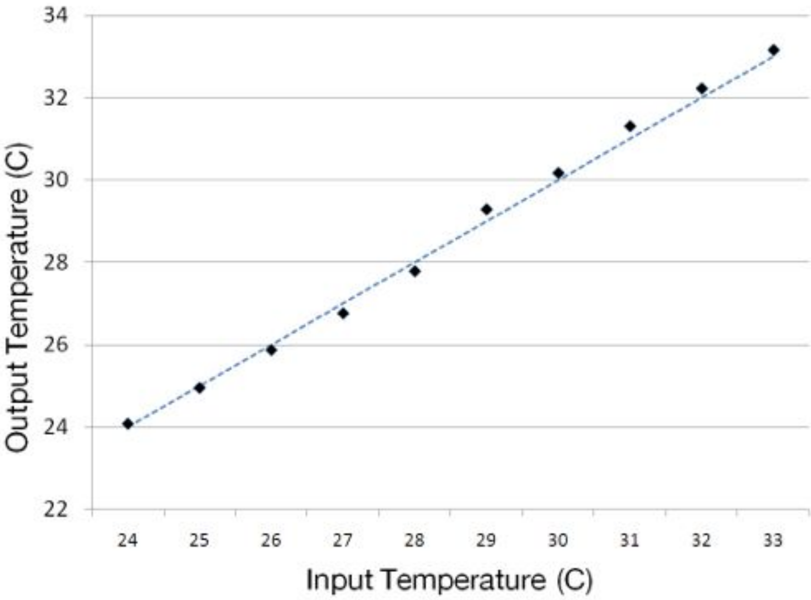


Figure 4.3: Static temperature response of the system

The curve in Figure 4.3 depicts the steady state errors of the system. As observed here, the temperature controller is able to control the temperature within an accuracy of approximately 2% ($\pm 0.3^0$C) for the given temperature range. This is an acceptable indication of the controllability of the temperature and hence the controllability of the color.

4.1.2 Color controllability

Just as Figures 4.2(a) and 4.3 are evidence of the accurate temperature controllability of the system, we conducted experiments to check the actual color controllability of the system. For this purpose we used a KEYENCE(R) CZ-H32 color sensor with its CZ-V21A amplifier. This sensor unit displays the degree of correspondence between the target color calibrated as a reference, and the target color currently being detected. The value read as a result is the reflected light intensity effected by the target color. For our purpose, we calibrated the reference color to be the color of the thermochromic ink. For readability, the values are displayed in a normalized form where 0 is the color of the thermochromic ink and 1 is the color of the fabric.

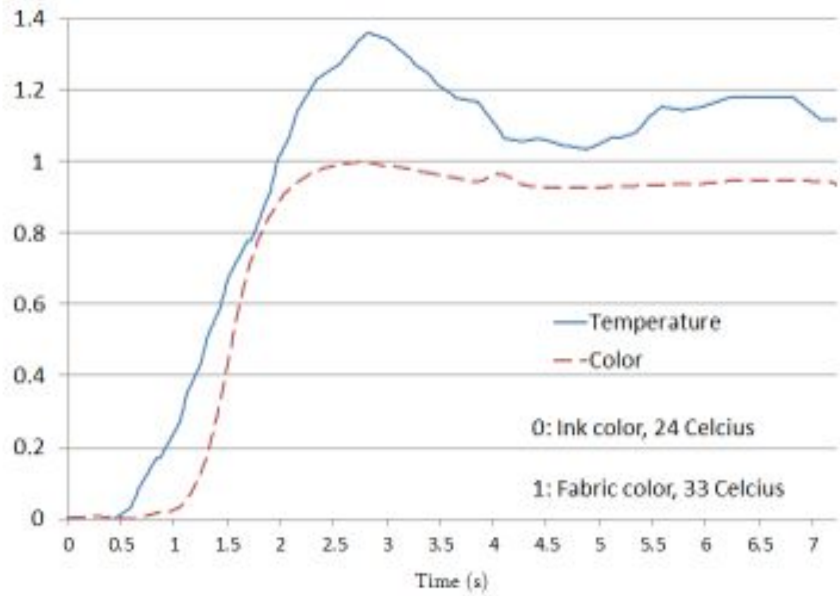


Figure 4.4: Color and Temperature transient response of the system

Figure 4.2 depicts the color change resulted by the temperature change of the Peltier element. The normalized temperature values of Figure 4.4 indicate 0 as the temperature at which the ink regains its full color, i.e 24^0C and 1 as the actuation temperature i.e is 33^0C. As expected the temperature curve leads the color curve which is an indication that the color change is triggered by the temperature. The temperature curve settles slightly higher than 1 since the target temperature has been set to slightly above 32^0C at 33^0C to ensure the color change. In addition, once the ink becomes completely colorless it still leaves a small quantity of 'colorless' residue of the ink behind which could be observed upon close inspection. Hence, it could be observed from Figure 4.4 that the color curve settles slightly below 1 (1 is the fabric color).

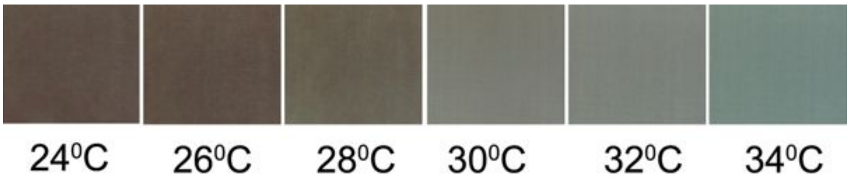


Figure 4.5: Actual color output against various temperature settings

Figure 4.5 indicates the actuated color of the fabric for the respective temperature settings. This is indicative of the color controllability. It should also be noted this may change across various color or across various manufacturers of the ink.

4.1.3 Multi color display study

As an additional study we conducted an experiment on using several colors as a multicolor display. Thermochromic inks of Red (15^0C), Blue (31^0C) and Green (37^0C) were mixed together in equal quantities, combined with textile binder and screen printed to on a yellow colored fabric. Upon changing the heat applied to this combination of colors, each ink would individually be activated revealing the remaining colors. The resulting color changes are shown in Figure 4.6. Hence upon heating up (increasing the temperature) red would be colorless as red has the lowest actuation temperature. And subsequently blue and green would be actuated ultimately revealing the base fabric color, yellow. One draw back of this method is that when one color is actuated the combination of other colors are revealed instead of a single color. Additionally, actuating of a color directly is not possible as when the temperature moves up or down across to the desired temperature each color would be actuated in a sequence.

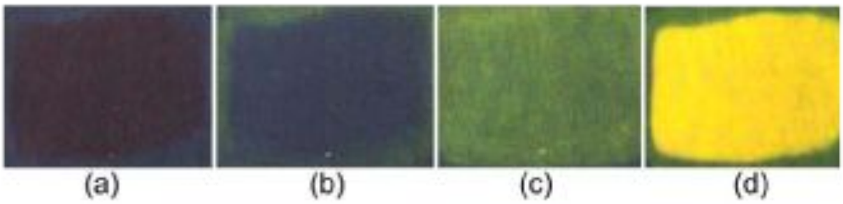


Figure 4.6: Actuation of the multi-color display (a) Red (at 14^0C) (b) Blue(at 25^0C) (c) Green (at 35^0C) (d) Yellow- color of the base fabric (at 37^0C)

4.1.4 Power characteristics of the system

Next, we conducted a detailed analysis of the power consumption characteristics of the textile display system. This is of great importance for the future applications in developing this project further. These studies were conducted at a constantly maintained room temperature of 24^0C.

Figure 4.7 depicts the power consumption characteristics of the system for 60mmX60mm Peltier module during its steady states (Curves 2 and 3) and during actuation to change from color to colorless and colorless to color states every three seconds (Curve 1). As seen in the Curve 1 the peak power consumptions occur when the transition happens from one state to the other as power is drawn to either heat or cool the fabric. The RMS (root mean square) power consumption over the 10s period for continuous actuation is 21.04W. In addition, it is important to note that once the temperature has reached the set point and in-turn the system has reached the stead state, the power consumption is significantly lower compared to the transient states. This implies the working of the PID controller

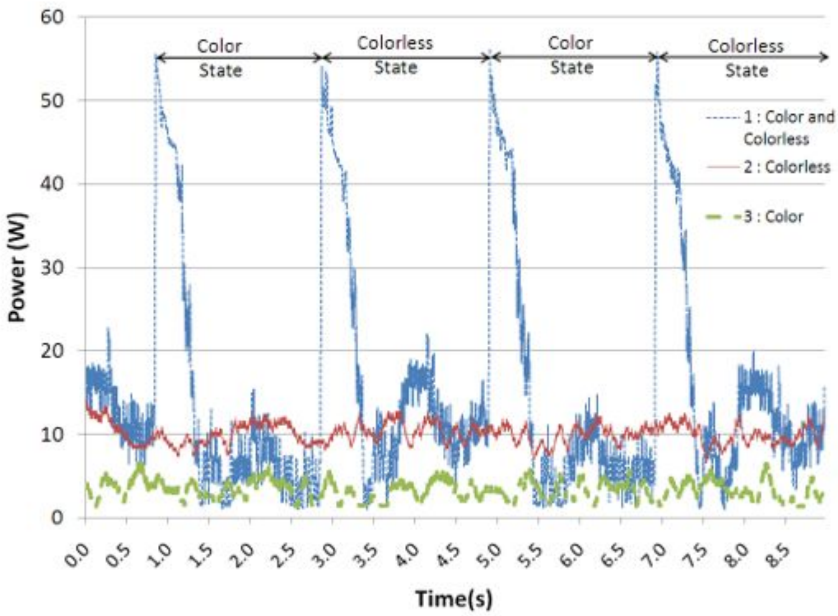


Figure 4.7: Power consumption characteristics for switching between 'colored' and 'colorless' states (Curve 1), Steady state Colorless (Curve 2), Steady state Color (Curve 3)

where the power consumptions are optimized between states.

Curve 2 of Figure 4.7 depicts the colorless state at which the temperature of the fabric is maintained at approximately 32^0C. The RMS power consumption during this state is 10.51W. The RMS power consumption during the 'color' state (temperature maintained at approximately 24^0C) is 6.87W. The reason for the difference of these results are due to the fact that the 'color' state is more closer to the room temperature hence the power required to maintain this temperature (24^0C) is lower.

Similarly, the Table 4.1 summarizes the power characteristics for the other Peltier elements (The results have been obtained to maintain the similar transient profile using all Peltier elements)

Figure 4.8 details the different levels of power required for maintenance of

Peltier	Continuously transient between 24^0C - 32^0C	At 32^0C	At 24^0C
60mmX60mm	21.04W	10.51W	6.87W
30mmX30mm	8.43W	3.24	2.65W
15mmX15mm	4.69W	1.78W	1.12W

Table 4.1: RMS Power Characteristics of Peltier elements

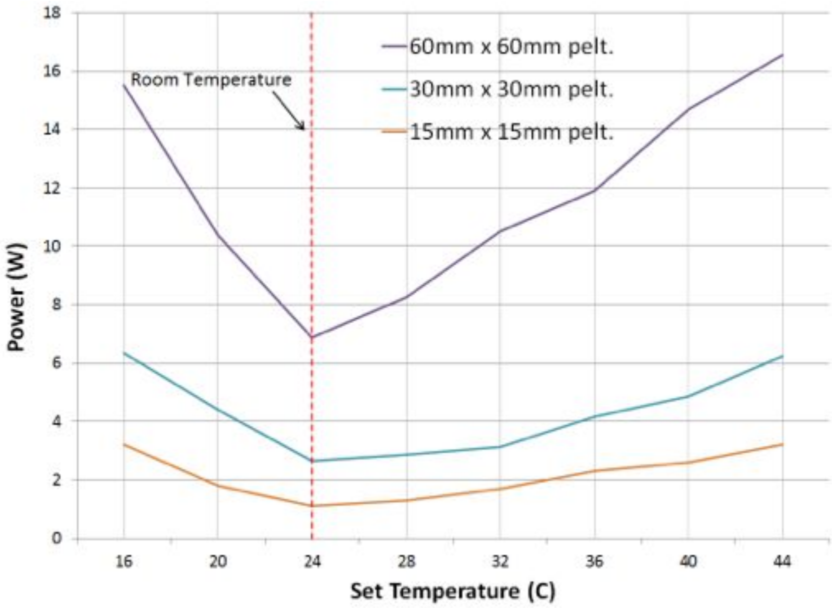


Figure 4.8: Steady state power consumption

different temperatures. This is a clear indication that if the actuation temperature of the thermochromic ink is closer to the room temperature, the power required is less. In this case the lowest point was recorded at 24^0C for all Peltier elements.

4.1.5 Initial prototype test

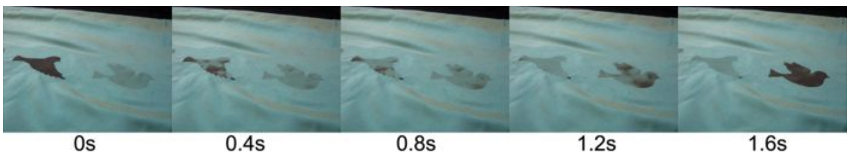


Figure 4.9: Prototype test of a bird animation

After finalizing the system a prototype of an animated fabric was implemented as shown in Figure 4.9. Here, two bird patterns printed with thermochromic inks were used with the Peltier elements and the controller. As seen in the picture the system was able to animate the birds in a very calm and subtle way to depict an animation of the bird flying.

4.1.6 Experimenting with different temperature ranges

As we have seen here the temperature controller can actuate the temperature relatively faster than the previous works. As mentioned before, the temperature range was selected based on the off the shelf inks that were used for the experiment. However, to extend this experiment further, we analyse the speed and power characteristics for different temperature ranges. Having this knowledge would be helpful in customizing the thermochromic ink actuation temperature ranges to achieve specific speeds of color changes, and limit power requirements.

To conduct this experiment, we selected a mid point temperature and the two set points for colored and colorless states were set in multiples of 2^0C equally above and below the mid point (For example if the mid point was 25^0C, the first set of set points 23-27^0C, next 21-29^0C, followed by 18-31^0C). Next, we observed the transient and settling times and the power characteristics for each of these system for heating and cooling. Then, we repeated these results for mid point temperatures of 20^0C, 25^0C, 30^0C and 35^0C. Table 4.2 shows the used temperature details. The Peltier modules used in this case were 15mmX15mm only. This was since the main goal of this experiment was to identify the characteristic behavior for different selected temperature ranges. Therefore, through our experience from the previous results, we can extrapolate these results to other the other Peltier modules.

Mid Point	ΔT	Low set point	High set point
20	4	18	22
20	8	16	24
20	12	14	26
25	4	23	25
25	8	21	27
25	12	19	29
30	4	28	32
30	8	26	34
30	12	24	36
35	4	33	37
35	8	31	39
35	12	29	41

Table 4.2: Temperatures for temperature range experiment

4.1.6.1 Speed of color change

The Figure 4.10 shows the speeds of transient and settling times. As observed, the transient times are faster for smaller temperature ranges. This is also true for the settling times which are slightly higher than the transient times but settle faster for smaller temperature ranges. In addition, one of the key characteristics that can be observed through this study is that the transient and settling times are similar for same temperature ranges irrespective of the mid point temperature.

4.1.6.2 Power characteristics

The Figure 4.11 shows the power characteristics for power requirements for continuously transient states between the two set points for different temperature ranges. As it can be observed, the required power is higher when the temper-

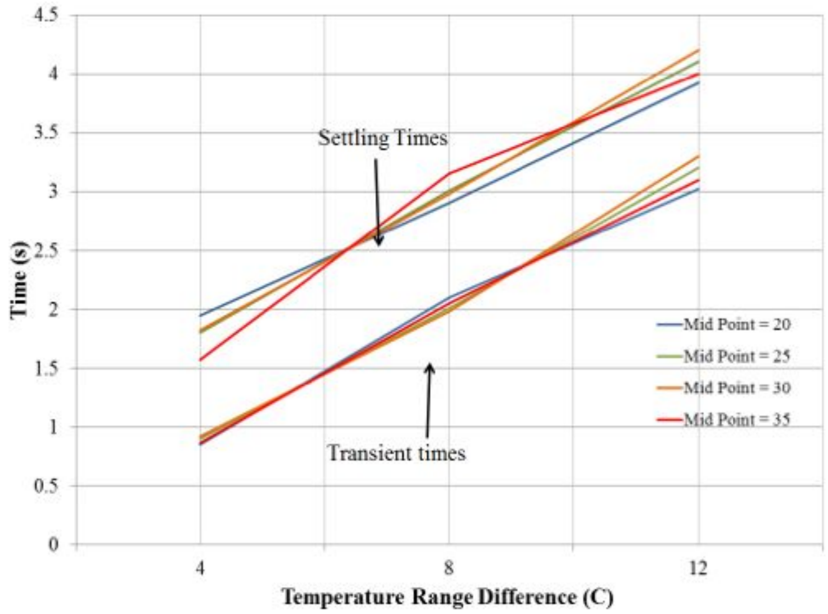


Figure 4.10: Transient and Settling times for different temperature ranges

ature difference between the set points are higher. However, the steady state power for each of the temperatures can be inferred from Figure 4.8

4.2 Discussion

A summary of the technical results for the current implementation of the system is as follows

- Speed of temperature control : Approx. 3-4^{0}C/per second
- Time taken for color change of inks used in the fabric : Approx. 2s
- Animation speed : Approx 0.7FPS

As seen in this chapter, we present the results as an analysis of the performance of the controller and the resulting color changing capabilities of the fabric. From

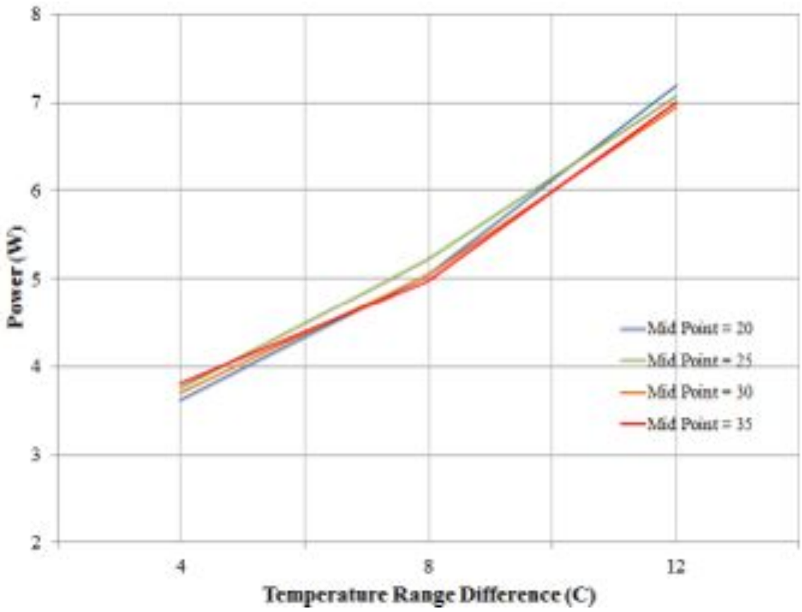


Figure 4.11: Power requirements for continuously transient states between two temperatures

these early workings of the system it is evident that a considerably fast color change can be achieved by heating and cooling the fabric at rapid rates. As mentioned this allows an approximately 0.7 frame-per-second animation on the fabric. However the speed could be increased by choosing an ink that has an actuation temperature range closer to the ambient temperature.

However the current system has a few drawbacks such as the high power consumption and the inflexibility of the Peltier elements to be integrated with the fabrics .

4.2.1 Power consumption

The power consumption characteristics show a relatively high power requirement for the system. This is mainly due to the fact that the current Peltier modules are large in size and also due to it being less efficient [25]. However if this technology was to be used in a mobile or a more miniature sized context the current power consumption issues will posit a considerable challenge.

Currently to overcome these issues we discuss the possibility to minimize the power consumption of the system by using smaller size Peltier modules in Chapter 7). In addition, as observed in Figure 4.8 the set points close to room temperatures can minimize the power requirements. Thus, customizing the actuation temperature range to be smaller and closer to room temperature can significantly reduce the power requirements.

4.2.2 Flexibility

As one of our main goals is to make this technology wearable, it is important to preserve the wearability of the fabric. The Peltier modules we use currently are covered using rigid ceramics. This ceramic layer, while providing a protective layer to the Peltier module, presents a rigid interface of the Peltiers making it inflexible. This is a grave issue when considering the usage of fabrics. The fabrics are usually flexible and this main characteristic would be lost if integrated with such inflexible Peltier modules. Thus, in the Chapter 7 we discuss a proposed solution of using miniature Peltier elements to overcome some of these issues.

4.2.3 Heat dissipation

Functionality of a Peltier element is such that when one side heats the other side of the Peltier cools and vice verse. Therefore when cooling the top side of the Peltier , we use heatsinks to remove excess heat from the bottom side Peltier element. This is one of the key disadvantages of the current system. However we discuss the option of using miniature Peltier elements in the future which would help reduce this limitation in Chapter 7

4.3 Summary

This Chapter details the in-depth technical analysis of the system. As such, we discuss the temperature/color controllability of the system, power characteristics of the system and an initial prototype test. In addition, we have conducted a temperature range study which could be beneficial in future applications where the temperature of the thermochromic ink can be customized. Next we discuss the main results of the system and some limitations.

5

Prototypes and Applications

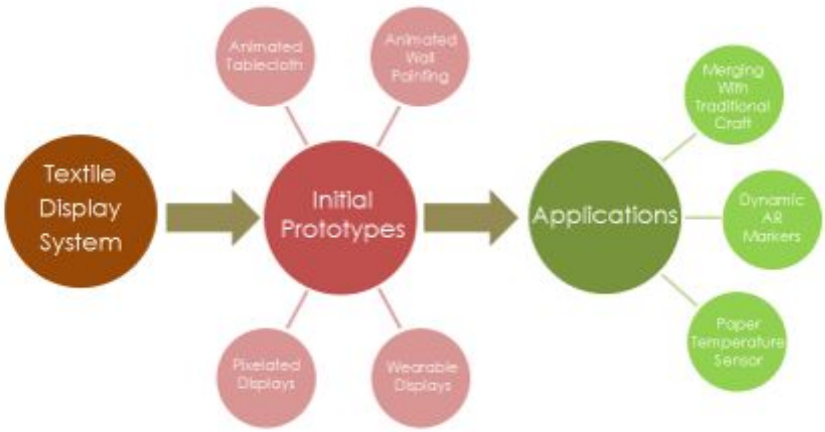


Figure 5.1: Summary of implemented prototypes

This chapter presents some of the initial work and applications that can use our textile display system. We built a range of prototypes as summarized in Figure 5.1 to explore characteristics such programmability, animateability, and ubiquity of the textile display system. As such, we present some initial prototypes that suite various contexts and situations. Next, we present and evaluate three different applications that have been derived out of the color changing technology.

5.1 Initial Prototypes

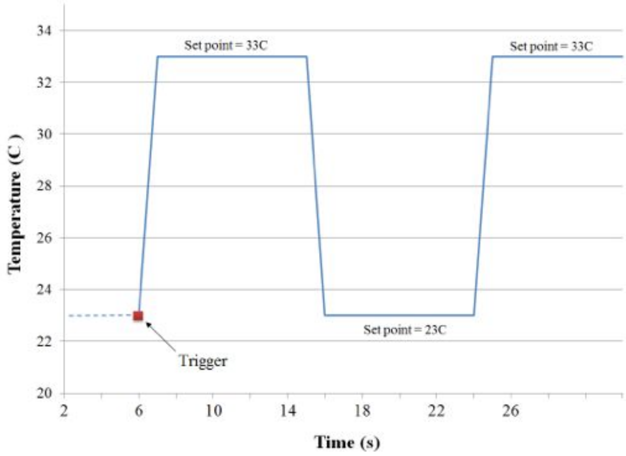
Several prototypes were designed and implemented to explore the capabilities of the textile display system. For these prototypes a range of Peltier elements from 60mmX60mm down to 15mmX15mm have been used. The selection of Peltier elements for these prototypes were based on the context and the application of use. I.e., in certain applications larger Peltier elements up to the size of 60mmX60mm were used to actuate whole images as pixels, while, smaller elements were used to formulate single pixels for pixelated displays and improve the flexibility of the textile. The following are some of such application prototypes.

5.1.1 Furniture garments using textile display

As a decorative piece, we initially created a wall hanging painting that would animate a bird on the painting once a person steps closer to it. The bird in the middle is printed with thermochromic ink and two 60mmX60mm modules are attached behind it. Using an infrared proximity sensor, a person's presence is detected and the animation is triggered to change the set point as indicated in Figure 5.2(b). This would make the bird in the middle to appear and disappear in a subtle manner.

Next, we implemented an animated table cloth that which has a subtle animation of a bird flying across the table when activated (Figure 5.3). This work used 60mmX60mm Peltier elements embedded behind each bird as seen in Figure 5.3(a)(c). The Figure 5.3(a)(b) indicates the table cloth when de-activated with all the the birds appearing and Figure 5.3(a)(c) shows the animation in progress. The Figure 5.3(b) shows the programming the set point to display the

(a) Image sequence of an animated wall hanging painting using the textile display system



(b) Programming the set points for the wall painting animation

Figure 5.2: Animated wall painting

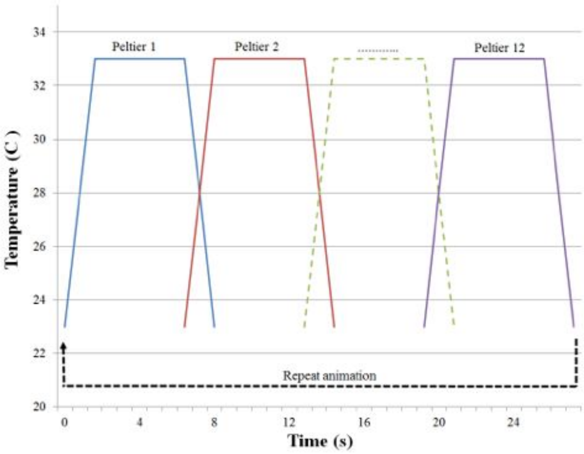
animation. As observed, the subtle animation is achieved by carefully starting each Peltier is set to turn on as the Peltier before it is turning off.

Both prototypes used thermochromic inks of 24^0C-32^0C actuation temperature range.

5.1.2 Pixelated displays

The Figure 5.16 shows a multicolored pixelated display. This 5X5 pixel display currently shows an animated clock using 30mmX30mm Peltier elements and a multicolor display which uses a combination of green (37^0C) and red (15^0C) inks

(a) Animated table runner (a) Animation of the flying bird (b) Table runner switched off displaying all the birds (c) Setup of the table runner



(b) Programming the set points for the table runner animation

Figure 5.3: Table runner system

on a white fabric base.

5.1.3 Wearable displays

Figures 5.5(a) and 5.5(b) depict the time lapsed images of some early versions of wearable applications as a single pixel display and a pixelated display respectively. In the single pixel display, the heart image is animated to turn on and off randomly. The pixelated display depicts various animations such as the hearts moving in circles from the center to the boundary of the display. The

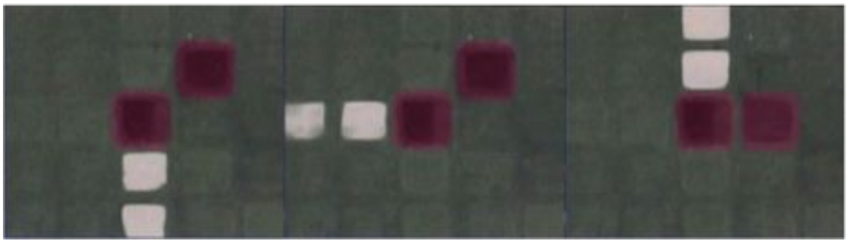


Figure 5.4: Low resolution pixelated display

Figure 5.5(c) indicates few different scenarios we envisioned such as identifying the context and displaying appropriate messages such as "Hi" or smiley faces. However, these prototypes could only be operated for a short time (a span of few minutes) with batteries due to the high power consuming nature of the Peltier. Some of the solutions for this are investigated in the Chapter 7.

5.1.4 Discussion

The prototypes described in the above section discuss some of the early prototypes that uses the color changing textile display. The prototypes range from applicable areas from stationary furniture/decorative pieces to smaller scale wearable/mobile applications. In addition, we showed the possibility of animation of fixed patterns and pixelated displays. By observing the resulting prototypes, it was quite clear as to how this fabric technology can ubiquitously blend with our everyday objects. The wall hanging piece and the table runner are everyday objects such as a regular wall painting or a table cloth. However, with this technology such have become a medium of display, yet subtly blending to the background.

In addition, we presented examples of how the set points can be programmed in order to manipulate the animation of the textile. Thus, the ability to simply program for random animations or animations to be triggered by external sensors

(a) Tshirt with a single wearable animated pixel

(b) Tshirt with a pixelated wearable display

(c) Scenarios of the wearable system

Figure 5.5: Wearable applications of the textile display

indicates the programmability of the textile display system.

5.2 *Applications* : Merging textile display technology with Byobu

In the previous chapters we introduced a non-emissive color changing fabric technology. This technology, leverages on current trends in ubiquitous and pervasive computing and it incorporates the framework set out by OUIs [27], where the "non-planar displays... actively or passively change shape via analog physical inputs [28]." In the case of the technology, change occurs in the very fabric itself, and in terms of the color of the ink. Thus it enables smooth color changes on the fabric depicting subtle animations on the fabric surface. Leveraging on these 'organic-like' qualities of this technology, we present an interactive Byobu (Japanese room divider) installation that uses textile animation as a mode for interaction.

5.2.1 Byobu

Room dividers or screens known as Byobu were an indispensable piece of furniture in the homes and temples of Japan from the 9th Century [23]. These paneled free standing screens served various purposes from being backdrops during tea ceremony and weddings to racks for clothes and for privacy at homes. Natural landscapes were the most common paintings depicted on these screens, sometimes accompanied with a 'waka' poem. Being paintings, they can only evoke a sense of the passage of time even though nature in its very essence grows and dies continuously in a cycle, reminding man of the temporality of life and existence [20].

Our work explores ways in which boundaries between physical and virtual, static and dynamic, material and immaterial can be blurred through everyday textile craft artifacts. Here, the fabric is an analog media which combines with the contemporary digital technology [44]. Thus, our technology enables the fabric itself to change the color. Therefore the interaction happens on the actual fabric itself and not with any other material or display that is embedded on it. This is a key property we identify in the merging of this technology and the traditional craft as it helps preserve the integrity of the actual fabric and allows users to interact with the actual fabric itself. This property preserves the organic qualities of the textile and the craft. Therefore, the textile medium is the mode for input and output.

5.2.2 Technology

5.2.2.1 Color changing technology

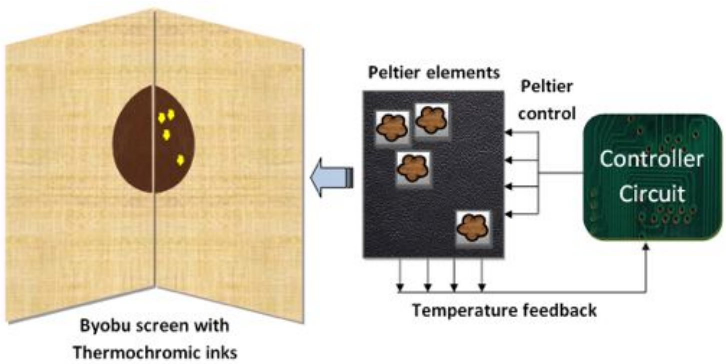


Figure 5.6: Overall system

The Byobu animates flowers that randomly appear and disappear and three butterflies that are triggered by the interaction. In this prototype we use flowers and butterflies to recreate a sense of nature on to the byobu furniture. Japanese

Byobu screens are mostly used in home settings which depict beautiful art works of landscapes. In this Byobu installation, we intend to use this same metaphor but enhance the experience by making these landscapes dynamic and interactive. Hence with an animation of various flowers that calmingly appear and disappear on the face of the Byobu screen, we hope to engage the user with the nature's uncertain natural phenomena such as the blossoming of a flower.

The overall color changing system is depicted in Figure 5.6. The system uses the same technology described in the earlier chapter with minor changes (adding copper moulds) to achieve the color changing byobu screen with Peltier modules and thermochromic inks.

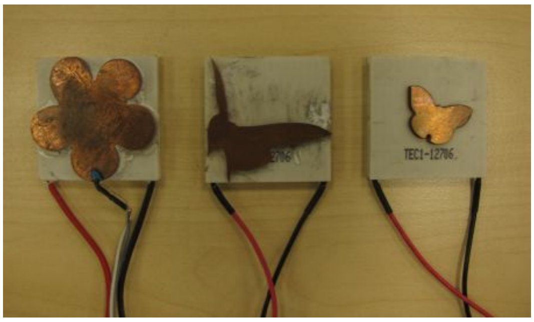


Figure 5.7: Peltier elements with copper patterns

The interaction details are discussed in the next section. Each of these patterns are controlled by a single Peltier element each. For this purpose we use 30mmx30mm Peltier elements. Since Peltier elements are square shaped, the patterns of the flowers and butterflies were obtained by 1mm copper moulds attached to each Peltier as shown in Figure 5.7.

To construct each of these Peltier pixels, the system contains few different elements that need to be carefully put together. To integrate the system together, we initially mounted the copper pattern mould onto the Peltier element using

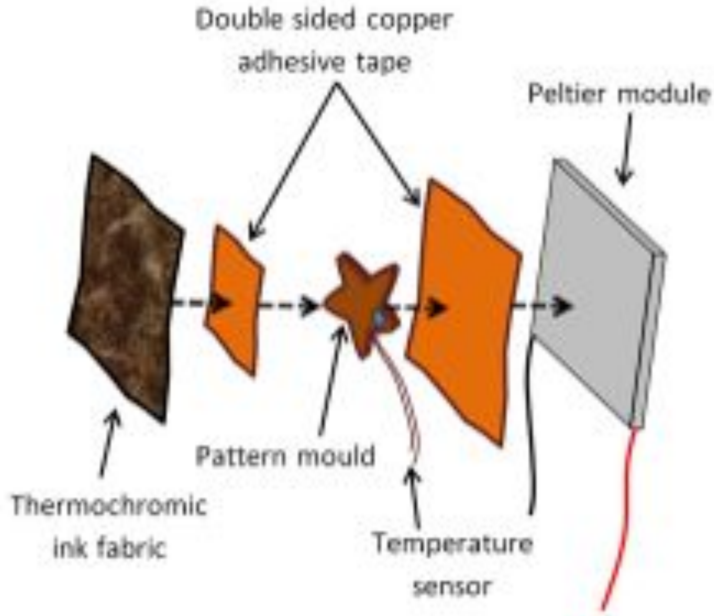


Figure 5.8: Integration of the system

thermally conductive adhesive. This was followed by the temperature sensor on the Peltier element using a copper adhesive tape (Figure 5.8). The copper adhesive tape allows efficient heat transfer between the Peltier element, temperature senor and the fabric in that area. The Peltier elements are attached to the fabric by a thermally conductive adhesive which allows efficient heat transfer between the fabric and the element (Figure 5.8).

5.2.2.2 Interaction system

For this version of the installation, the interactive system is triggered by the proximity of the participant. In the current form, SRF05 Ultrasonic Range sensor, which is attached to the bottom of the Byobu frame is used to detect the proximity of the participant.

The installation interacts with the user when he/she comes within a two meter range from the installation. This event would trigger an animation of a butterfly flying away from a flower as seen in the sequence of images in Figure 5.14. The animation was implemented by carefully triggering each butterfly to turn on while the previous one fades out, similar to the table cloth animation described in Section 5.1.1. As the controller was able to accurately control the temperatures symmetrically, the timing was hardcoded in to the controller to allow the butterflies to slowly appear and disappear one by one.

5.2.2.3 Integration with Byobu

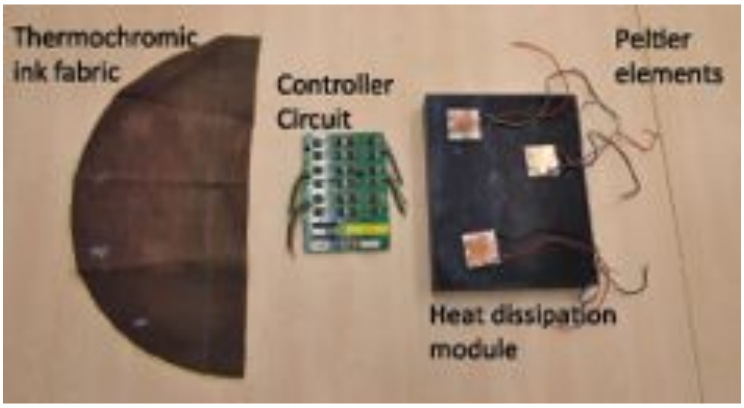
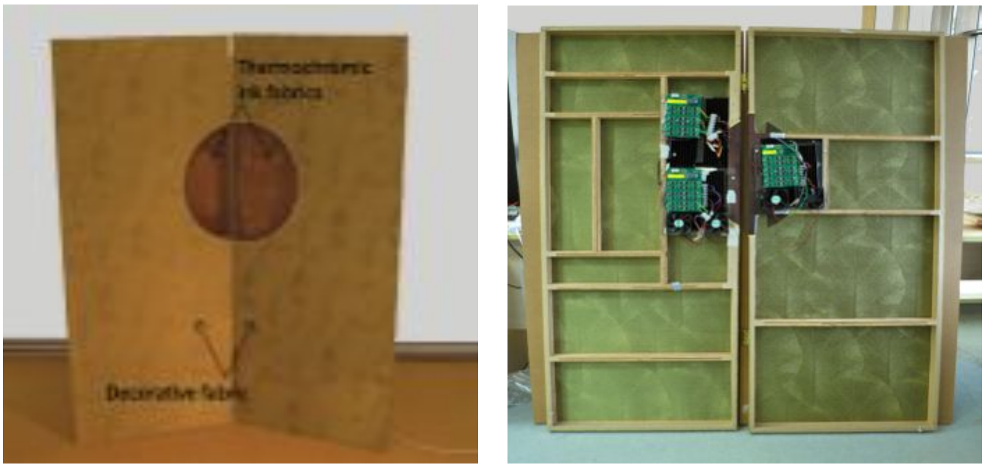


Figure 5.9: Components of the Byobu system

The main components of the system are as seen in Figure 5.9. A Bybou frame was custom made with two panels with the animations on each panel. Differently arranged Peltier elements and the circuits were attached to three heat dissipation modules which were slotted into the Byobu frame (Figure 5.10(b)). We used these heat dissipation modules since the Byobu installation was meant as an installation intending to run for few hours a day without any over heating problems. As Peltier elements are thermal actuators, they need to dissipate the excess heat continuously. Therefore these heat dissipation modules were used in a careful manner such that the appearance of the Byobu was not altered from the front face. However we talk about some of the limitations of this implementation in the Section 5.2.4.4.

Next, a decorative fabric was stretched on to cover the front face of the frame with the components attached at the back. As seen in the Figure 5.10(a) the thermochromic ink fabrics were attached to the proper positions such that the Peltier pixels are able to actuate the inks.



(a) (b)

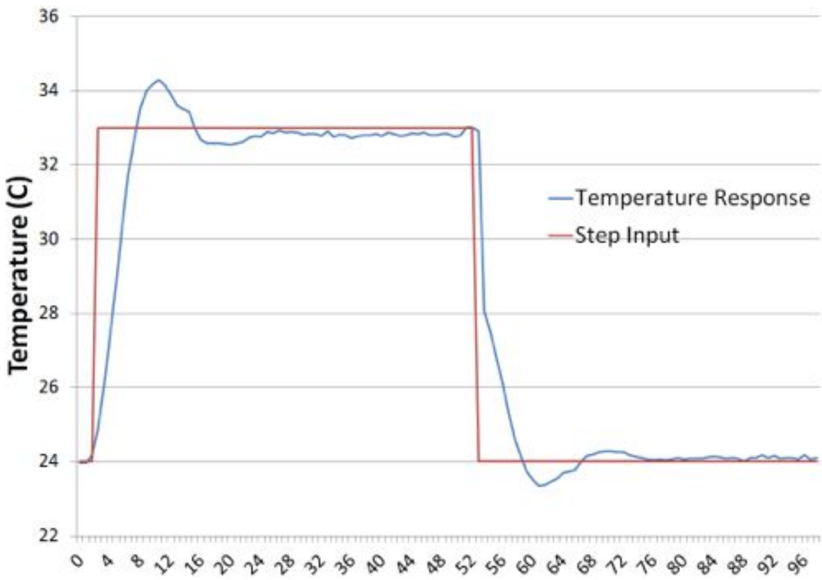
Figure 5.10: System integrated with Byobu (a) Front (b) Back

5.2.3 Results

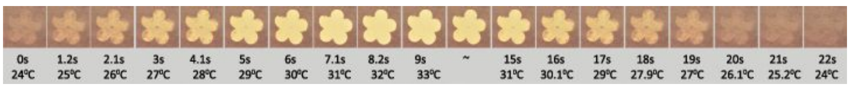
This section details the results of the Byobu installation in two subsections. Firstly, we explain the technical results of the controller of the system. Next the actual output results are discussed.

5.2.3.1 Controller results

The controller results mainly concerns the speed and controllability of color change of the thermochromic inks. The thermochromic inks that we use for the Byobu work is of 24^0-32^0C actuation temperature range. The ink is printed on a yellow color common silk fabric. Therefore when the thermochromic ink is actuated and becomes colorless, the yellow color base fabric would appear. The temperatures measured here are the temperatures on the surface of the copper mould which is heated or cooled by the Peltier element.



(a)



(b)

Figure 5.11: Transient characteristics (a) Transient response of the system (b) Resulting color change of the fabric

The temperature response curve is as shown in Figure 5.11(a).The resulting

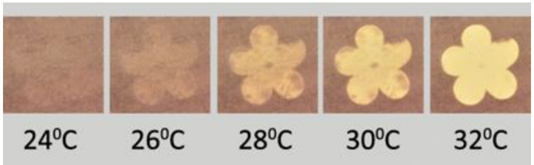


Figure 5.12: Degree of color change at each temperature

color change of the fabric is seen in Figure 5.11(b). The system is able to actuate the temperature with a maximum rate of approximately 1^0C per second. The system was also able to accurately control the temperature to the nearest degree celsius within a range of 22^0C to 35^0C on the surface of the copper mould and thus achieve the required degree of color change (degree of appearance of the flower) as seen in Figure 5.12.

5.2.3.2 Byobu Installation

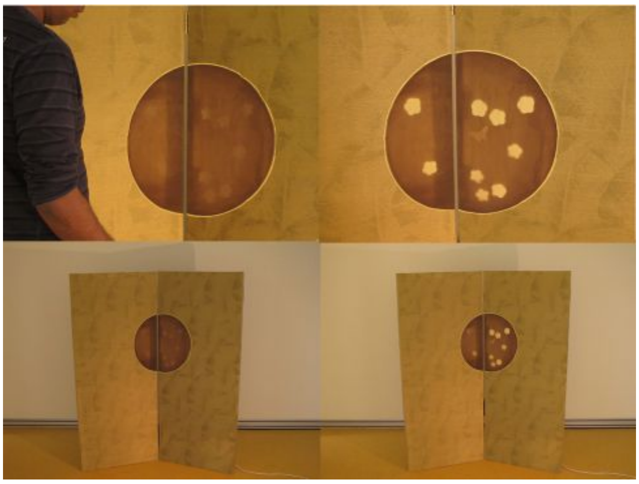


Figure 5.13: Byobu installation

The final system looks as in the Figure 5.13. In a normal idling state the system randomly actuates the flowers as shown in Figure 5.14. In the event of a person walking towards the installation it triggers the interaction even where a butterfly is shown to be flying away from a flower. This sequence is shown in Figure 5.14.

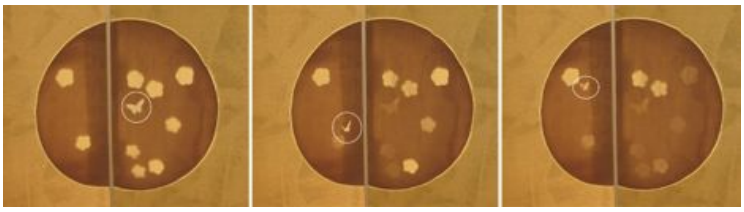


Figure 5.14: Random flowers and the butterfly animation triggered by the interaction event (butterflies are in the circles)

5.2.4 Discussion

Here we discuss the results in detail. Firstly the speed of color change is discussed to understand why the current speed was set. Next, we discuss the cultural implications of this work and how Byobu merges the culture and technology. In addition, as we have not yet conducted a formal user study, we discuss the demonstrations of the Byobu installation itself and interesting feedback from some participants which is important in understanding the results of our attempt. Finally we discuss some of the limitations of the results and methods and directions to improve such.

5.2.4.1 Speed of color change

The actuation rate of 1^0C per second is a relatively lower speed in comparison to our previous studies with Peltier elements. There are few reasons behind this rate.

Firstly, Chapter 4, we observed a rate of 3-4^0C per second rate of temperature change [56]. But, with the Byobu installation, since we use a copper mould to achieve various patterns, the rate is slowed down due to the copper thickness in comparison to the temperature change at the surface of the Peltier itself. Hence, by placing the temperature sensor on the copper mould itself, the rate of change of the temperature is maintained at a constant.

Secondly, as this work is meant as work that combines cultural tradition with technology, we deliberately made the color change slower. This was done with the intention of invoking a calming feeling within the user and yet engage with the fusion of technology and tradition. In addition, by actually slowing down the speed of color change we intended to let the observers or users spend more time with the installation and thereby spend time with this age old craft [76].

5.2.4.2 Cultural implications

The color changing textile technology, is used to animate a byobu screen which frees the landscape paintings on textiles from this static form to one that is dynamic, animated and interactive. With the animation of the byobu screen, the landscapes can now move, change and grow to once again depict the passage of time and temporality of nature. The integration of this traditional byobu screen craft with cutting edge technology allows the participants to experience what otherwise would be absent in these screens - the movements and passing of time one experiences and sees in nature. In addition, the participants can interact with the screen and hence become a main part of what was once a static traditional piece of art. The byobu installation attempts to seamlessly integrate ubiquitous technology into everyday decorum of a traditional Japanese household without interrupting the lifestyle that the traditional art form represents [70].

Our work looks at ways in which traditional textile crafts in Asia can recreate itself in the Digital Age to ensure its survival and still remain true to itself as a craft [69]. The room divider, a panel that creates a division in a space, has now become a canvas to blur the division between the old and new, the static and dynamic, the physical and virtual, craft and technology, the material and immaterial.

The byobu work is intended to be installed in a space such as a home. Without initiating the technology, byobu screen exists as an aesthetically pleasing example of traditionally painted, silkscreen art. It functions as any other byobu would, in the sense that it can be used to divide and isolate a space, as well as provide decorum and decoration.

When the technology is initiated, the byobu becomes an animated display device that can sense the presence of dwellers in the space. As a user approaches the byobu screen, possibly to admire the fine and detailed craftsmanship, the system senses the presence of the user. It then begins to animate the motifs painted on the surface in an unobtrusive way. Flowers painted on the silk begin to bloom. Birds reveal themselves and fly across the vista.

Possibly without knowing but apparent when a user looks carefully, the composition found on the byobu screen reconfigures, providing a new decor for the room it is present in. This slow interaction is ambient in nature, and reflects the purpose intended by the traditional practitioners of this art form centuries ago. In an accelerating world, the byobu installation aims to slow life down just a little, so as to facilitate appreciation of one's surroundings [8, 76].

5.2.4.3 Byobu installation exhibit

Amongst few different demonstrations, the Byobu installation was an exhibit at the Ars Electronica Festival 2010 in Linz, Austria [57]. We presented 'AmbiKraf - Breathing life into textiles' as an installation in the 'Future Factory' category. The name 'AmbiKraf' illustrates the merging of 'ambi' - an ambient technology with 'kraf' - Malay word for traditional craft. Here, with the color changing technology we showcased how the future technology can 'repair' the traditional arts and crafts of textiles by merging those age old traditions with the future technology. In addition to the system itself, we added more decorative elements such as a tatami mats, bamboo stick decor, etc. to enhance the engagement of the person with the installation.

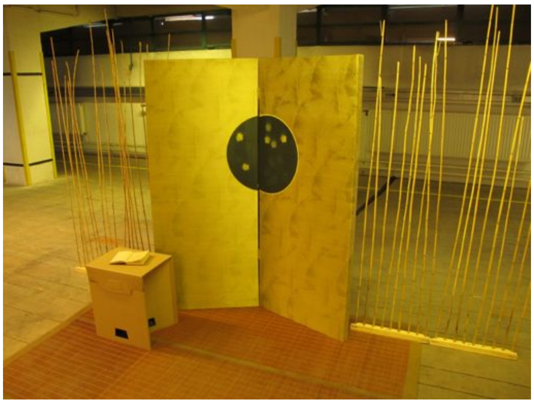


Figure 5.15: AmbiKraf Byobu at the Ars Electronica 2010

At the Ars Electronica Festival we had approximately 200 visitors over four days of the exhibition. They interacted with the system for approximately 10 minutes on average. As we could not conduct a formal user study, we took this opportunity to observe 12 of the above visitors to observe their interactions, and behavior with regards to the system. We also interacted with some of them to get their feedback and opinions on the system. The notes from this informal study helped us gain many important insights as follows.

- *Subtlety of technology* : About 11 of the visitors agreed that the technology was not a glaring add-on but seamlessly merged with the craft. One participant mentioned, "I like how the installation does not show any obvious technology [such as lights, etc.] when looked at from the front".

- *Merging technology and textile art* : About 5 of the participants perceived the technology to be as simple enough to easily be accepted by traditional craft makers. One participant added "I like how the idea of the technology is simple [heating and cooling of heat sensitive inks] such that textile crafts can easily adopt it".

  However, there were three visitors who considered the technology to be detrimental to the tradition. Furthermore, one of them did not agree to our concept of repairing the dying traditional arts with technology as he felt that it's still the technology that we are presenting. This was an important observation since the purpose of our technology was not clear to these participants. Through further discussions, we understood that he felt that the traditional crafters would still find the technology to be rather daunting and further from their expertise. This motivated us to work with more actual users to enhance our work into developing a form of a toolkit, if possible plug-and-play style, such that it could be easily integrated with textiles, especially by the practitioners of the textile crafts.

- *Installation observation* : As a result of the subtlety of the intervention, the installation was missed by many visitors. We observed approximately 14 more visitors who missed our installation. In our later interviews we found out that some of them thought the installation was not working. Thus, the very effect that we wanted to create of letting people stand for a while and observe the art work also made it loose attention. This motivated us to make the interactions more apparent or obvious, and finding out the ways that a visitor could realize that purpose and the interactions of the installation.

- *Participant behavior observation* : The intervention had the potential to change users' behaviors by forcing them to slow down enough to see the animations, demonstrating the importance of enhancing the cultural aspects of the craft in a delicate way.

The above observations helped us gain important characteristics in identifying the user's behaviors and interactions. Thus, in our future works, we plan to conduct a formal user study with more participants. This study would have to be placed in a living room environment as it is supposed to and conduct a proper user evaluation methodology. This would help us gain more extensive knowledge of the user's reactance to the system and improve on those findings.

5.2.4.4 Limitations

Currently, as the first prototype of AmbiKraf Byobu, there are few limitations that we need to address in the future work in this project and the process of implementation.

One of the key limitations of the technical aspects of AmbiKraf is the power consumption. Currently, as we use 30mmx30mm Peltiers, the power consumption is higher. In addition, due to the use of the copper moulds, there is a loss in the efficiency of the heat transfer between the thermochromic ink fabric and the Peltier element. Therefore we are looking into using miniature Peltier modules (discussed in Chapter 7) which are higher in efficiency in comparison to Peltier modules of 30mmx30mm. This would reduce the power requirement and also increase the heat transfer efficiency as they can be arranged in different formations without the use of a copper mould.

Another one of the main limitations of this installation is that the technology, still in its early stages is rather bulky. This is mainly due to the current Peltier elements which require large heat dissipation modules. Therefore the integration of the technology is obvious at the back of the screen as seen in Figure 5.10(b). However, although as an initial prototype AmbiKraf Byobu was quite successful in merging technology with traditional byobu art, we need to radically simplify and miniaturize the technology to allow a seamless integration with such traditional art works. For this purpose too, we are looking at working with miniature Peltier modules in the next Chapter.

5.2.5 Potential applications

The AmbiKraf Byobu installation could be meant as a decorative furniture installation that can be integrated into environments ubiquitously. Even though the current implementation and interaction scenario simply demonstrates the idea of AmbiKraf Byobu, it can be extended to display many other patterns, animations etc. with similar other interaction scenarios. This would allow this piece of furniture to be an interactive item in our background that responds to various conditions or states, moods, etc. of the user.

In addition, without limiting to byobu, it can be extended to other household items and even wall papers. Such an interactive wall paper in a room which changes according to a person's mood, context (party, gathering, relaxing, etc.) could be a great ambient display.

AmbiKraf Byobu was a first step in our work to attempt to merge traditional textile crafts and technology. However without limiting to byobu, we intend to expand this circle by merging with crafts such as those from Asian countries which still have rich traditional and cultural connections with textiles. Currently we are looking at the popular Sri Lankan/Indonesian batik or Japanese Shibori as other forms of textile crafts that could be influenced with the AmbiKraf platform. The integration of such technologies with traditional textile techniques once again redefines craft itself. Craft can now become dynamic (patterns are no longer static and timeless), interactive and possibly even evolving into a new kind of craft in itself. These crafts give us numerous layers of elements to play with and expand our translation of the applications of AmbiKraf.

5.3 *Applications :* dMarkers : Ubiquitous dynamic makers for Augmented Reality

In this Section we try to explore the applicability of our technology in yet another field. We try to combine the display system with the Augmented Reality field to combine and develop novel dynamic markers. In addition, this attempt also demonstrates the applicability of this technology on materials such as paper without limiting to textiles.

5.3.1 Introduction

Augmented Reality (AR), 2D Barcode, etc. are becoming powerful technologies that surround us in the world today. Many such technologies are used in various fields to present more information, enhance interactivity, experience, etc. One common feature that most such technologies have is the use of a marker/tag which is recognized through the use of a camera. Technologies for such recognition and processing of these markers have become more and more powerful and even have moved onto mobile devices such as smartphones [54]. As these devices get smaller but more powerful, users today are able to install these complex programs and carry them around making the Augmented Reality technologies move towards ubiquity [32, 55].

However, these AR technologies do posses their own limitations. Currently one of the main limitations is the use of a distinctive marker which is generally recognized through the AR application. Such markers need to be embedded distinctively in the environment. To overcome this issue, much research has been focused on new markerless technologies such as natural feature tracking [51]. However these technologies are still maturing towards robustness and so far are not used as commonly as AR marker technologies. The other main issue is that these markers could represent only one pattern or image thus making it only as a single input. However there are some instances where more than a single marker may be required for dynamic content or more inputs [46, 79]. Thus in most cases many different markers are used even though they may not be used simultaneously.

Hence moving beyong this point, we introduce "dMarkers" or dynamic markers as a new interaction channel to the framework of the AR technologies . Our motivation here is to explore the feasibility of using ubiquitous dynamic markers or markers that can change (based on various stiumuli) to enhance the experience of using Augmented Reality, 2D barcode or QR code technologies. Thus we attempt to use traditional paper based marker itself as the dynamic marker. So far, in almost all applications that use such technologies the markers that are used are of fixed shapes. Therefore, few different markers are used in many situations to identify different inputs. With our current attempt we focus moving from this point to introduce dynamicity to the marker in a ubiqiutous manner. As a proof of concept for the initial phase, we use dMarkers for QR codes. In addition, we present one possible application for an early work of an Augment Reality based marker. Hence with this work, we aim to make a dynamic QR tags and discuss its results and limitations. From thereon we discuss how such dynamicity on a marker could enhance the interaction experience for AR technologies through useful scenarios.

To implement the dynamic marker we use the technology we discussed in the previous Chapter. The main reason to use this technology is due to its ability to change the color of the material (fabric, paper) itself. In addition, this also gives the marker a degree of ubiquity to be embedded directly into the texture of the fabrics or the paper. That is, when the thermochromic ink that is screen printed or simply printed on to a material such as paper or fabric is thermally actuated, it changes the pattern or the color of the material itself. Therefore the interactions takes place with the actual material (fabric) and not with any new or different embedded display module. Hence, we use this non-emissive technology which does not emit any light and is preferred for our purpose as it would be similar to a real marker.

5.3.2 Technology

We use the previously discussed thermochromic ink and Peltier technologies for this work. We chose this method due to its relatively fast animateability of the medium. This is an important characteristic that allows the marker to change in a fast manner.

5.3.2.1 Display arrangement for the dMarker system

As mentioned before, we use a QR code application as a proof of concept for our dMarkers system. For this purpose we use a QR Version 1, 21x21 pixel arrangement for the display.

For this purpose, we take a range of Peltier elements and arrange them in a matrix format such as a pixelated display(Figure 5.16). For initial prototyping we use 10mmx10mm Peltier elements in a 21x21 pixel arrangement due to the ease of implementation. Therefore, the current QR tag is approximately 21cmx21cm

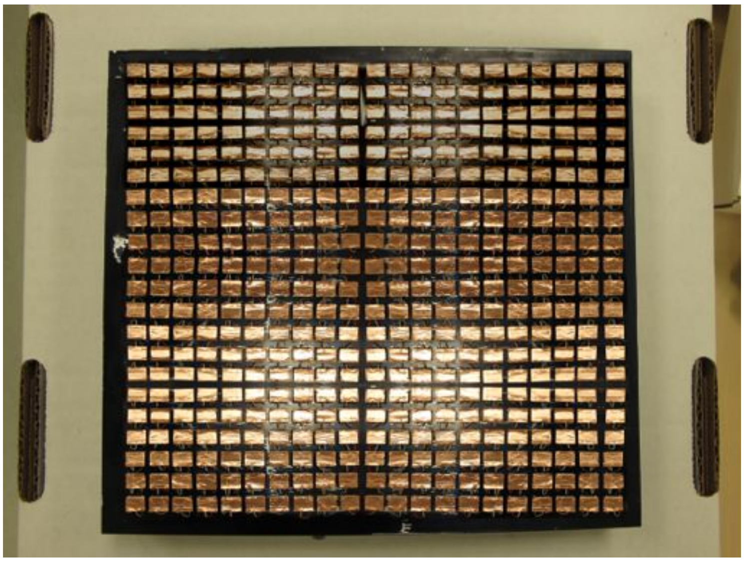


Figure 5.16: Arrangement of Peltier elements in a matrix for dynamic QR/AR applications (each Peltier with the thermally conductive adhesive tape on top)

but can be made much smaller in our future works (much smaller Peltier elements can be utilized for this purpose which we will discuss later in the next Chapter). Each pixel (Peltier element) in this arrangement is individually controlled which can display the color or colorless states. Colored state would denote a black pixel and a colorless state would denote a white pixel analogous to the QR code format. This way we can achieve the format of a QR code through this pixelated display.

5.3.2.2 Detection

Most current QR code applications are such that they are used ubiquitously with handheld devices to read the code. Therefore, at this initial phase, we used a third party application on an 'HTC Desire' [30] phone for the detection of the dMarker QR code. The application is named 'QR Droid' [4] and is downloadable via the Android Market [1].

5.3.3 Results

This section details the results in two sub sections. Firstly we present some results of the color changing technology through the analysis of the color change of a single pixel. Next we present the details of the dMarker system which combines a series of such color changing pixels.

5.3.3.1 Results of a single color changing pixel

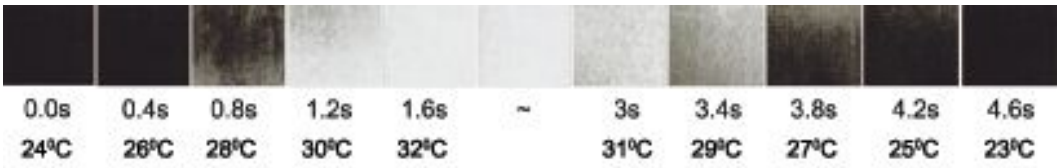


Figure 5.17: Sequence of color change on a paper based material

The system was able to actuate the ink to the colorless state and do the reverse in approximately 1s each. Here, we used Black ink actuated at 31^0C as the thermochromic ink on white color paper and common taffeta silk fabric. The results for both materials were similar with no significant differences between the color change speed. The color change for the fabric is shown in Figure 5.17.

5.3.3.2 dMarker system results

The testing was carried out in two phases for the paper and fabric materials. The first testing was carried out on a white A3 size paper surface where the thermochromic ink was screen printed on the whole front face of the paper. Next, we tested the same method on white fabric as the base. Here too the thermochromic ink was screen printed on to the fabric. In both cases the Peltier pixel system integrated behind the fabric. The testing was carried out by actuating the dMarker

Figure 5.18: Detecting the dMarker QR tag with the QR application

system to actuate various phases such as "dMarkers", "Hello World", etc. Upon actuation, the HTC Desire smartphone with the QRDroid application was used to detect the pattern displayed on the paper/fabric surface (Figure 5.18).

The results for the two surfaces are as follows (Paper: Figure 5.20 Fabric: Figure 5.19). These were actuated to display various informations such as "dMarkers", "hello world", etc. Figure 5.19 and Figure 5.20 display instances of each of these. The Figures 5.19, 5.20 and 5.22 are readable through a QR reader.

5.3.4 Discussion

The key aspect of the color changing technology is its ability to make a contents on a surface of different materials dynamic in nature. The only requirement to successfully implement this technology is for the surface to be relatively good enough for heat conduction. With the current implementation, we tested the system for paper and fabric materials. In the next subsections we discuss the

(a)

(b)

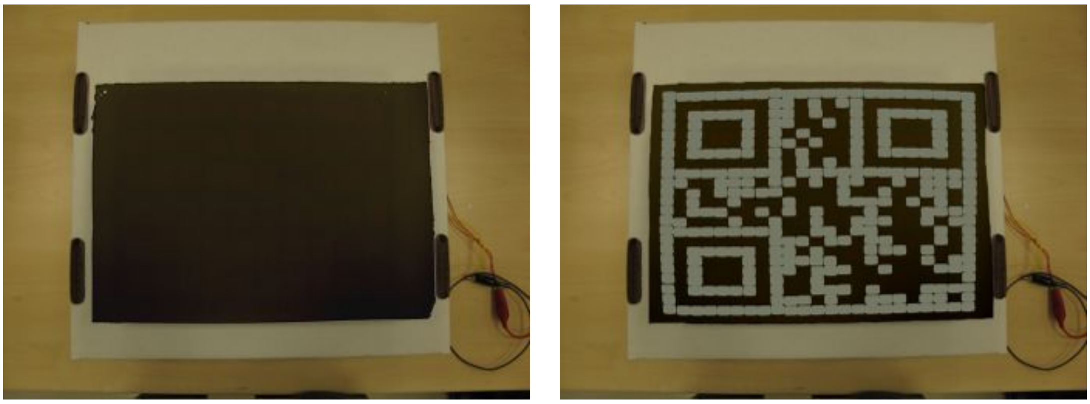
Figure 5.19: Testing the system on fabric materials (a) Without actuation (b) Actuated system

results obtained and some of the key limitations of the system.

5.3.4.1 Results discussion

For the using of Black inks with white fabric, it was observed that comparatively, the recognizability of the markers were higher for the paper based markers. The texture of the fabric surface, and sometimes the unequal heat distribution often requires the QR reader to be readjusted a few times before accurately reading the marker. In comparison, the paper material output a sharper pixel with clearer pixels. However, out of about 15 trials the longest time taken for the fabric based QR marker was approximately 2 seconds. The paper based marker was detected almost immediately in all cases.

This indicates that both materials are acceptably usable for the dMarkers QR codes. However, the paper material would be the ideal solution. This would be important in the future works where we try to embed these technologies more ubiquitously into our sorroundings.



(a) (b)

Figure 5.20: Testing the system on paper materials (a) Without actuation (b) Actuated system

5.3.4.2 Limitations

- Blurred Pixels

  One of the key issues of using this technology is that the edges of each pixel are not perfect edges. As seen in Figure 5.21, the edges of the pixels are slightly blurred which may result in slight errors in the reading of the code. However, with the QR code application, the detection algorithms are robust enough for detecting the pixel pattern. With the testing on the current implementation, the edges of the pixels were not blurred so much that it prevented detection. However, as we intend to implement dMarkers for Augmented Reality Markers, the sharpness of the edges should be improved further. To address this issue we are considering experimenting with the use of different materials as the base with a combination of proper actuation temperature of the inks. That is, since the blurring of the edges is caused by the heat conducting across the the base material to closer regions

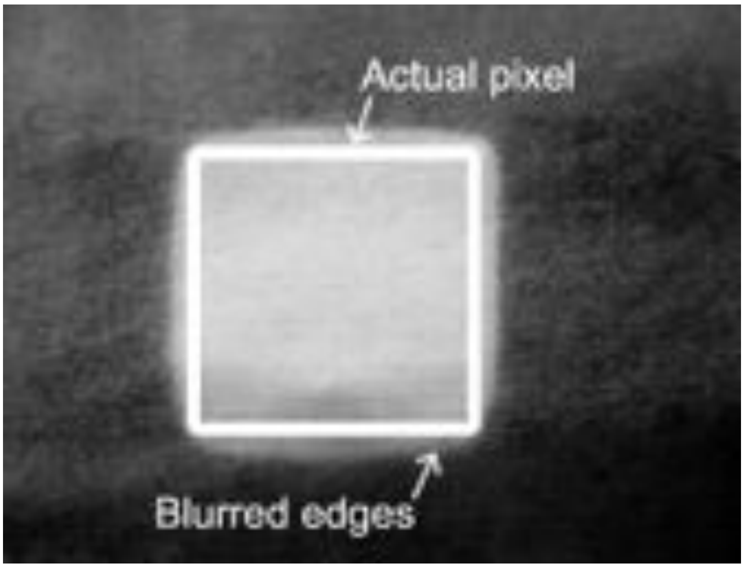


Figure 5.21: Blurring of the edge of a pixel

and actuating thermochromic inks of those regions. Therefore if we use a less thermally conductive material with a thermochromic inks with less actuation temperature, the heat conduction could be reduced to a certain extent.

- Color

Another main limitation of this technology is the sharpness of the color. In some occasions, due to the ambient temperature, the color of the black pixel varies to a lighter shade. I.e. if the actuation temperature of the thermochromic ink is about 25^0C, at a room temperature of 24^0C the ink may be slightly actuated resulting in a lighter shade of black. To overcome this limitation, we are looking at two methods. Firstly is to simply use a thermochromic ink which is of higher actuation temperature such that it is not close enough to the room temperature. Secondly is to pre-process the

(a) (b)

Figure 5.22: Converting the image to complete black and white image (a) Before conversion (b)After conversion

picture and convert to a black and white image before the QR detection algorithm. The Figure 5.22 depicts the conversion of the image with a simple algorithm. However, this work is still at the initial stages with the main aim of integrating with Augmented Reality Markers. With the current algorithm upon conversion, the image can be detected almost immediately with a QR reader. This would also enable the dMarkers to use colored thermchromic inks as shown in Figure 5.23. In Figure 5.23 experiment, we used another thermochromic ink screen printed fabric that was used in another project to test the color detection. Upon fine tuning some values in our algorithm, we were able to produce a black and white image that was detectable. However, this was not done with the camera, but with static images and thus has to be tested further more to improve the robustness.

(a) (b)

Figure 5.23: Converting a colored image to complete black and white image (a) Without actuation (b) Actuated system

5.3.5 Potential applications

5.3.5.1 dMarkers for QR codes

One of the key limitations of QR codes is that it can display only a single set of information per tag. Therefore by introducing dMarkers we can represent more information (given the limitation of the QR tag size) by changing the QR pattern as the user reads through it. This might be useful in cases such as to display more useful information such as names, weblinks, etc. using just a single tag. In addition, with the advancement of technology, we hope we can present this technology as an affordable widget with connectivity to Internet. In such case the information can be constantly updated or more information can be presented remotely through the connected QR tag. This would enable offline users to still grab the same amount of information through the actual dynamic information presented to users.

Figure 5.24 demonstrates this application concept being used with one of our

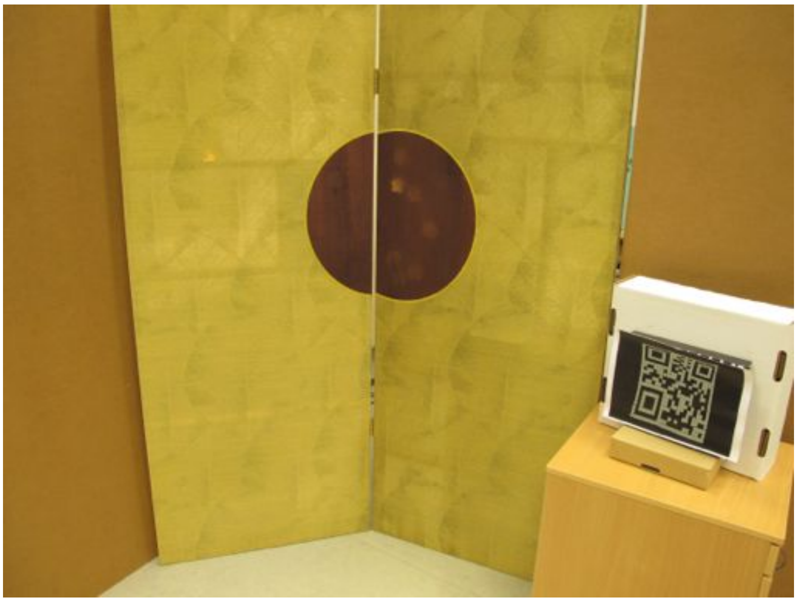


Figure 5.24: dMarkers used to present more information about the project

projects. In our lab, we have set up this dMarker next to one of our project to display “Welcome”, “to our lab” in two frames with each frame displayed for five seconds. Due to the limitation of the size and resolution of the current implementation we cannot display much information such as the website address. However, in our future version as we make the tag smaller we intend to have a higher resolution allowing to display more information about the project.

5.3.5.2 dMarkers for Augmented Reality

In addition to representing more information on dMarkers for QR codes, we intend to extend this technology to Augmented Reality Markers. This enable dynamic markers for Augmented Reality applicaions. Currently, the main limitation is the too much blurring of edges for detection of the marker. We have done initial testing using the ARToolKit [2] but has not yet yielded satisfactory results. In addition, since we use squared Peltier elements as the pixels, it could not represent sharp rounded images as the pictures of some markers contain. Hence we intend to use a square pixel based martix as the marker similar to QR tags and explore its capability and usability in Augmented Reality environments and applications.

- Applications for dMarkers in AR

  Integrating dMarkers with AR could present various new avenues for research and applications. One of the key advantages of dMarkers is that, the pattern of the marker can be linked to various external stimuli. Even though this feature has not been implemented yet, it is easily implementable depending on the type of input required. Having such a capability would open another channel for interaction between the AR application and the marker.

  For example, there are many AR classroom learning tools that have been developed in the recent past [42, 50, 60]. Most of these applications are in the form of pop up books where the markers printed on an actual book is used as the input to the AR application. If such a system combined with dMarkers is used in a classroom a teacher may be able to control various information on the same page of the book for each student. This would allow each student to use the same AR application without any customization for the data to be presented.

- Using colored dMarkers

  In the future, we also intend to explore the feasibility of using color with AR markers. Currently black and white markers are used due to its robustness in various conditions such as lighting. Using colored markers would present a grave challenge but could be possible in the future when considering the progress being made in fields such as natural feature tracking. If such color markers becomes a reality, this technology of dMarkers would be an ideal candidate for various scenarios. For example the colored dMarkers could be 'stealthliy' embedded into various artifacts and dynamically be triggered to reveal themselves upon user presence. Such would prevent the requirement to attach distinctive markers into these artifacts and the AR applications can be used in a more ubiquitous manner.

- Clothes

  One of our main goals for the immediate future is to make this color changing system wearable. Currently we are working on a few wearable prototypes that use this color changing technology. Making this system wearable presents us a great deal of challenges. Low power consumption for mobility and comfort of the wearer are two key factors that need to be radically addressed during this process. Hence some of our early prototypes are focusing on using miniature Peltier (Chapter 7) modules. This provides a great deal of improvement in the flexibility of the fabric but not satisfactorily acceptable. However, as the number of Peltier modules increase, the thickness of the required conductive yarn also would increase necessitating to arrive at a compromise of technology. In addition, special attention should be given to insulating the system from the wearer. Choosing suitable actuation temperature of the inks is a key factor in this process while also making sure that the body heat of the wearer does not effect the display. If these challenges are overcome in the future, we envision that such technologies be used in various fields ranging from animated pattern displaying clothing to military camouflaging (the military uniform automatically camouflaging according to the sorroundings). In addition, the dynamic QR/AR concept could be combined with this wearable concept to create interesting platform for interaction on our clothes!

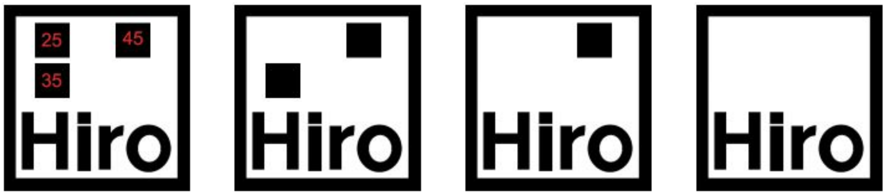
5.4 *Applications* :A dynamic AR marker for a paper based temperature sensor

In this section we describe a new type of paper based temperature sensor that is derived out of the previously discussed dMarker technology. As a proof of concept, this section presents the initial work, the development of a paper based temperature sensor using dynamic AR markers. For situations where a device temperature needs to be measured through a computer, we envision an application where we use this dynamic marker as a temperature sensor. Thus, in most cases, this method will replace complex temperature sensing circuitry with a simple paper based sensor and a camera. In addition, it could also be a simple piece of paper that you could carry in your wallet or bag as a mobile temperature sensor by simply reading it with your smart phone.

One of the closely related works to this work is the use of thermal markers used in a medical related application [14]. This work uses the difference between the body temperature and reflective marker read by a thermal camera to identify persons. However, in this section we focus more on the change of the marker due to the temperature. Thus we present the paper based temperature sensor.

5.4.1 Method

As our concept, we look at a modified ARToolkit [2] marker as a temperature sensor as in Figure 5.25(a). In this case, as shown in the example Figures 5.25, inks with different actuation temperatures are printed in the form of a AR marker with each pixel being a different temperature inks (or groups of pixels strategically



(a) (b) (c) (d)

Figure 5.25: Example AR marker for temperature sensing (Red marking are the actuation temperatures of each pixel and would not appear in the marker) (a) Marker at temperatures below 25^0C, (b)Marker at temperatures between 25^0C and 35^0C, (C)Marker at temperatures between 35^0C and 45^0C, (d) Marker at temperatures above 45^0C

placed being same ink). As the temperature increases each pixel would become colorless as seen in Figures 5.25(b),(c),(d). With more pixels with different actuation temperatures, we could achieve a higher resolution for the temperature.

Once this tag is placed on the device we require to measure the temperature, the relevant pixels will disappear and the tag will reveal the current temperature of the device. Then a simple web camera with an AR application could read the temperature off the AR maker.

For this initial version, in addition to a simple OpenCV AR algorithm for the marker detection, we implemented a basic AR application for the temperature detection. Thus upon detection of the marker, the application displays the range of the temperature on to the display (Figure 5.26).

5.4.2 Results

Figure 5.27 depicts the initially implemented dynamic marker with two color changing pixels that disappear at 24^0C and 31^0C. As the temperature increases the marker morphs into different markers. Figure 5.28 indicates the first version

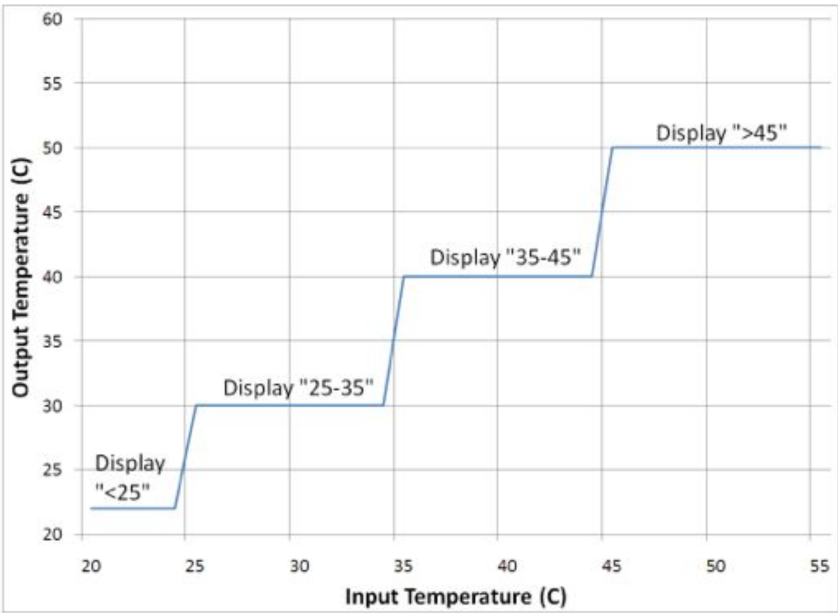


Figure 5.26: Measuring and displaying the temperatures

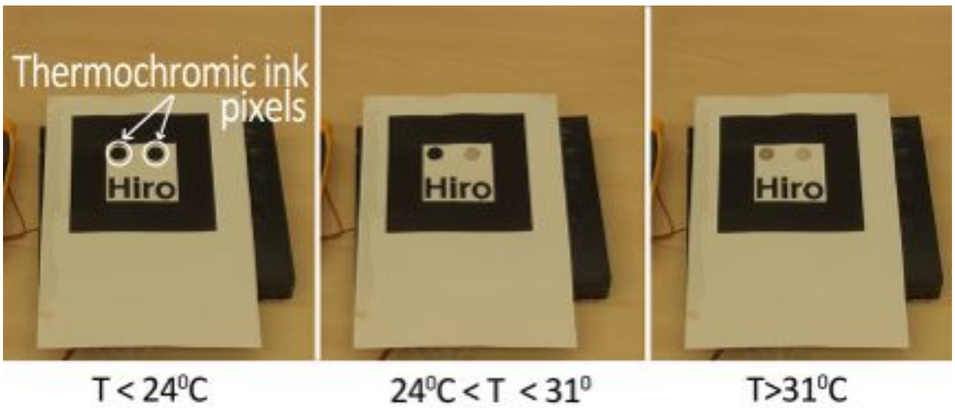


Figure 5.27: Thermochromic ink pixels disappearing as the temperature increases

Figure 5.28: Detecting different markers at different temperatures

Figure 5.29: Measuring the temperature of a 3D printer

of the detection algorithm. Here, different objects are displayed for each of the different markers.

Example application is as in Figure 5.29 and Figure 5.30. Here, we attached the marker to a 3D printer during its idle time. Currently the detection shows the temperature to be between 35^0C to 45^0C (Actual temperature was 37^0C). In the second application we attached the marker to a server machine which displays the temperature as 20^0C to 35^0C. These readings can be improved further by adding more pixels with thermochromic inks of different actuation temperature.

As the results indicate, as the inks have a gradual change over about 2^0C, the reading is not accurate during the margins of the ink actuation tempera-

Figure 5.30: Measuring the temperature of a server

tures. However, as mentioned before the use of inks with customized actuation temperatures would increase this accuracy.

5.4.3 Discussion

As observed, this temperature sensor gives fairly easy reading of the temperature. However, the current implementation is limited in its range and resolution due to the use of off the shelf thermochromic inks. The actuation temperature of thermochromic inks are customizable. Hence, based on the application, this temperature sensor can be extended in its range and resolution to get a more accurate temperature reading. Thus, this marker has the potential to be applied anywhere in a very ambient manner.

5.4.3.1 Limitations

However, there are some key limitations to this technology. First is, as this technology uses, AR methods, lighting, and clear vision should be available for proper reading of the marker. In addition, in some occasions, if the temperature is such that, some of the pixels are only slightly actuated, it may result in incorrect readings. For this purpose, the actuation temperatures must be fine tuned.

In addition, a flat surface is preferred for this marker to be read accurately and robustly. However, the use of QR (Quick Response) codes, can enhance the robustness of the detection of the marker where the pixels of the QR code would be printed in thermochromic inks to actuate based on varying temperatures.

5.4.3.2 Potential applications

The simplicity and the ease of use this temperature sensor holds a key possibility to apply this technology to many fields of application. One of the earliest possible uses is the personal uses, where as mentioned earlier, the users can carry this temperature sensor in their wallets or bags just as a piece of paper. Thus upon requirement the temperature can be easily read using a smart phone instantly.

In addition, similar to QR codes on various products, the marker can be also integrated on to temperature sensitive products. Thus by simply placing the marker on the product, the users can read the temperature of the marker. To increase the robustness of this application on products, we are exploring the use of QR codes instead of AR markers for this purpose. In addition, this would help the use of widely available third party applications to read the dynamic QR codes.

The ability to use this temperature sensor as an inexpensive 'wireless' sensor could be useful in various industrial applications. In particular cases where the use of isolation chambers, etc. are required, such a sensor can easily replace messy or expensive wiring and temperature sensing equipment to simply use this sensor with a web-camera. Thus in similar applications, this type of paper based sensor could be useful as an inexpensive and simpler alternative.

5.5 Discussion

This chapter presents some of the initial prototypes and a few applications that were implemented using the textile display system. The main motivation behind these works were to identify the applicability of the textile display system in the real world. As observed we present some key points identified with the system.

Material : The system was implemented in two main types of materials, textiles and paper. These materials are two of the widely used materials in everyday scenarios. These materials can be easily used in such applications due to thermochromic inks' ability to be screen printed onto textiles or papers. As such, any material that can withstand thermochromic inks, and have enough thermal conductivity can be converted to a non-emissive display.

Programmability : As illustrated in the initial prototypes, the system can be customized to display many different forms of animations. However, considering the current limitation of approximately 0.7FPS frame rate, the system can display subtle and ambient animations on many different materials or surfaces as mentioned above.

Ubiquity : Similarly, the usability of widely used materials such as paper or textiles makes the system suitable for a wide range of daily objects such as furniture, wall papers, calendars, etc. One of the main characteristics of the system, non-emissivity, would enable merging of the technology and material seamlessly.

Wide area of application : Combining the summary of above results, it is evident that the system can be used in many different areas of applications. For example we illustrated the merging of this technology from merging with traditional crafts to enhancing Augmented Reality applications to fabricating a new type of temperature sensor.

Thus, as the above points indicate the technology as a great amount of potential for application in the real world. However, some key limitations such as the power consumption issues and flexibility issues exist for which we will discuss solutions in Chapter 7.

5.6 Summary

This Chapter presents the prototypes and applications that were implemented as a part of this study. As such, we present a wide range of initial prototypes such as furniture related displays, pixelated displays and wearable display, that discusses the applicability of the prototypes in our environment. Next we discuss the applicability of the technology in a wide range of application areas such as merging with textile craft, augmented reality and sensor fabrication. Thus, through all these prototypes we have identified the applicability of the ubiquity of this work in different contexts and different materials such as paper (without limiting to textile).

6

Exploring a temperature based Input system for the display

Through various demonstrations of our work to the public, we observed how the users interacted directly with the textile display. That is, in many cases the users, especially children, were seen to curiously touch the animating pixels on the fabric expecting some form of a reaction. In addition, in many of the discussions we had with the users, they indicated how they might prefer to have such interaction with the system that could be seen in the form of a drawing board on textile, etc. Thus, we wanted to explore integrating a touch sensing mechanism with the system. However, a new sensing layer would ideally have to be placed directly behind the the fabric on top of the Peltier element to detect touches efficiently (Figure 6.1). But it would be problematic as adding a new sensing layer (such as capacitive or resistive sensor) between the Peltier element and the textile layer could be an issue as it would interrupt the efficient heat flow effecting the performance of the display system. In addition, the changing temperatures could effect the sensor's characteristics continuously. Thus, in this chapter we explore the making of an interactive textile display based on our non-light-emissive textile display technology.

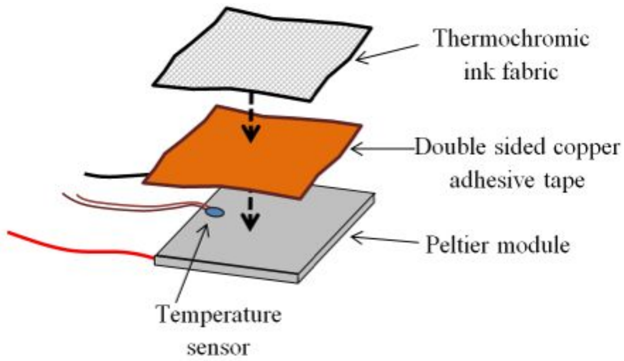


Figure 6.1: System setup of a single Peltier pixel

6.1 Temperature based touch sensor

Including our work described above, most thermochromic ink textile display systems accompany temperature control systems since thermochromic inks are actuated based on temperature. However, as seen in most of the recent thermochromic ink related works, the textile display is not directly interactive. I.e., the technology functions only as a display which may be programmed animations, or is passively interactive through external triggers such as body heat [38]. Therefore this section explores the implementation of a temperature based touch sensor based on our existing technologies of thermochromic inks and Peltier semiconductor elements. The main motivation here is to have the display and the sensing through the same textile interface similar to a touch screen. To achieve this functionality, we recognize touch input by analysing temperature variations and conduct a transient analysis on such variations to detect the touch. This way, we can modify existing temperature control systems for thermochromic ink based textile displays to make them touch sensitive for interactivity without the use of external touch sensors such as pressure sensors allowing the sensing and the display through the same textile interface.

6.2 System Description

We use the same technology described in Chapter 3 for the textile display. Peltier semiconductors (30mmX30mm) are used, as it allows rapid temperature changes [56] which is suitable for our work. The Peltier semiconductors' ability to actuate within a wide range of temperatures is another main reason for its use. Due to the temperature sensitive nature of this work, we evaluate our work with a temperature range from 16^0C to 44^0C. We used black color thermochromic inks of actuation temperatures 24^0C-32^0C for our experiments and prototypes (when heated beyond the actuation temperature the ink changes color and regains the original color when cooled). Double-sided copper adhesive tapes are used to attach surfaces and components on to the Peltier element for optimal heat transfer. The temperature of the Peltier elements is controlled by a closed loop PID (proportional, integral, derivative) controller. A temperature sensor placed on each Peltier pixel gives a feedback of the temperature to the controller.

6.2.1 Touch Sensing Principle

Touch sensing is achieved by making use of this PID temperature controller. Closed loop PID temperature controllers have the ability to achieve and main-

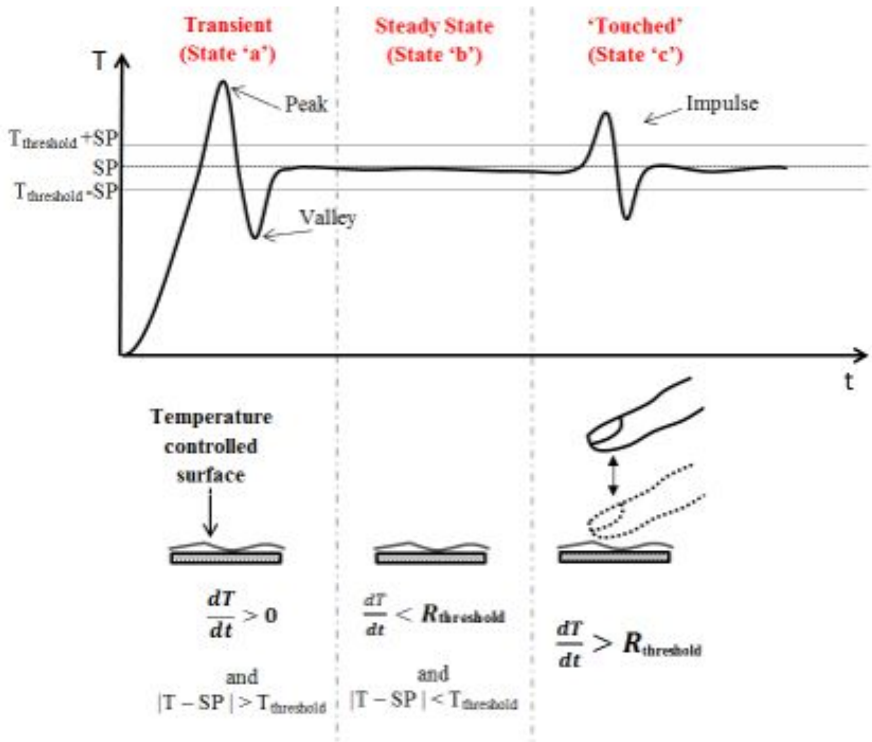


Figure 6.2: Overall operation principle (SP-set point, T-Temperature, t-time)

tain a desired temperature with relatively high accuracy. Thus, once the system reaches this steady state, it would maintain the temperature within a certain threshold unless effected by an external thermal source. This external source can be considered as an impulse input to the system. As a result to this 'impulse', it would once again adjust itself to reach the steady state after a certain time. In this work, we use this principle where we consider the finger to be an external temperature source. Figure 6.2 shows this principle where a steady state temperature is affected by an external source (finger).

Thus, as indicated in Figure 6.2 the touching of a temperature controlled surface could induce a temperature change on the surface due to the difference between the temperature of the finger and the maintained temperature (set point).

Therefore, by monitoring such impulsive changes in the temperature, it is possible to sense the touch on the surface of the textile display.

The system monitors for touch inputs at the steady state where the temperature is maintained at the set point (state 'b' of Figure 6.2). Thus, the controller identifies the steady state using the following observations.

- In the transient state, $\left|\frac{dT}{dt}\right|$ is (significantly) greater than zero, or, at the peaks/valleys the rate could be zero (Figure 6.2).
- At peaks/valleys, the difference between set temperature and the current temperature is significant.
- Therefore, at steady state, $\left|\frac{dT}{dt}\right|$ is closer to zero or less than $R_{threshold}$ within the $T_{threshold}$

Thus, the algorithm to detect the steady state can be summarised as,

$$\begin{aligned}
&if\{(\left|\tfrac{dT}{dt}\right| < R_{threshold}) \;\; and \;\; (|T - SP| < T_{threshold})\} \\
&then, \;\; state \; = \; `steady\ state' \\
&else, \;\; state \; = \; `transient\ state'
\end{aligned} \tag{6.1}$$

where T - temperature, t- time, SP - desired temperature set point, $T_{threshold}$ - maximum steady state error, $R_{threshold}$ - minimum temperature change rate to detect the touch.

$T_{threshold}$ value should be small enough such that the temperature change due to a touch can exceed this threshold value. In addition, it should be large enough to allow a quicker settling time into steady state to allow a faster refresh rate for the detection. Once the condition in equation (6.2) is satisfied, the system can move to the detection mode to detect the touch.

Hence, the presence of an external source can be detected in the steady state (Figure 6.2), where, when the touch occurs, temperature change rate is higher than $R_{threshold}$. I.e.,

$$\begin{aligned} &if\{(state\ =\ \text{‘}steady'\)\ \ and\ \ (\left|\tfrac{dT}{dt}\right|_c > R_{threshold})\} \\ &then,\ \ touched\ =\ \text{‘}true' \\ &else,\ \ touched\ =\ \text{‘}false' \end{aligned} \tag{6.2}$$

where c is the touched state.

Thus, by implementing this condition in the firmware, we can achieve a low fidelity touch sensor with a low refresh rate without any modifications to the hardware.

6.2.2 Firmware

The main controller algorithm contains two main components, PID controller and the touch detection mechanism. Figure 6.3 depicts the firmware algorithm of the controller.

The controller, if not already in the ‘steady state’, seeks for the condition in equation (6.2) to be satisfied to enter into the detection ready mode (steady state). Once this condition is satisfied, the controller moves into the detection mode while running the PID controller. At the detection mode it continuously scans

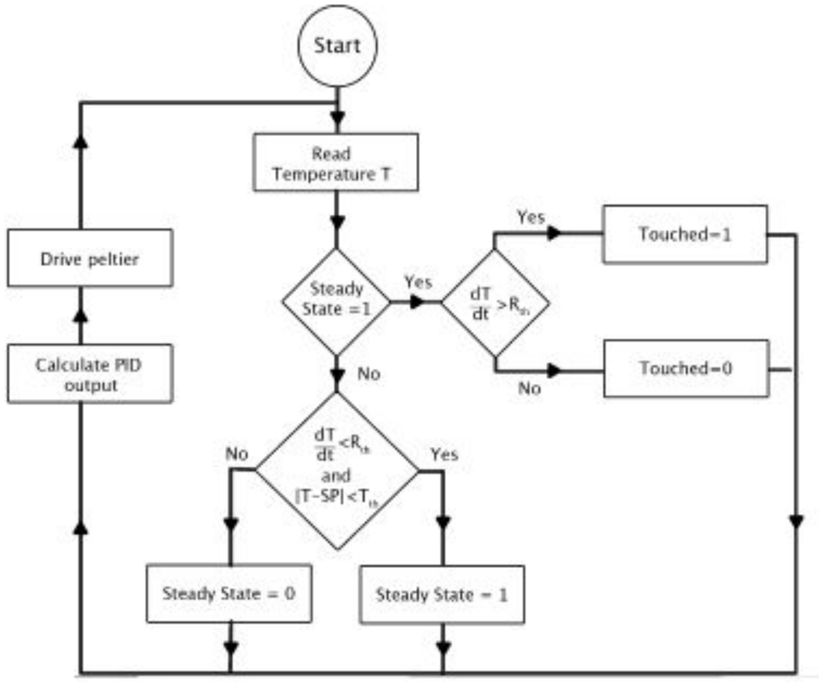


Figure 6.3: Algorithm of the controller

for temperature transients which could be caused a by a touch. This checking is carried out at the same frequency as the temperature sampling rate. The main detection frequency limitation occurs during the transient state which could vary based on the application which is discussed in the Discussion section.

6.3 Results

This section will discuss the results of the controller and the detection system. For the current implementation a black color thermochromic ink of 31^0C actuation was used on a yellow textile. I.e., beyond 31^0C, the ink would become colorless revealing the yellow color textile. Figure 6.4 shows the components of the final system. The controller circuit can control upto 6 Peltier modules. Its size has not been optimized due to the proof-of-concept prototyping nature of the work.

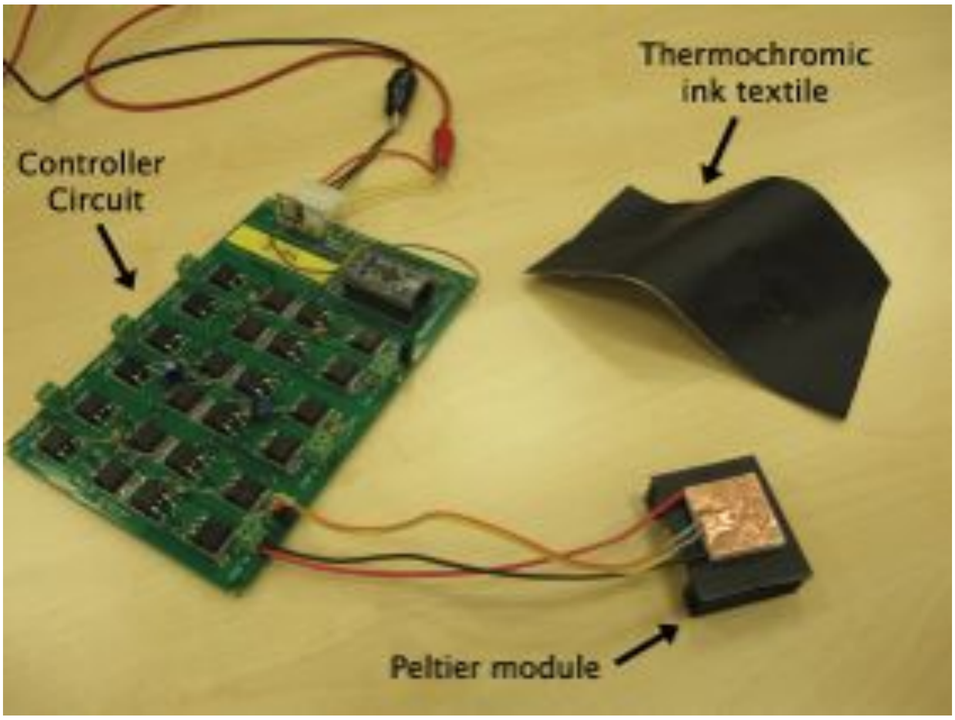


Figure 6.4: Components of the final system

6.3.1 Controller results

Figure 6.5 indicates the step response of the system for a temperature change from 24^0C to 36^0C. As observed the controller has a rise time of approximately 2.3s and a settling time of approximately 4s. As seen in Figure 6.6, the controller is able to accurately maintain a temperature with a maximum error of about 0.6^0C. Therefore we set our $T_{threshold}$ value to 0.6^0C.

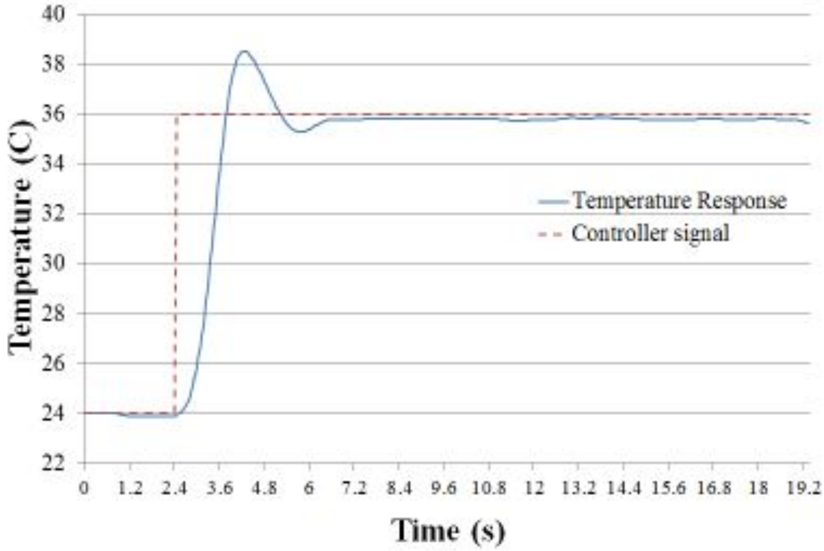


Figure 6.5: Step response of the system

6.3.2 Preliminary Study

A preliminary study was conducted to identify the impulse patterns created by a single touch. We used our temperature controller at steady state for different temperatures and logged the changes that were caused by a single touch. The average finger temperature was 31.27^0C and the ambient temperature was 22^0C. The touch was performed for approximately 1s. Figure 6.7 indicates the impulses caused by a single touch for different temperatures. The temperatures have been normalized for ease of reference with 1 being the desired set point(SP).

Figure 6.8 indicates the $\left|\frac{dT}{dt}\right|$ for the touched state. Through observation it can be concluded that the temperature change rates are higher when the difference between the steady state temperature and finger temperature is higher. In addition, the change of temperature at higher steady state temperatures are generally low but the rate of change is higher as observed by Figures 6.7 and 6.8.

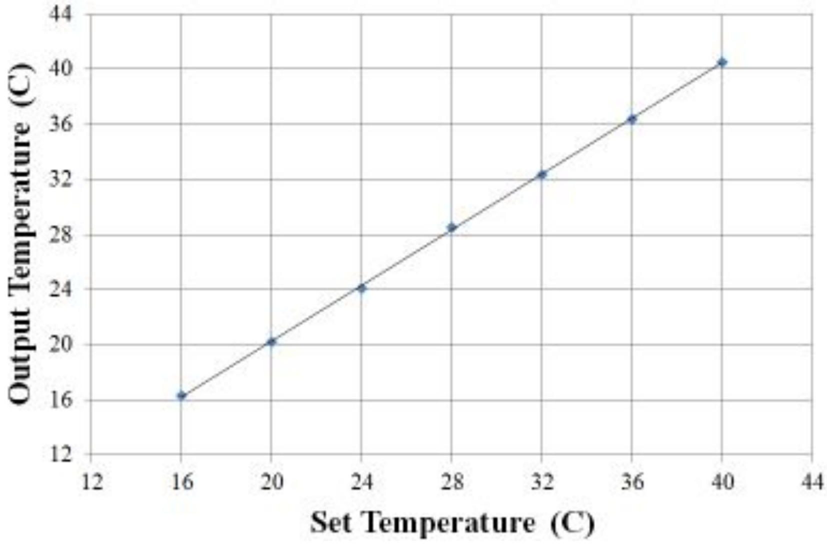


Figure 6.6: Steady state error of the system

6.3.3 Touch sensing results

As seen previously in Figures 6.5 and 6.6, the controller settles in approximately 2.3s on average and has an accuracy of 0.6^0C. Based on this data, the controller was able to detect the sensing in approximately 0.6s on average upon the removal of the finger.

Figure 6.9 depicts the usage of this system where the color changing pixels operates as a switch to turn the color on or off. As seen, as the user touches the textile, the system triggers the color change from color to colorless and vice versa. The resulting temperature change for colorless to color state (36^0C to 24^0C) is as seen in Figure 6.10.

We conducted technical evaluations to evaluate the performance and the robustness of the system. For each evaluation we tested 9 right handed participants (age 24-30 years, M = 27.33, SD = 1.92, 5 males, 4 females) with an average finger temperature of 31.04^0C (SD =1.77). In these evaluations, we observe the

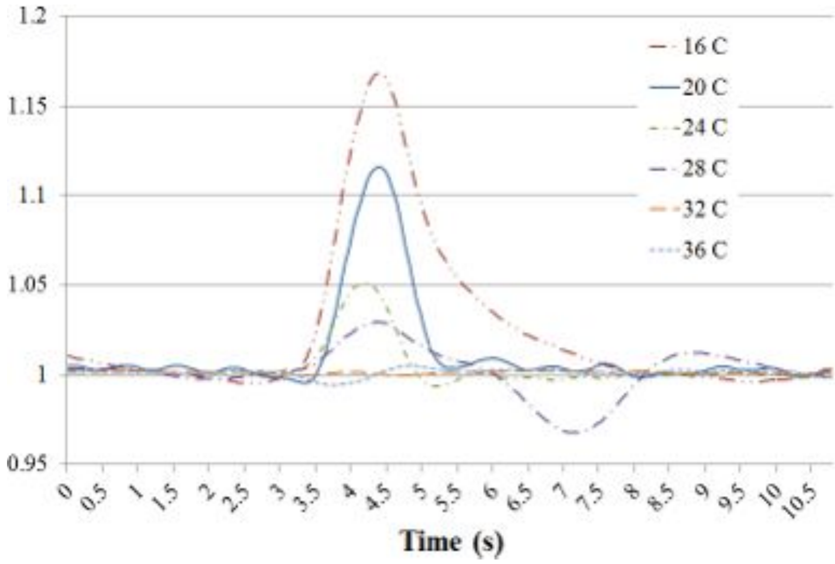


Figure 6.7: Normalised temperature changes caused by the finger for different steady state temperatures

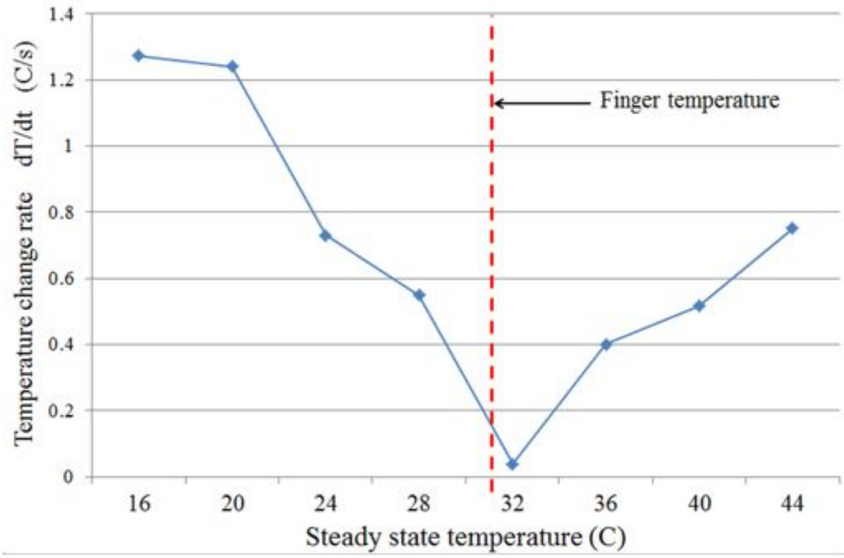


Figure 6.8: Temperature change rates caused by a touch at different steady state temperatures

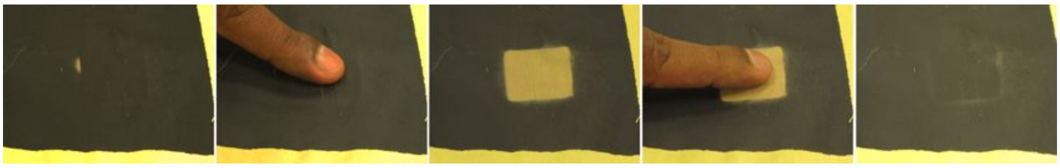


Figure 6.9: Sequence of images showing a Peltier pixel working as a touch-sensed switch to switch between color and colorless states

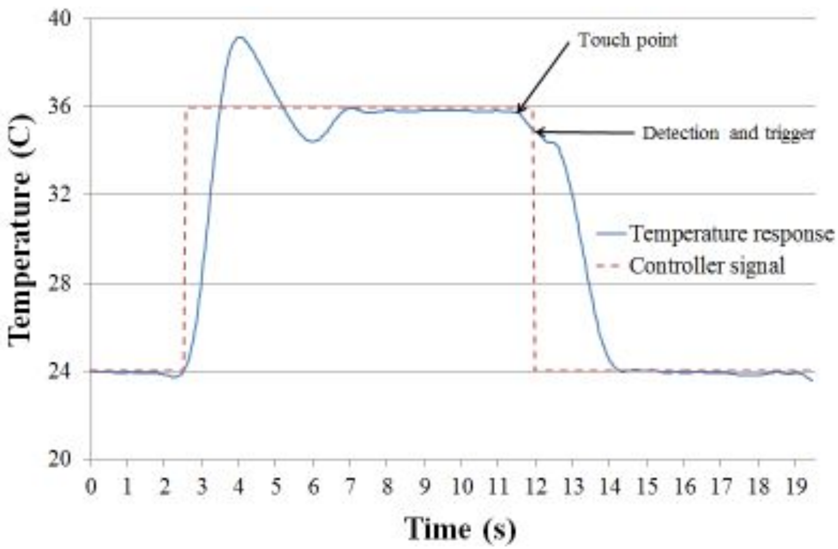


Figure 6.10: Transient detection and trigger by the system

temperature changing rates since we base the detection of touch based on these rates.

6.3.4 Evaluation 1: Detection speed

This evaluation tries to identify the detection speed of the system. To conduct this evaluation, we attached a capacitive touch sensor electrode to the Peltier pixel's double sided copper adhesive tape (the layer between the fabric and the Peltier module as seen in Figure 6.11). This allowed us to register the time the actual touch occurs and in turn calculate when the system detects the touch. We

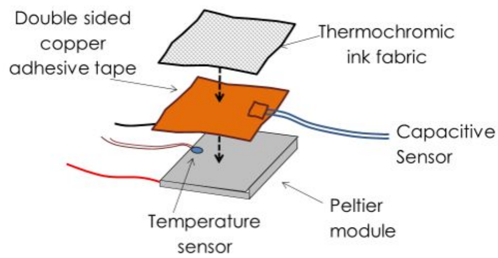


Figure 6.11: Attachment of the capacitive sensor

asked each participant to perform a single finger touch on the pixel 4 times for each set point between 16^0C and 44^0C.

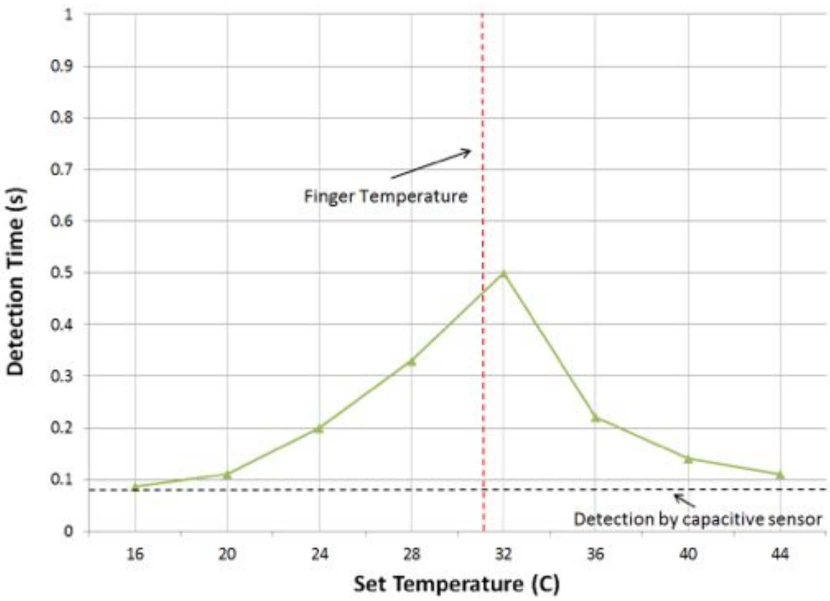


Figure 6.12: Detection speeds for different temperature set points

Figure 6.12 indicates the detection times for each set point. Through repeated experiments we found that the time for capacitive touch sensor to register a touch was approximately 0.09s for all set temperatures. With this, we can observe that the detection speed of the temperature based touch sensor increases when the difference between the finger temperature and the set temperature is higher.

6.3.5 Evaluation 2: Effect of finger temperature

The main goal of this evaluation is to monitor the temperature change rates when users of different finger temperatures use the system. Our preliminary experiment identified the performance of the system for users with an average of 31.27^0C. However, since some users may be from colder or warmer environments or simply with slightly different finger temperatures, we widened this temperature range using a separate second temperature controller to simulate wider finger temperatures. I.e., we used the second temperature controller which was set at different temperature levels. Before conducting the evaluation, through preliminary trials, we fine tuned the second controller and the set temperatures to achieve the correct finger temperatures. To conduct the evaluations, we asked the user to place the finger on the first controller for five seconds and instantaneously place the finger on the touch sensing controller.

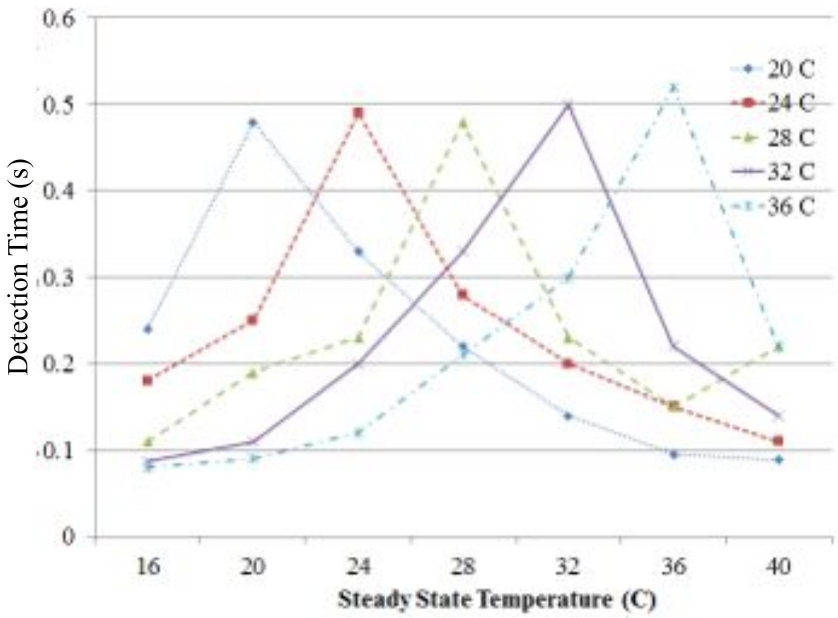


Figure 6.13: Detection speeds for users with different finger temperatures

Figure 6.13 indicates the results of this experiments. As per the previous observations in Figure 6.12 the detection speed curves take similar characteristic profiles where the speed is highest when closest to the temperature of the finger. Thus this result can be important to select the proper actuation temperatures when using this systems in different contexts where the user's finger temperature could be different.

6.3.6 Evaluation 3: Ambient temperature

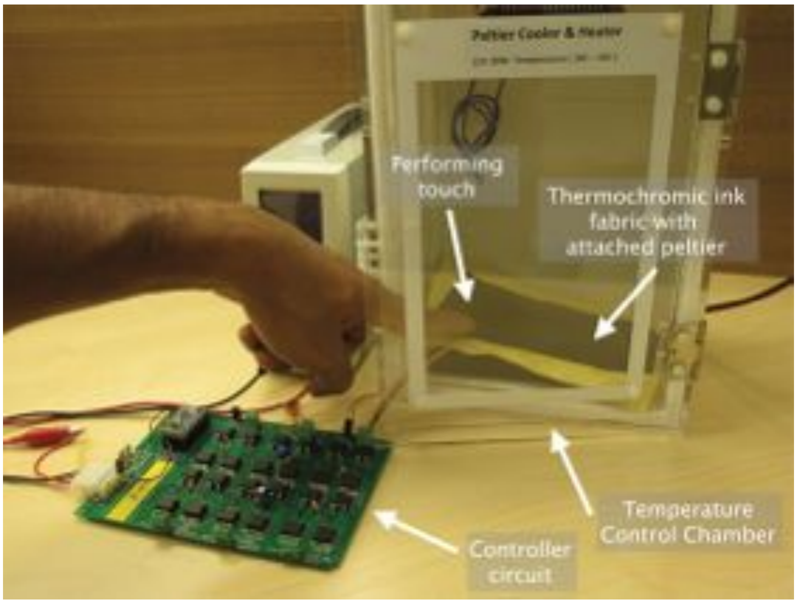


Figure 6.14: Setup of the ambient temperature control chamber for simulation and testing of the touch sensing system for different ambient temperatures

This evaluation tries to identify the effect of the ambient temperature on the system. As this system can be used in many wide contexts, it is important to identify the effect of different ambient temperatures on the system. We used a temperature controlled chamber to simulate different ambient temperatures ranging from 20^0C to 40^0 at 4^0C intervals. Once the system was placed in side the temperature chamber with different ambient temperatures, we asked each participant to touch the temperature controlled surface instantaneously and logged the temperature transient data. During the experiment we monitored the ambient temperature inside the chamber to ensure that it was maintained steadily. Figure 6.14 shows the setup of this evaluation. Figure 6.15 shows the averaged detection speed data for each of the room temperatures.

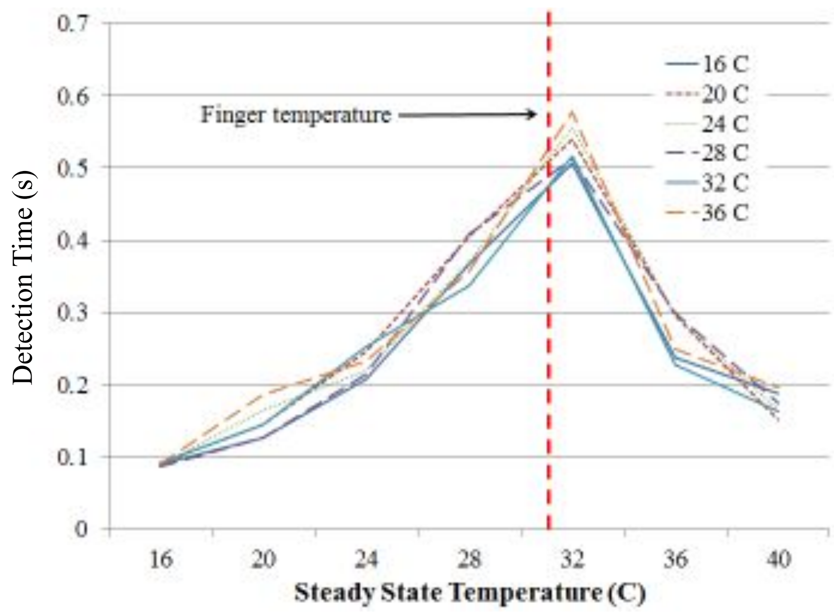


Figure 6.15: Detection speeds for different ambient temperatures

With Figure 6.15, we observe that the ambient temperature has no significant effect on the touch sensing mechanism. The ambient temperature mainly effected the rise time and settling time of the controller. As expected, the detection speed mainly relied on the finger temperature rather than the ambient temperature.

6.3.7 Evaluation 4: Effect of different textiles

Since the system is a non-light-emissive textile display that implements a touch sensing mechanism, this evaluation focuses on the effect of using different materials for the system. In addition, this is an important characteristic to observe as the material should facilitate enough heat to transfer from the finger to the temperature controlled surface. To conduct this study, we placed three different materials (silk taffeta-0.3mm thickness, cotton-0.7mm thickness and jeans-1mm thickness) on the temperature controlled surface and evaluated the touch detection speeds at different steady state temperatures. The resulting touch times are shown in Figure 6.16.

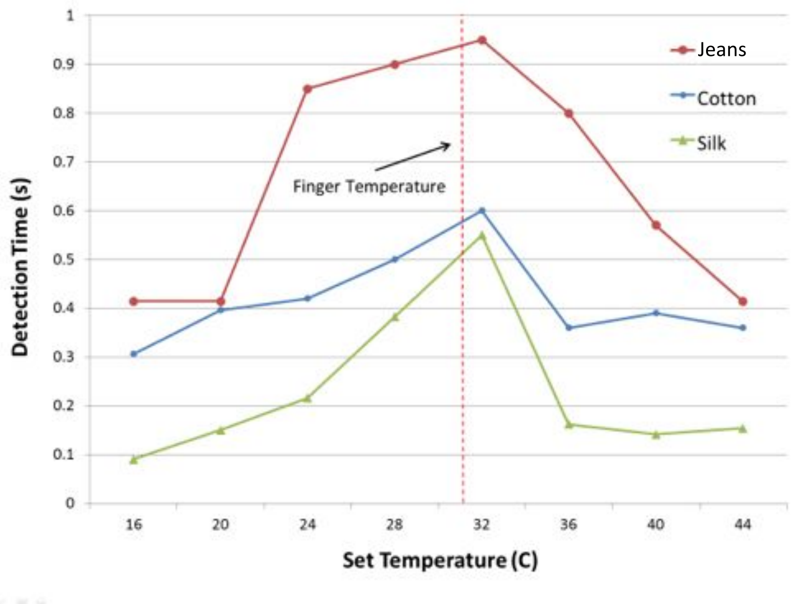


Figure 6.16: Temperature change rates caused by different textile materials

Accordingly the best performance was with the silk textile. With thicker materials such as jeans or cottons the temperature change rates decreased due to the higher thickness and the high thermal resistance of the material.

6.4 Applications

We implemented two table cloth based prototypes to identify potential applications of the above sensing technique. These prototypes are used to demonstrate the new interactivity of the system in comparison to most previous works which were fixed animations. For this purpose we use different arrangements of Peltier modules and black color thermochromic ink of 31^0C actuation temperature screen printed on to a yellow color silk textile.

6.4.1 Tic-tac-toe table cloth

To identify an application for this concept, we implemented a simple game on a 'table cloth'. We base this game on the popular tic-tac-toe game where two participants compete to select squares to try to form three in a straight line to win the game. The system setup is seen in Figure 6.17(a). At the start of the game the temperature of all nine squares are maintained at 28^0C which turns the ink into a faint black color. Next as each user alternatively selects squares by touching them, the system alternatively turn each square to a 'colored' (black) or 'colorless'(yellow) square as seen in Figure 6.17(c). Figure 6.17(d) indicates the final status of the game.

6.4.2 Drawing-pad table cloth

In this application, we used a 6x10 array of Peltier elements to implement a drawing pad on a table cloth. At the beginning all the squares would be maintained at

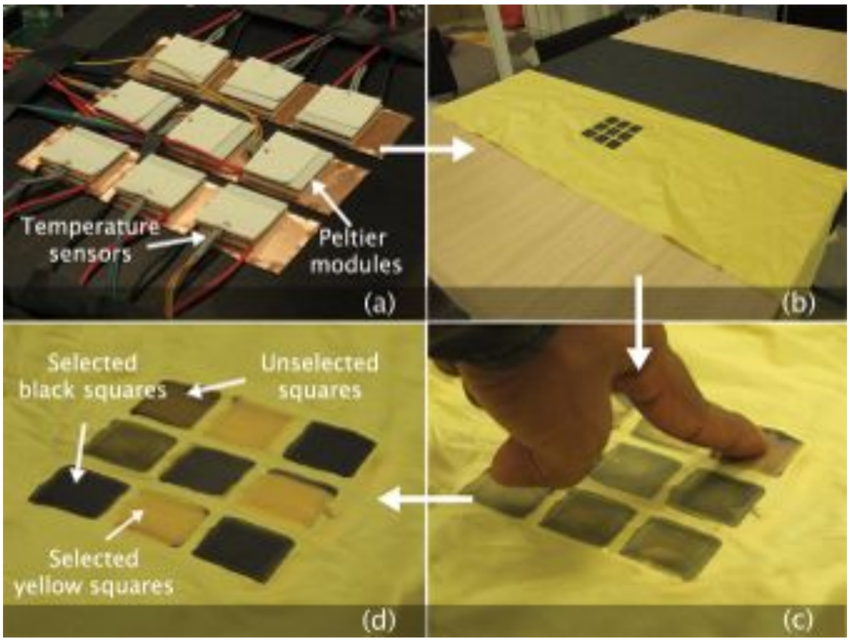


Figure 6.17: Tic-tac-toe game implemented on a table cloth (a) System set up with 9 Peltier elements and temperature sensors, (b) Table cloth with the tic-tac-toe game (c) touching to select squares (d) final stage of the game with four black squares three yellow-ish squares and two unselected light black squares

the ‘colored’ state at 24^0C. With the user’s touch, they are actuated to become colorless at 36^0C. If the user needs to ‘erase’ a certain actuated pixel, she can do so by touching that pixel again which will turn it back to the ‘color’ state (as was depicted in Figure 6.9). Figure 6.18 shows the usage of this prototype.

6.5 Discussion

This work presents a methodology for implementation of a temperature based touch sensor for thermally actuated textile displays. In this section we shall discuss the results, evaulations and present some of the limitations of the system.

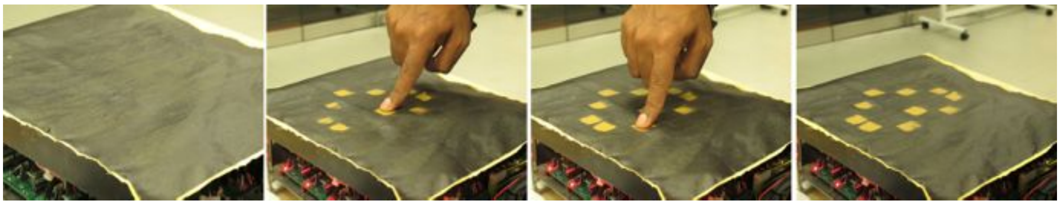


Figure 6.18: Interacting with the Drawing-pad application to draw a heart shape on the textile

6.5.1 Results and Evaluations

As observed earlier, the controller has a fairly acceptable transient time of 2.3s and an steady state error of 0.6^0C. This is of importance in determining the parameters for the touch sensor. With these results, the currently implemented touch sensor allows a $T_{threshold}$ of 0.6^0C and a minimum temperature change rate of 0.35^0Cs^{-1} to detect a touch. As observed, a touch can be detected within 0.6s which is of satisfactory levels for the current use contexts. In addition, since each Peltier pixel can be temperature controlled individually this system could also detect multipe touchs at the same time. Using this technology on the tic-tac-toe and drawing-pad prototypes were some examples of how a simple table cloth can become a subtly interactive with this technology.

Through the evaluations we presented the system's usability in different contexts. The system's ability to maintin the profile for different ambient temperatures was an important characteristic that presents the concept's usability at different conditions. In addition, by simply altering the working temperatures to suit the users' finger temperature profile, the system can work with fairly high robustness. However, the system should avoid the usage of thick textile materials which do not provide efficient heat transfer to ensure efficient detection.

6.5.2 Limitations

There are few limitations to the system. The first major limitation is the refresh time of the sensor. Since the system needs to enter into the steady state to move into the detection mode, it limits the ability to continuously detect the touch as a common touch sensor. Secondly, another limitation is the detection of a prolonged touch. I.e., we observed that if a user touches the system in a prolonged manner, after the first detection at the instant of the touch, the system compensates for the presence of the finger and reaches the required steady state temperature. Thus, the system currently can only detect instantaneous touches. However, in our next steps we will be investigating in identifying to resolve these issues where we can detect touch for prolonged times and on a continuous basis.

6.5.3 Expandability

The system uses Peltier semiconductor elements as the thermal actuator for the temperature sensitive inks. We mainly used Peltier elements due to its rapid temperature change rates and the ability to actuate a wide range of temperatures which was useful for our evaluations. Currently for evaluations and proof-of-concept prototypes purposes we present only a flat surface of textile for interaction. However, in Chapter 7 we present the use of 'miniature Peltier semiconductors' embedded on textile to present a flexible textile display. Thus, theoretically, we can use this principle to expand our technology into making a flexible interactive non-light-emissive textile display. As explained previously this sensing mechanism mainly requires a well tuned closed loop temperature control system irrespective of the thermal actuator. Thus, next, we discuss the expendability of this touch sensing mechanism to other commonly used thermal actuators.

One of the most commonly used thermal actuators in the field of textile displays are conductive yarns. They use their resistivity to generate heat as a current passes through the yarn. To conduct a preliminary study we did a basic experiment with a few pixels with conductive yarn controlled by a closed loop temperature controller. Even though a touch can be detected using the mechanism mentioned in this chapter, it was noted that the refresh time of the touch sensor with conductive yarn was relatively low. The slow heating rates and the absence of a cooling mechanism are the main contributors to this low rate as the controller takes a longer time to reach the steady state temperature. In addition, we also noted that if the pixel size is bigger, the temperature controllability is less due to the inaccurate measurement of the temperature. Thus, unless if the temperature was distributed uniformly, the user would have to directly touch the temperature sensor to trigger the touch sensor. But, it still was able to add a lower level interactivity to the textile display. (This work requires further evaluations to confirm these results)

Looking at the above result, it is possible that the same mechanism can be extended into other thermal actuators such as flexible heater pads to convert such into a touch sensor. Thus, with more improvements to the limitations mentioned above, this technology has the potential to convert such temperature controlled thermal actuators into low fidelity touch sensors to make them interactive.

6.6 Potential applications

As another aspect, we intend to improve the interaction scenarios of this concept. Currently we use this technology for two simple prototypes, a game and a drawing application. Therefore, in our next steps we intend to explore the technology's usage possibilities such as in clothes and other applications areas which could benefit from touch sensitive non-light-emissive textile displays.

6.7 Summary

This Chapter presents the development of a temperature based touch sensor. We were motivated to implement this touch sensor based on the observation and feedback of users at different international and local demonstration venues. However, the key novelty of this work is that the touch sensing has been implemented without the use of any additional hardware. As such, this new touch sensor can be implemented on any work that features a temperature controller. We have demonstrated this through two prototypes based on table cloth displays.

7

Continuous refinements to the system

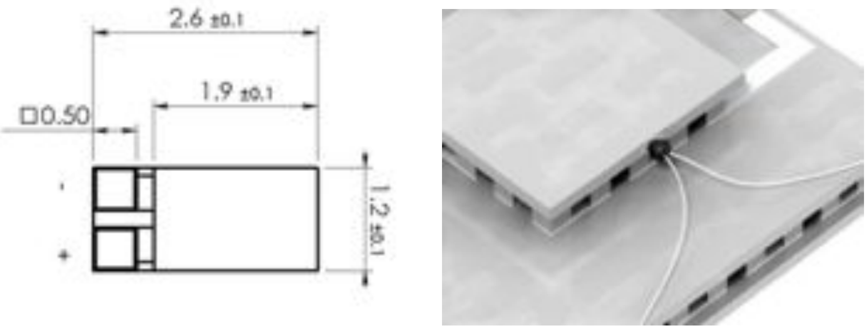
This chapter tries to address some of the possible improvements to the existing system. As such first we look at improving the system components with the introduction of a new miniature Peltier element.

7.1 System components

As observed, some of the limitations of the above systems were the relatively high power consumption for mobile applications and flexibility of the fabric after the integration. Even though they were well fitted for the stationary displays such as the furniture, they were used with difficulty in cases such as the wearable displays due to the weight and the rigidity of the existing Peltier elements. Thus as a significant change from our previous works, we use custom made miniature thinfilm Peltier elements for the actuation (Figure 7.1).

Figure 7.1: Miniature Peltier Element (MPE)

7.1.1 Miniature Peltier elements



(a) Miniature Peltier element footprint (b) Sensor attached to miniature Peltier element

Figure 7.2: Miniature Peltier elements

Our previous prototypes used Peltier elements of 60mmX60mm, 30mmX30mm and 15mmX15mm (Figure 3.4). Thus, to significantly improve on the previous system limitations, we use custom built Peltier modules of 2.6mmX1.2mm footprint size(Figure 7.2(a)). Here too, we have attached a temperature sensor to each of the Peltier modules, as shown in Figure 7.2(b), to accurately control the temperature through a feedback control system. The miniaturization of these thermal actuators allows them to be integrated at individual pixel level which increases the resolution of the display, it's flexibility, and significantly reduces the power consumption as compared to the larger Peltier elements used in prototypes.

7.1.1.1 Integration

To attach the Peltier modules to the fabric, we used double sided thermally conducting adhesive tape similar to the previous versions (Figure 3.10(b)). Using such tapes allowed firm attachment to the fabric. In addition, we used two thin layers of copper as the bottom layer for the Peltiers which acted as a heat dissipators to discard any excess heat. The use of materials such as thermal adhesive tapes and thin copper layers contributed to maintaining the flexibility of the new integration.

7.1.1.2 Technical Results

In this section we describe some of the key characteristics of the miniature Peltier elements (MPEs) and the closed loop control system and compare it with the similar results for the previously used larger Peltier elements(LPEs). Unless otherwise stated, the LPE in this chapter refers to a 15mmX15mm Peltier module which is the closest counter part to the MPE from our previous systems. The experiments are conducted at 24^0C room temperature with green and blue thermochromic inks screen printed in standard cotton fabric. Both inks are of an actuation temperature of about 31^0C. Hence the 'color' state refers to the temperature at 24^0C and 'colorless' state refers to a temperature of 32^0C.

- Temperature Controllability

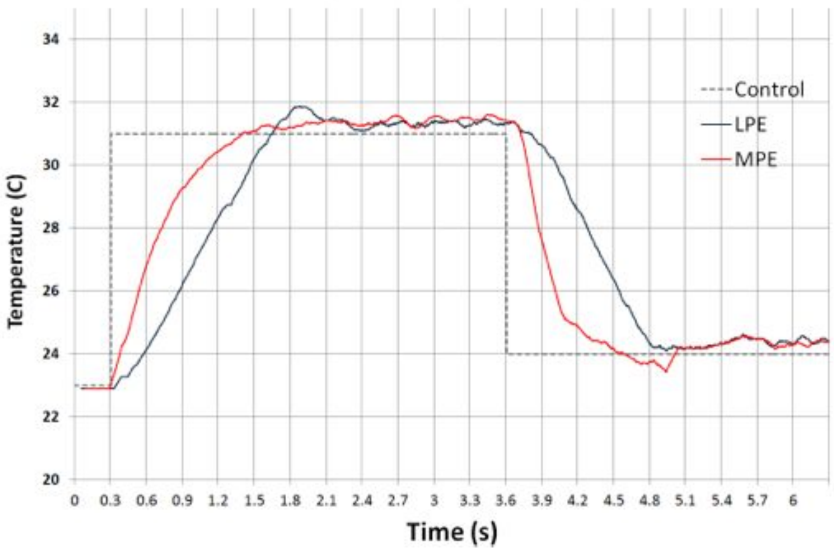


Figure 7.3: Temperature transient response

The transient characteristic for a single Peltier module for MPE and LPE is as in Figure 7.3. As seen, the rise time and fall time for the LPE is about 1.8s each and MPE is about 1.2s. This is rather an improvement of our previous results resulting in a much faster animated display. In addition, the steady state controllability of the system is with a maximum steady state error of 2% and an accuracy of about 0.3 to 0.5^{0}C.

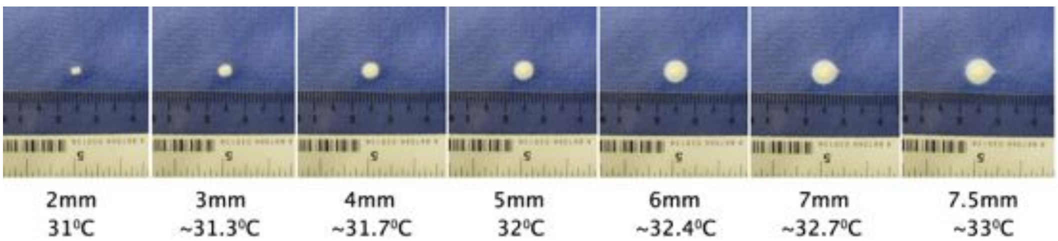


Figure 7.4: Pixel sizes and steady state power consumption for different temperatures

Figure 7.4 indicates the different pixel sizes for different temperatures. However for this prototype version, thermochromic inks of 32^0C actuation temperature were used which gives a pixel size of about 5mm.

- Power Consumption Characteristics

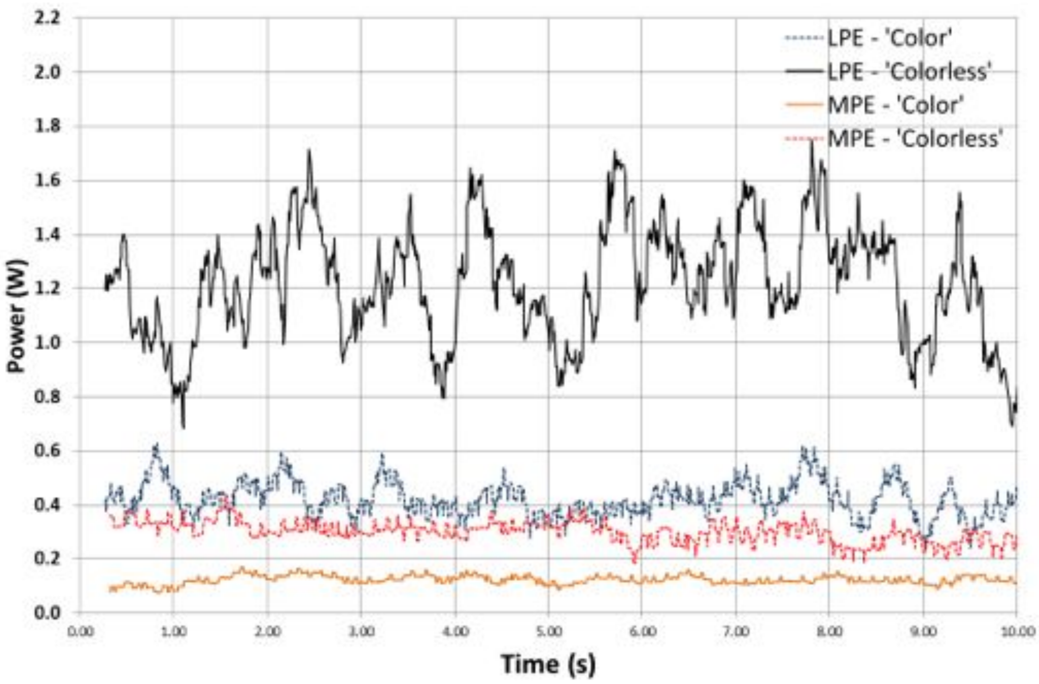


Figure 7.5: Power characteristics

For comparison reasons, the power characteristics are conducted for the 3x3 MPE pixelated display (15mmX15mm) and the LPE (the power consumption for a single MPE is approximately 1/9th of the MPE pixelated display values). The power consumption for MPE pixelated display and the LPE for colorless (32^0C) and color (24^0C) steady states are as shown in Figure 7.5. As observed the power consumption for the actuated colorless state for the MPE pixelated display and the LPE was 0.81W and 1.1W respectively. The power consumption for 'color' state for the same situations were 0.35W and 1.7W respectively. The steady state power consumption for the MPE is seen in Figure 7.6.

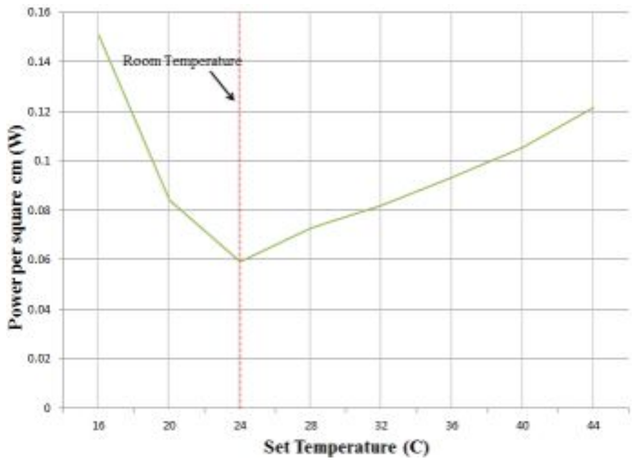


Figure 7.6: Steady state power for 1 MPE module

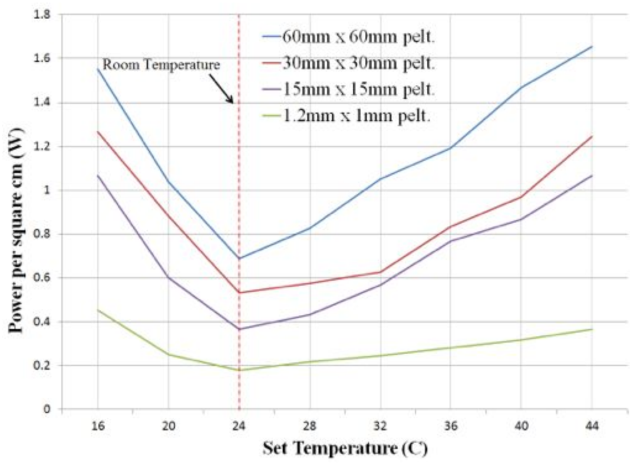


Figure 7.7: Steady state power for $1cm^2$ of each module

Figure 7.7 indicates comparison of the steady state power for 60mmX60mm, 30mmX30mm, 15mmX15mm and 2.6mmX1.2mm Peltier modules. For the comparison we have calculated the power required per 1 cm^2. Through this Figure, we can observe that the miniature Peltier element required significantly less power for the same area as compared to the other modules.

- Experimenting with different temperature ranges

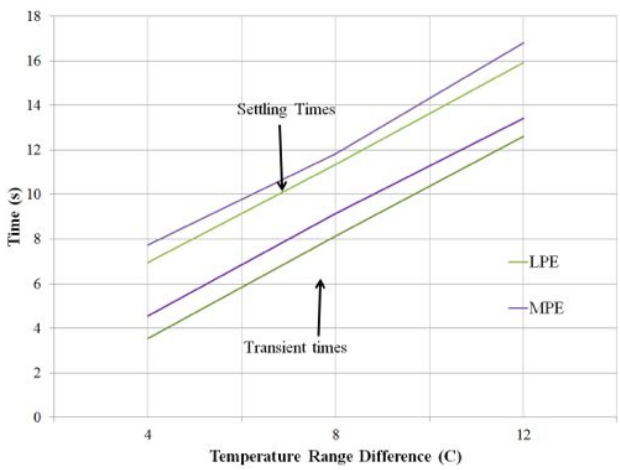


Figure 7.8: Transient and Settling times for different temperature ranges

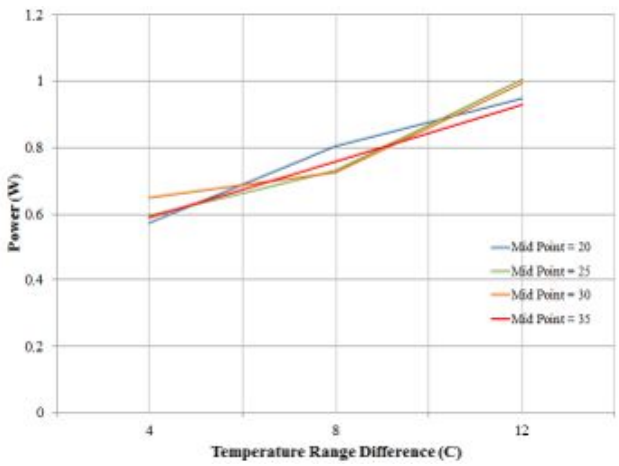


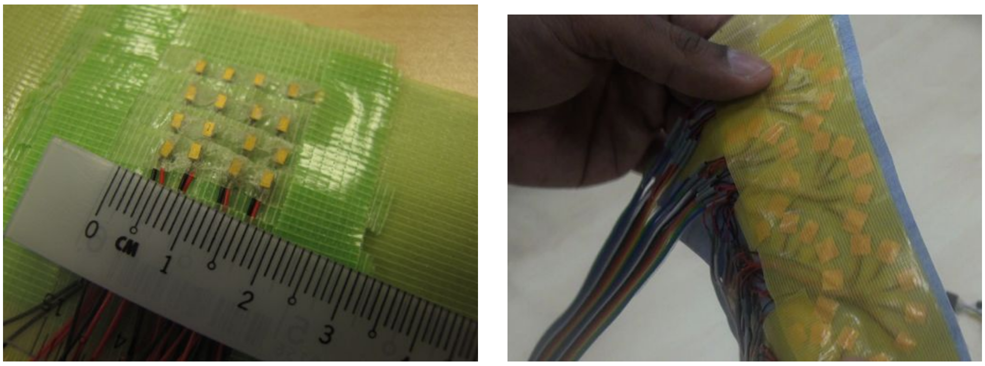
Figure 7.9: Power requirements for continuously transient states between two temperatures

In order to understand the timing and power characteristics for different temperature ranges, we conducted an experiment similar to Section 4.1.6. Figure 7.8

indicates the timing characteristics while Figure 7.9 indicate the power characteristics for a continuous transient state between two set points for 1cm^2 of MPE. We use the same temperature settings as mentioned in Table 4.2. As it can be observed, the timing characteristics are similar while the power characteristics follow a similar profile to the previous experiment was shown in Figure 4.11.

7.1.2 Prototypes

- Flexible Displays



(a) MPEs of the pixelated display (b) MPEs arranged in a wavy pattern

Figure 7.10: Attatching MPEs to the fabric

As an initial prototype (Figure 7.10(a)), a pixelated display was implemented on the fabric. For this purpose, each pixel was placed 5mm apart from each other. The pixel size according to the Peltier temperatures are discussed in the Section 7.1.1.2. Figure 7.10(b) depicts another prototype with the Peltier modules arranged in a wavy pattern.

Figure 7.11(a) and Figure 7.11(b) indicate some of the prototypes that utilize the MPEs. As observed the use of MPEs have significantly improved the flexibility of the display.

(a) 4x4 pixelated display

(b) Wave pattern textile display

Figure 7.11: Prototypes of textile displays

- Wearable Display

Figure 7.12: Wearable dress with miniature Peltier elemet textile display

Figure 7.12 depicts a dress fitted with the miniature Peltier elements that display 'necklace' patterns on the dress. In addition, the dress was completely battery operated with two AAA type batteries allowing it to to be operated continuously for approximately 4 hours.

7.2 Discussion

As observed in the Section 7.1.1.2, the miniaturization of the technologies has significantly improved the characteristics of the system. Currently, the transient time has been improved by 33% which gives 0.8 to 1 frames-per-second animateability. To actuate the same area of fabric, the MPE display takes 60% less power than the LPE. This is as important results as it is an early indication of the system's potentiality of being mobile and battery operated in the future. In addition, MPEs give a resolution of roughly 5 dots-per-inch.

Such characteristics could be observed as due to the difference in the mass of the pelter elements. Using MPEs presents noteworthy advantage in the weight per area average where it is 0.08g/mm^2 for MPEs and 0.2g/mm^2 for LPEs. Therefore from Q=mcΔt (Q-thermal energy, m-mass, c-specific heat capacity, t-temperature), the miniaturization of the system improves the transient and power requirement characteristics drastically. In addition, the flexibility of the system also increased as seen in Figures 7.11.

One of the key limitations of using LPEs is the requirement for larger heat sinks. However, with the MPEs, due to the higher efficiency and the reduced size, the system currently uses thermally conductive adhesive tapes with a thermal conductivity of 0.6W/m-k. In addition to the significant reduction in the power consumption, this is a major improvement which increases the material's flexibility, mobility and reduces the weight.

We have demonstrated these characteristics through the implemented prototypes. The flexibility and the mobility of the textile display has significantly improved over the previous versions by using the miniature Peltier elements. In addition, with the more efficient low power consumption, the textile displays on wearable show promising possibilities.

7.3 Summary

This Chapter introduces the main refinements of the system by using miniature Peltier elements. With the use of these new customized elements, the system's performance in relation to power requirements, flexibility and mobility have increase significantly. We have presented few prototypes to demonstrate these qualities with flexible, wearable and battery operated displays.

8

Discussion

This chapter attempts to summarize the knowledge achieved through this thesis. Thus, here we present some of the discussion related to the system, prototypes and application. Next, we present a design methodology for designing non-emissive textile displays where we present a guideline and discuss the how to select components and parameters for designing of a non-emissive textile display.

8.1 Discussion on the system

One of the main goals of this research was to identify key technologies that would enable a fully controllable, programmable non-emissive textile display. As such, we used thermochromic inks and with Peltier semiconductor elements combined with a tuned PID controller to achieve this goal. The Peltier elements' ability to rapidly heat and cool the thermochromic ink printed textile gives our system the advantage in producing subtle, yet, controllable and programmable animations on the textile.

We have presented the use of few different types of Peltier elements with the systems. These Peltier elements were selected based on the application context where the Peltier elements were chosen based on parameters such as the pixel size and power requirements. With our detailed technical analysis of the system, we presented critical results to analyse the performance of the system. In addition, with the introduction of the new custom made miniature Peltier elements, the results indicated significant improvements over the previous parameters. Thus, here, we summarize some of our results.

8.1.1 Speed of color change

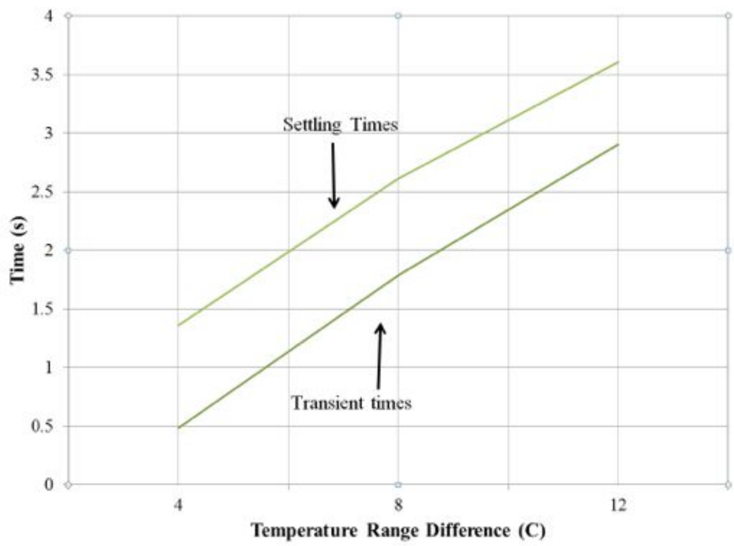


Figure 8.1: Summary of timing characteristics for temperature ranges

Through the observed systems, the color change was relatively fast compared to the previous system. In addition, the results indicated that there was no significant difference in the speed of temperature change for different Peltier elements. However, the temperature ranges experiments described in Section 4.1.6 and Section 7.1.1.2, show how the animation speed can be improved by customizing the actuation range of the thermochromic ink. These results are averaged and summarized in the Figure 8.1. Through observation we can see that for the tested results, the color change can be triggered within approximately 0.8s which can increase the frame rate of the animations on the textile up to about 1.5 FPS. Since the transient time refers to appearance of a single pixel of a single frame of the animation, the Frames-per-second animation can be determined by the inverse of the transient time. As such, the derived Frames-per-second graph is depicted in Figure 8.2.

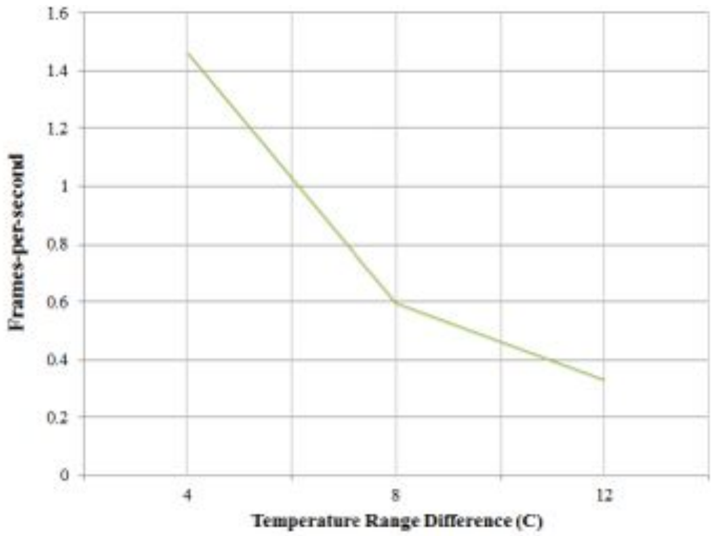


Figure 8.2: Frame rate for different temperature ranges

8.1.2 Power requirement

As the display system uses thermal actuation as the main enabling technology, power consumption is often a critical design factor. To address this we have done a number of power consumption analysis to identify optimal parameters for the

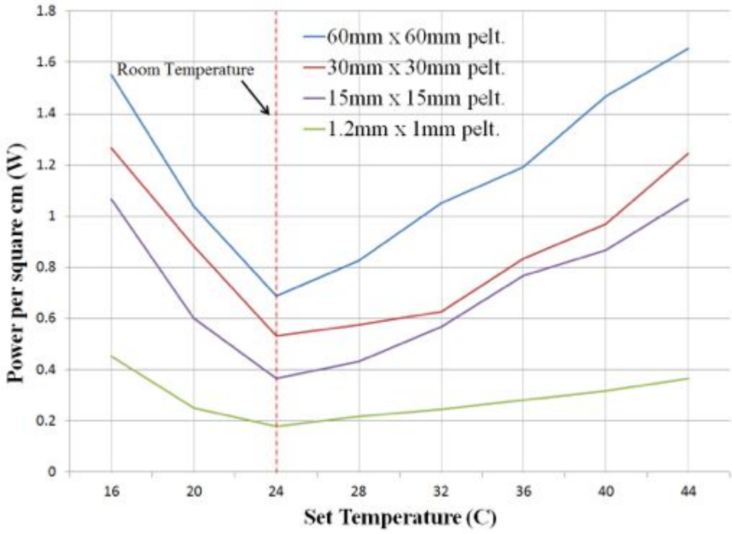


Figure 8.3: Steady state power requirements for 1cm^2

system's use. These results are summarized in Figure 8.3. Figure 8.4 show the temperature range test for the Peltier elements. For ease of reference, the results are calculated for the the actuation of a 1cm^2 area on the textile. These figures show a few interesting characteristics of the power consumption of the system.

- When the Peltier elements differ in size, their characteristics change with larger Peltier elements using the highest amount of power (Figure 8.3).
- The power consumption is minimal around the room temperature (Figure 8.3).
- The power consumption is minimal when the the temperature range between the color and the colorless temperatures are minimal (Figure 8.4).
- Power consumption is higher in the transient states compared to the steady state. This indicates that the power consumption would be higher for continuous animations on the textile(Figure 8.4).

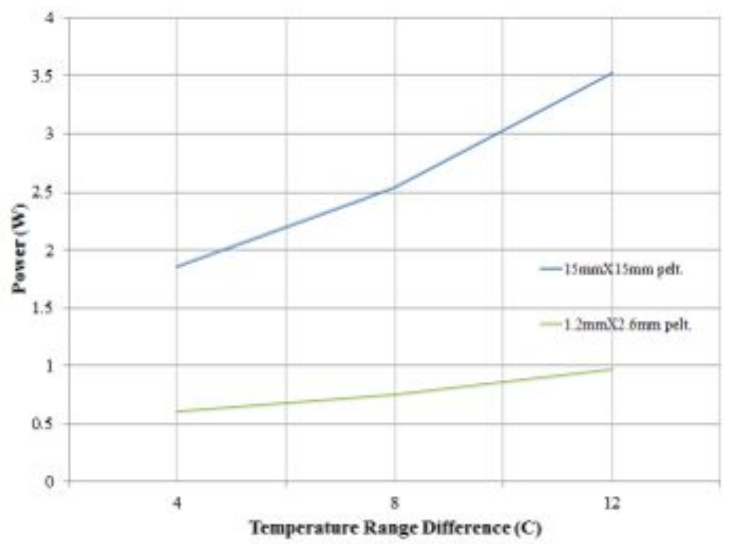


Figure 8.4: Transient power requirements for $1cm^2$

- All results indicate that the miniature Peltier elements possess the best power consumption characteristics for a non-emissive textile display. But in the case of stationary and flat displays with larger pixels, the use of larger Peltier elements could be suitable to ease the process of integration. For mobile displays, the use of miniature Peltier elements would be the best choice(Figure 8.3, Figure 8.4).

8.1.3 Prototypes and applications

Table 8.1 summarizes the prototypes we have developed and their features. Using the non-emissive textile display system, we have completed almost ten different prototypes and applications. These featured a range of application areas such as furniture related displays, pixelated displays, wearable displays, traditional textile craft, Augmented Reality, sensor fabrication, and flexible displays. This is an indication of the diverse applicability of a controllable non-emissive textile

Prototype	Used Peltiers	Ink actuation range (^{0}C)	Features
Wall painting	60mmX60mm	24-32	Proximity sensor triggered animation
Furniture - table cloth	60mmX60mm	24-32	Fixed animation
Pixelated Wearable	30mmX30mm	15 (Red), 31 (Green)	Fixed animation
Single Pixel Wearable	60mmX60mm	24-32	Fixed animation
Pixelated	30mmX30mm	5X24-32	Fixed animation
Byobu	30mmX30mm	24-32	Proximity sensor triggered animation
dMarkers	10mmX10mm	24-32	Sensor, program triggered animation
Sensor 35, 45	N/A No Peltiers	24, 25, 31,	

Table 8.1: Specifications of prototypes

display system. In addition, the programmability to perform various functions such as fixed animations, external sensor triggered applications show the dynamic nature the prototypes can be used. The use of miniature Peltier elements display promising possibility of the textile display as an integrated display that can have various different mobile applications.

8.1.4 Sensing system

We developed a temperature based sensing system as described in Chapter 6. The development of the sensor on top of the existing display platform with minor firmware changes allows any of the existing display prototypes to be used as touch sensitive displays without any additional hardware. As we displayed, the system is has relatively good sensing speed and is only reliant on the finger temperature and the material thickness.

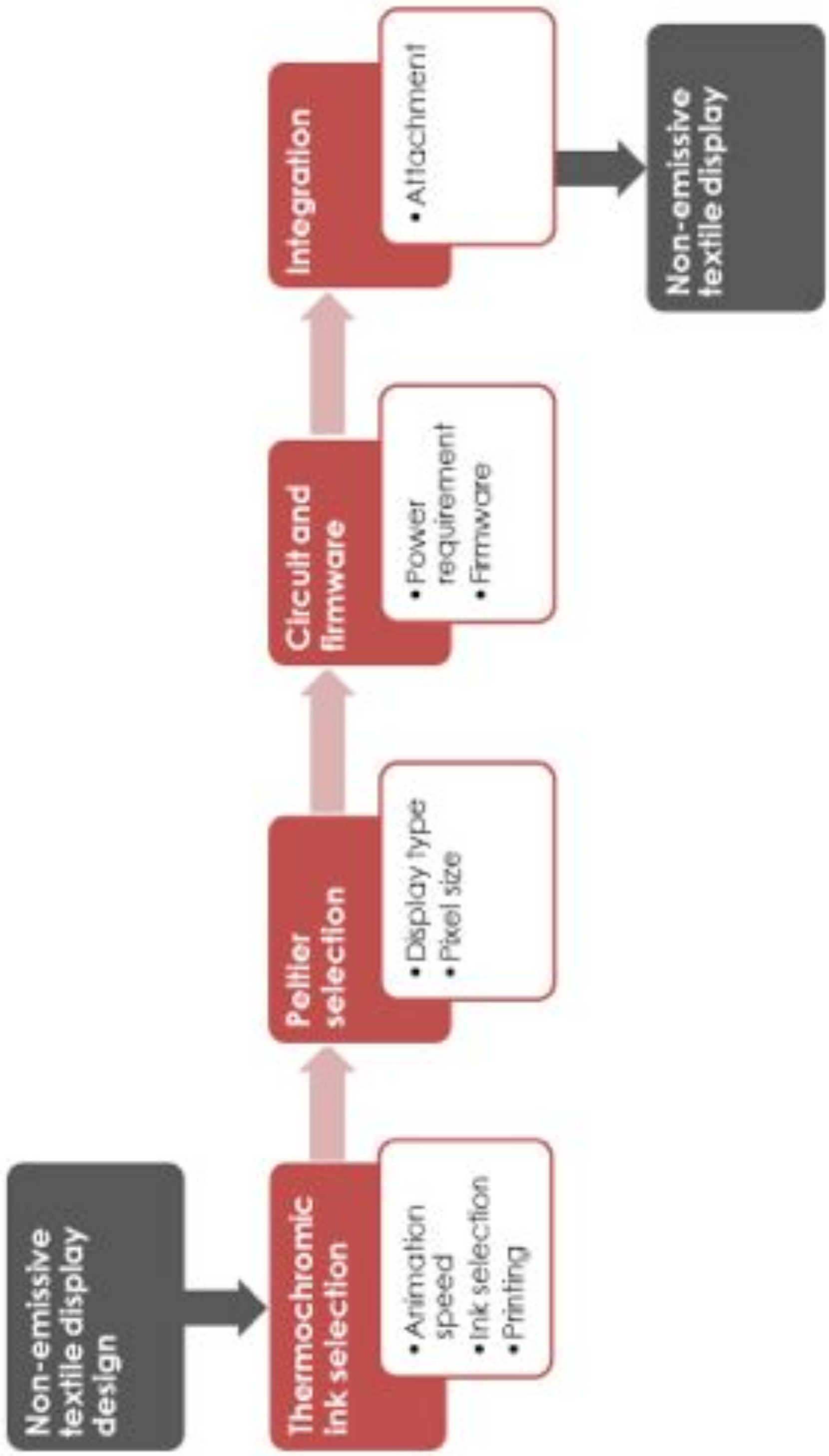


Figure 8.5: Design Methodology for a non-emissive textile display

8.2 Design methodology

Based on the design processes we experienced from the development of the prototypes Figure 8.5 summarizes the design methodology of the system. We identified four key steps for the process of designing a non-emissive textile display system. They are,

- Thermochromic ink selection
- Peltier selection
- Circuit and firmware design/implementation
- Integration

Next, we discuss the process of each of these steps.

8.2.1 Thermochromic inks

Thermochromic ink selection is the first step of this design process. This step consists of two sub steps: identifying the animation speed (which is useful for the next steps), ink selection and the printing.

- Animation Speed

Animation speed is critical in identifying the thermochromic inks for the system. Based on the animation speed in frames-per-second rate, we can determine the customization of the actuation temperature ranges for the thermochromic inks. I.e., by referring to Figure 8.2 we can estimate the actuation range of the thermochromic inks. Through our observed results, if the animation speed is to be 1 FPS, the suitable temperature difference should be approximately 6^0C for the thermochromic ink.

- Thermochromic ink selection

Once the thermochromic ink actuation range is selected, the color can be customized to the requirement of the system. It should be noted that once the thermochromic ink is heated, the base fabric would appear. Thus the color selection should be according to the requirement and such that there is enough color difference between the ink and the base fabric for the animation to be visible. In certain cases, the color change might be to a different color (instead of colorless). In such cases, the user can customize these colors according to the base fabric.

- Printing

The most common method used for printing thermochromic inks is screen printing. Generally, most such thermochrmoic inks require mixing the ink with a textile binder solvent which is usually provided by the supplier. Please refer to the supplier for the mixing details. According to the requirement, either the full fabric or individual pixel patterns (as seen in Section 5.1.1) can be printed with thermochromic inks.

8.2.2 Peltier selection

- Display type

The type of display could be flat and stationary, mobile or flexible. Ideally, even though miniature Peltier elements would be the best choice for any display, in some cases due to ease of integration, larger Peltier elements are suggested. However, this selection can be extrapolated into any type of Peltier element available in the market since, here, we only use the Peltier elements that were used in this research as a guide.

- Pixel size

If the user decide to use a Peltier other than a miniature Peltier element, the pixel size, could be the main factor to determine the selection of the Peltier element. Other than for mobile displays, larger Peltier elements, according to their size, are suitable for flat and stationary displays. As we have demonstrated in our prototypes in Chapter 5, the use of Peltier size can be dependent on the kind of image the user wishes to animate.

8.2.3 Circuit and Firmware

This step is mainly dependant on the selected temperature range of the thermochromic inks and the selected Peltier elements.

- Circuit design

The basic circuit design for a single Peltier element is as described in Section 3.1.1.3. For multiple Peltier elements this circuit can be repeated. The main factors in this step is the determination of the parameters of the MOSFET modules. Based on the parameters of the selected Peltier module, the maximum current required per module can be identified. Using this data the MOSFET modules can be selected such that the maximum current of the Peltier module is less than the maximum drain current rating of the MOSFET module. Next, based on the selected temperature range, the maximum required power per $1cm^2$ can be identified by referring to Figure 8.4 since the maximum power would occur during the transient state of the animation. As such the circuit can be designed to withstand the identified level of power.

- Firmware design

Upon the design of the circuit the firmware for the PID controller can be programmed as explained in Section 3.1.1.4.

8.2.4 Integration

The basic integration layout is as described in Section 3.1.1.6. The key element here is making sure of efficient heat transfer through all the layers from the Peltier element to the fabric.

8.3 Summary

This Chapter discusses and summarizes the work presented in this thesis. As such, we discuss the system with reference to speed of color change, power requirement, prototypes/application and the sensing system. In addition, we present a step-by-step design methodology for any future users of this technology to develop an non-emissive textile display.

9

Future Works

Besides the numerous applications made possible through this technology, we aim to work further on the fine tuning of this technology. To look at the future technological improvements of the system, we look at few main aspects.

9.1 Miniaturization using micro/nano technologies

A relatively new field of research in textiles is the use of nano/micro technologies [21, 62]. Nano technologies are applied in variety of textile applications such as surface modifications (water proof, wind proof, self cleaning, etc), smart materials (smell release/odor control, comfort and heat insulation, etc), etc. Therefore there is a vast potential of nano-technologies to be applied into the field of electronic textiles. As such, we look at the possibility of leveraging these advancements into the further development of this textile display system from a few stand points.

Firstly, the main novelty of the system leverages on the capabilities of the Peltier semiconductor modules. Thus, these semiconductors can be investigated for implementation at micro or nano levels to improve their characteristics such as efficiency, size and flexibility [24].

Next, we wish to investigate an alternative technology for Peltier elements using carbon nano-tubes and nano-scale heaters. A promising possibility for this research is the investigation of in the field of nano-electronics is the carbon nano-tubes. Carbon nano-tubes are cylindrical nano-structures that posses extraordinary thermal conductivity and electrical properties. Larger structures of carbon nano-tubes have been utilized for thermal management of nano-electronics. If such carbon nano-tubes could be utilized as coolers combined with nano-scale heaters, it could vastly improve the current efficiency issues of the Peltier elements. In addition, integration of such technology would be easier as the textiles and the nano-electronics can be integrated more flexibly.

By investigating these techniques we believe that the thermal actuators for thermochromic inks can be developed in the form of a string. These strings can be used in a similar fashion to those used in textile fabrication industry which we discuss next.

9.2 Weaving technology and textile together

During the course of this research, we have revisited the textile fabrication industry in order to understand the fundamentals of the textile fabrication aspects. As such we have come across techniques such as spinning yarn manufacture, weaving fabric manufacture or knitting manufacture as different fabrication processes that are used in the textile industry. This is important since, in order to make this technology and the textile a synergy, it needs to be streamlined from the beginning of the process.

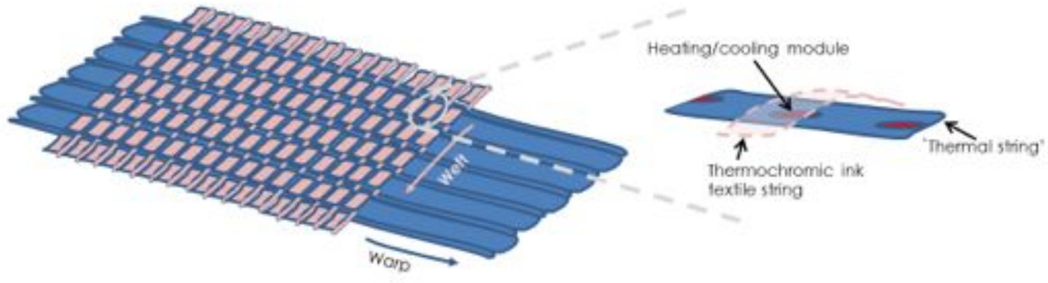


Figure 9.1: Weaving concept

Some research that uses the weaving technique shows promising potential for our research [80]. As such, we wish to integrate these technologies into the fabric as a complete material using the weaving techniques. We intend to use the miniaturized 'thermal string' (as described in the previous section) in the warp direction and the thermochromic ink textile string in the weft direction (Figure 9.1). However, as indicated in Figure 9.1, this work requires careful coordination between the thermal string and the textile string (with thermochromic inks) such that the thermal string lays below the thermochromic ink string.

We fabricated flexible PCBs (Figure 9.2(a)) to construct the 'LED string' and integrated them with textile strings using a hand-made and hand operated mini-loom (Figure 9.2(b)) to conduct this initial phase of testing. The Figure 9.2(c) shows the conceptualization of this initial attempt using LEDs as a guide. The Figure 9.2(d) and Figure 9.2(e) show the second version of this display using individually controlled multicolor LEDs. Using these observations, we are confident that we can achieve a completely woven and programmable textile display that

(a) Flexible PCBs (b) Mini-loom (c) Woven LEDs - version 1

(d) Woven multicolor LEDs structure

(e) Woven multicolor LEDs

Figure 9.2: First and second version of woven LEDs using a mini-loom

can be used a normal textile material.

9.3 Future Applications

The numerous prototypes we have demonstrated the ability of this technology to ubiquitously blend into many different application fields. Thus, through further refinement, we intend to explore the usability of this technology in application areas such as paper based non-emissive digital displays and camouflaging.

Paper based non-emissive displays could have a big impact with the rise of popularity of e-book readers such as Amazon Kindle [7]. In addition, coupling this technology with the presented touch sensitive system (Chapter 6) and commercially available thermochromic ink based pens [33] could device an application similar to normal writing paper where the written words (or drawings) can be detected and digitally stored. In addition, it could be enhanced for auto spelling corrections where the misspelt word can be automatically corrected and written on to the paper.

Another application area we are looking at is camouflaging. Since this technology does not use any light emissive materials, pattern based camouflaging can occur actively on the textile. This could be beneficial for military applications where the the soldiers clothes or temporary tent units can adopt to various environments and automatically camouflage themselves.

9.4 Summary

This Chapter presents future directions possible with this technology. Thus, by investigating these mechanisms, their processes, such could be used to integrate the current technology into the textile. For example, a yarn constructed out of the nano scale electronics of the system can be interwoven into the textile during the weaving process. Thus it would create a completely uniform, integrated textile material. Next, we have presented future application scenarios where animated paper that can detect writing and even auto-correct spelling mistakes and auto camouflaging materials that can be suitable for military applications.

10

Conclusion

This work presents a research entitled "Development of an integrated, programmable, non-emissive textile display material". Here we present a systematic approach to the development of the display system, implementation of prototypes, development of a touch sensor for the system with prototypes, improvements to the overall system, discussion of the whole work with a design methodology and future scenarios of the system. As such, this chapter concludes the works presented.

In the current field of ubiquitous computing research, textile displays have become a popular area of research. The usage of textiles in a wide range of daily uses has led to this popularity where this field of research tries to explore ways and methods of embedding information on these materials. As such, the field of textile displays can be categorized as emissive and non-emissive displays. In emissive displays, researchers use emissive materials such as LEDs, fiber optics, etc. which emit light. Alternatively, non-emissive displays use a more subtle and ambient approach with the use of materials such as thermochromic inks which allow the actuation of the actual color of the textile itself.

In this dissertation we focus on the implementation of a controllable non-emissive textile display that uses thermochromic inks. Due to current limitations such as the absence of an active cooling system, most such displays are only actuated in one direction which limits their controllability as an active display. We overcome this issue using Peltier semiconductor elements which is tied with the thermochromic inks using a feedback PID controller to accurately control the color change and in turn control the display. We present a comprehensive system description and numerous prototypes that illustrates the system's usability and ubiquity.

As such, Chapter 1 of the dissertation introduces the research area with our research objective motivation, background and a presentation of the dissertation structure. Our main research objective is *"Identifying the key development technologies for a non-emissive textile display material that can be seamlessly merged with the everyday textile objects around us"*. Using the ubiquity of textiles as almost an essential item in our daily routines today as our motivation, we present the use of current research frameworks such as Organic User Interfaces and Analog Digital Continuum.

Chapter 2 presents the details of the work related to this thesis. We present these works under the categories of textile displays, and in addition, works related to our prototypes such as merging with traditional textile craft, dynamic marker and sensing systems.

Chapter 3 focuses its attention on presenting the detailed description of the system. We present background of our main components of thermochromic inks and Peltier semiconductors, and detail the firmware implementation. Next we present the integration technique that is commonly used in our textiles display prototypes.

Chapter 4 conducts an in-depth analysis of the system. With focus on temperature controllability, color controllability, multi-color display study, power characteristics and experimentation with different temperature ranges, the chapter analyses the system's performance through many different focuses. In addition, we present some of the advantages and disadvantages of the system as observed through its performances.

Chapter 5 discuses numerous prototypes we have implemented with the described system. The initial prototypes of furniture related displays (animated wall paintings, and table cloths), pixelated displays, and wearable displays are presented. Next we present applications in the areas of merging of this contemporary technology with traditional textile craft of Byobu, construction of a dynamic marker for Augmented Reality application and the fabrication of a temperature sensor using thermochromic and Augmented Reality technologies.

Chapter 6 tries to address the implementation of a novel temperature based touch sensor using the existing display system. Here we present the detailed system along with its technical evaluation and two prototypes of a tic-tac-toe table cloth game and a drawing pad on textiles. This sensing system is built on top of the existing display system without the need for any additional hardware.

Chapter 7 describes the novel use of miniature Peltier elements as a significant improvement to the system. Here, with the use of the miniature Peltier elements, we present the improvements to the system in the areas of power consumption, flexibility and weight. As such with these improvements, new prototypes such as wearable and mobile displays are presented.

In Chapter 8, we present the discussion of the dissertation. We address a variety of areas such as system components, power consumption, color controllability and summarize the results of the research. In addition, we present a design methodology for the design of non-emissive textile display systems for future uses.

Chapter 9 presents some of the works we intend as the future research and development direction. As such we have proposed the use of nano-technologies for further refinement of technologies and the use of textile fabrication methodologies to integrated the textile and the technology.

As such, due to the calm and subtle nature of this animated fabric display, we envision that this research will be able to breathe life into textiles around us. Furthermore the ability of this technology to present subtle yet fast changing animations on fabric preserves the ubiquity of the fabric while turning it to a digitized display medium. Hence we envision that this technology would radically challenge the boundaries of current research.

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Appendices

A : Selected Publications

.1 Relevant Publications

- Journal Articles
  - Roshan Lalintha Peiris, Jeffrey Tzu Kwan Valino Koh, Mili John Tharakan, Owen Noel Newton Fernando, and Adrian David Cheok AmbiKraf Byobu: Merging Technology with Traditional Craft. Interacting with Comput. first published online February 6, 2013
  - Roshan Lalintha Peiris, Mili John Tharakan, Owen Noel Newton Fernando et al. (2012) AmbiKraf : Non-emissive, ubiquitous textile display. In Multimedia Tools and Applications. (http://www.springerlink.com/content/c560r6222gj10426/)
- Conference Publications
  - Roshan Lalintha Peiris and Ryohei Nakatsu. 2013. TempTouch: a novel touch sensor using temperature controllers for surface based textile displays. In Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces (ITS '13). ACM, New York, NY, USA, 105-114. DOI=10.1145/2512349.2512813 http://doi.acm.org/10.1145/251234

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- Roshan Lalintha Peiris, Mili John Tharakan, Newton Fernando, and Adrian David Chrok. 2011. AmbiKraf: A Nonemissive Fabric Display for Fast Changing Textile Animation. In Proceedings of the 2011 IFIP 9th International Conference on Embedded and Ubiquitous Computing (EUC '11). IEEE Computer Society, Washington, DC, USA, 221-228. DOI=10.1109/EUC.2011.13

- Roshan Lalintha Peiris, Owen Noel Newton Fernando, Chua Su Bee, Adrian David Cheok, Arij Glycin Ganesan, and Prabhash Kumarasinghe. 2011. dMarkers: ubiquitous dynamic makers for augmented reality. In Proceedings of the 10th International Conference on Virtual Reality Continuum and Its Applications in Industry (VRCAI '11). ACM, New York, NY, USA, 217-224. DOI=10.1145/2087756.2087787

- Roshan Lalintha Peiris, Owen Noel Newton Fernando, and Adrian David Cheok. 2011. A dynamic AR marker for a paper based temperature sensor. In Proceedings of the Second international conference on Ambient Intelligence (AmI'11), David V. Keyson, Mary Lou Maher, Norbert Streitz, Adrian Cheok, and Juan Carlos Augusto (Eds.). Springer-Verlag, Berlin, Heidelberg, 195-199. DOI=10.1007/978-3-642-25167-2_24

– Roshan Lalintha Peiris, Owen Noel Newton Fernando, and Adrian David Cheok. 2011. Flexible, non-emissive textile display. In Proceedings of the Second international conference on Ambient Intelligence (AmI'11), David V. Keyson, Mary Lou Maher, Norbert Streitz, Adrian Cheok, and Juan Carlos Augusto (Eds.). Springer-Verlag, Berlin, Heidelberg, 167-171. DOI=10.1007/978-3-642-25167-2_20

– Roshan Lalintha Peiris, Mili John Tharakan, Adrian David Cheok, and Owen Noel Newton. 2011. AmbiKraf: a ubiquitous non-emissive color changing fabric display. In Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments(MindTrek '11). ACM, New York, NY, USA, 320-322.

– Peiris, R. L., Cheok, A. D., Teh, J. K., Fernando, O. N., Yingqian, W., Lim, A., Yi, P., Polydorou, D., Ong, K. P., Tharakan, M., and Hoogendoorn, K. 2009. AmbiKraf: an embedded non-emissive and fast changing wearable display. In ACM SIGGRAPH 2009 Emerging Technologies (New Orleans, Louisiana, August 03 - 07, 2009). SIGGRAPH '09.

– Roshan Lalintha Peiris, Adrian David Cheok, James Keng Soon Teh, Owen Noel Newton Fernando, Mili Tharakan, Kris Hoogendoorn, Wen Yingqian, Andre Lim, Pan Yi 2009. AmbiKraf: An embedded non-emissive and fast changing wearable display. In proceedings of Interactive Tokyo-iTokyo (Tokyo, Japan, October 24, 2009). iTokyo '09.

– Peiris, R. L., Cheok, A. D., Teh, J. K., Fernando, O. N., Tharakan, M., and Hoogendoorn, K. 2009. AmbiKraf: An embedded non-emissive

and fast changing fabric display. In Smart Textile Salon 2009, Prototype Exhibition (Ghent, Belgium, September 25, 2009).

- Jeffrey Tzu Kwan Valino Koh, Roshan Lalintha Peiris, Kening Zhu, Doros Polydorou, and Ryohei Nakatsu. 2012. Uncovering analogness and digitalness in interactive media. In Proceedings of the 30th ACM international conference on Design of communication (SIGDOC '12). ACM, New York, NY, USA, 233-242.
- Jeffrey Tzu Kwan Valino Koh, Kening Zhu, Kasun Karunanayaka, Doros Polydorou, Roshan Lalintha Peiris, and Ryohei Nakatsu. 2013. Characterizing the analog-like and digital-like attributes of interactive systems. Communication Design Quarterly Review 1, 2 (January 2013), 8-36.
- Jun Wei, Xuan Wang, Roshan Lalintha Peiris, Yongsoon Choi, Xavier Roman Martinez, Remi Tache, Jeffrey Tzu Kwan Valino Koh, Veronica Halupka, and Adrian David Cheok. 2011. CoDine: an interactive multi-sensory system for remote dining. In Proceedings of the 13th international conference on Ubiquitous computing (UbiComp '11). ACM, New York, NY, USA, 21-30.

• Demonstrations

- AmbiKraf Repair, Festival Arst Electronica Linz, Austria September 2010
- AmbiKraf Open Space, International Communication Association Conference June 2010

  - AmbiKraf Digital ConTEX Tokyo, Japan November 2009
  - AmbiKraf Emerging Technologies, SIGGRAPH New Orleans, USA August 2009

- Awards

  - AmbiKraf Honorary Mention at the Nokia Ubimedia MindTrek Awards 2010

.2 Other Publications

- Journal Articles

  - Dilrukshi Abeyrathne, Chamari Edirisinghe, Nimesha Ranasinghe, Kasun Karunanayaka, Kening Zhu, Roshan Lalintha Peiris, Owen Noel Newton Fernando, Adrian David Cheok, Lan Lan, and Yukihiro Morisawa. 2011. Connected online and offline safe social networking for children.Computers in Entertainment. 9, 2, Article 9 (July 2011), 8 pages. DOI=10.1145/1998376.1998380
  - Cheok, A.D.; Tan, R.T.K.C.; Peiris, R.L.; Fernando, O.N.N.; Soon, J.T.K.; Wijesena, I.J.P.; Sen, J.Y.P., "Metazoa Ludens: Mixed-Reality Interaction and Play for Small Pets and Humans," Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on , vol.41, no.5, pp.876,891, Sept. 2011
  - Wei Liu, Keng Soon Teh, Adrian David Cheok, Roshan L. Peiris, Athanasios V. Vasilakos Charissa Lim Mei-Ling and Yin-Leng Theng: Internet-enabled and Ambient Intelligent Tangible User Interfaces for Distance Learning that Combine Art and Technology. International Journal of Technology and Human Interaction, Vol. 5, No. 1, Jan-March 2009, Pages 51-77
  - Adrian David Cheok, Roshan Lalintha Peiris, Charith Lasantha Fernando, Owen Noel Newton Fernando, Khoo Eng Tat: Energy and Touch-Information for Body-worn Ubiquitous Computing. International Journal of Energy Technology and Policy Vol. 7, No.2, 2009, 137-166.

  - Roger Thomas Kok Chuen Tan, Adrian David Cheok, Roshan Peiris, Vladimir Todorovic, Hui Cong Loi, Chiu Weng Loh, Dung Thi Khanh Nguyen, Janyn Yin Ping Sen, Elvin Zhiwen Yio, Tan Bing Siang Derek. Metazoa Ludens: Mixed Reality Interactions and Play for Small Pets and Humans: Leonardo Journal, Vol. 41, No. 3, June 2008, Pages 308-309

- Conference Publications

  - Adrian David Cheok, Jeffrey Tzu Kwan Valino Koh, Roshan Lalintha Peiris, and Owen Noel Newton Fernando. 2011. Mixed reality lab Singapore: a genealogy of lab projects employing the blue sky innovation research methodology. In Proceedings of the ACM 2011 conference on Computer supported cooperative work (CSCW '11). ACM, New York, NY, USA, 17-24.

  - Jun Wei, Roshan Lalintha Peiris, Jeffrey Tzu Kwan Valino Koh, Xuan Wang, Yongsoon Choi, Xavier Roman Martinez, Remi Tache, Veronica Halupka, and Adrian David Cheok. 2011. Food Media: exploring interactive entertainment over telepresent dinner. In Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology (ACE '11), Teresa Romo, Nuno Correia, Masahiko Inami, Hirokasu Kato, Rui Prada, Tsutomu Terada, Eduardo Dias, and Teresa Chambel (Eds.). ACM, New York, NY, USA, , Article 26 , 8 pages.

  - Jun Wei, Adrian David Cheok, Xavier Roman Martinez, Remi Tache, Yongsoon Choi, Jeffrey Tzu Kwan Valino Koh, Roshan Lalintha Peiris, Xuan Wang, and Qing Zhu. 2011. FoodGenie: play with your food edible interface for communication and entertainment. In SIGGRAPH Asia 2011 Emerging Technologies (SA '11). ACM, New York, NY, USA, , Article 23 , 1 pages.

- Dilrukshi Abeyrathne, Roshan Lalintha Peiris, Nimesha Ranasinghe, Owen Noel Newton Fernando, and Adrian David Cheok. 2010. Food internet communication. In Proceedings of the 7th International Conference on Advances in Computer Entertainment Technology (ACE '10). ACM, New York, NY, USA, 49-52.

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- Cheok, A. D., Fernando, O. N., Fernando, C. L., Zhu, K., Withana, A.I., Ranasinghe, N., Morisawa, Y., Karunanayaka, K., Danjo, M., Godage, I. S., Narangoda, M., Ma, N. L., Dayarathna, M., Peiris, R. L., Teh, J. K. S., Abeyrathne, D., Edirisinghe, C. P., Hoogendoorn, K., Hou, J., and Thang, W. 2009. Petimo: enhanced tangible social networking companion for children. In Proceedings of the international Conference on Advances in Computer Enterntainment Technology (Athens, Greece, October 29 - 31, 2009). ACE '09, vol. 422. ACM, New York, NY, 411-412.

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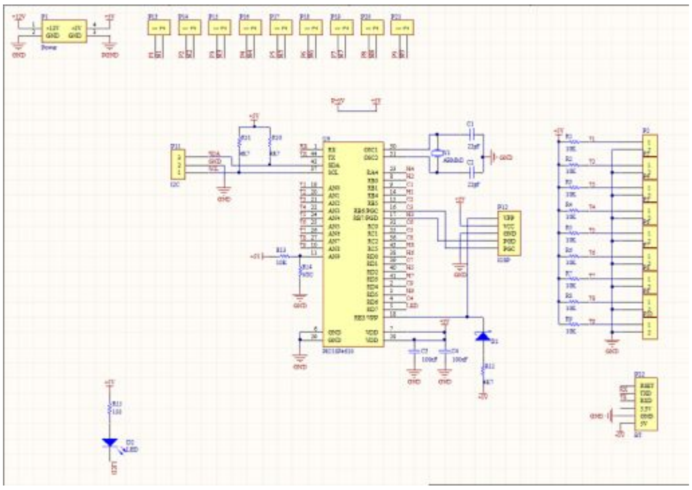
- Cheok, A. D., Fernando, O. N., Fernando, C. L., Zhu, K., Ranasinghe, N., Narangoda, M., Godage, I. S., Peiris, R. L., Teh, J. K. S., Edirisinghe, C. P., Karunanayaka, K., Merritt, T., Abeyrathne, D., Hou, J., Thang, W., Morisawa, Y., Dayarathna, M., Withana, A.I., Ma, N. L., and Danjo, M. 2009. Petimo: safe social networking robot for children. In Proceedings of the 8th international Conference on interaction Design and Children (Como, Italy, June 03 - 05, 2009). IDC '09. ACM, New York, NY, 274-275.

- Owen Noel Newton Fernando, Adrian David Cheok, Tim Merritt, Roshan Lalintha Peiris, Charith Lasantha Fernando, Nimesha Ranasinghe, Inosha Wickrama, Kasun Karunanayaka (2009): Babbage Cabbage: Biological Empathetic Media, VRIC Laval Virtual Proceedings, April 22-26, 2009, Laval, France. pp. 363-366.

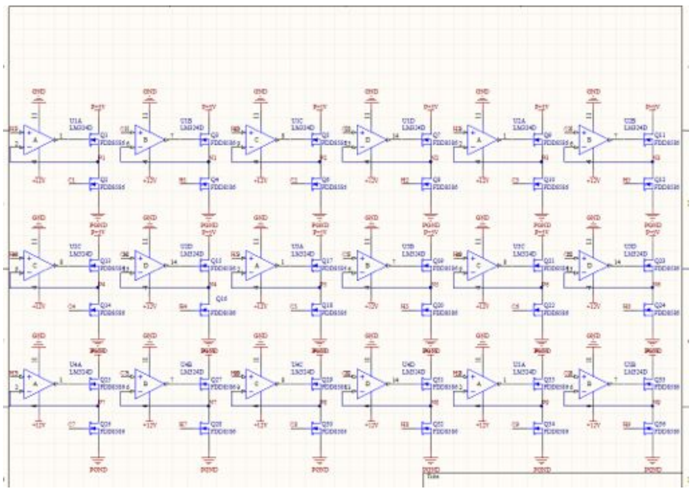
- Tim Merritt, Adrian David Cheok, and Owen Noel Newton Fernando, Roshan Lalintha Peiris, Charith Lasantha Fernando, Empathetic Biological Media, CHI09 Wkshp. on Programming Reality: From Transitive Materials to Organic User Interfaces, Boston, USA, April 2009

- Demonstrations
  - Petimo Art Gallery & Emerging Technologies, SIGGRAPH ASIA Yokohama, Japan - December 2009
  - Petimo Creative Showcase, ACE Athens, Greece October, 2009
  - Petimo Interaction design and children Como, Italy -June 2009
  - Huggy Pajama Interaction design and children - Como, Italy - June 2009
  - Babbage Cabbage Laval Virtual Revolution Laval, France April 2009

B : Schematics and Printed-Circuit-Board Layouts

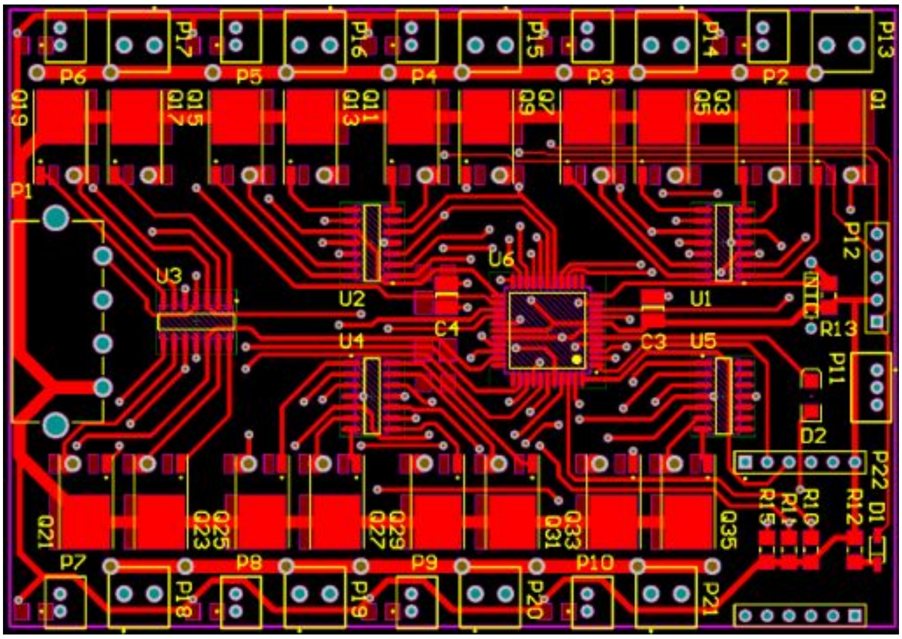


(a) Top Level Schematic

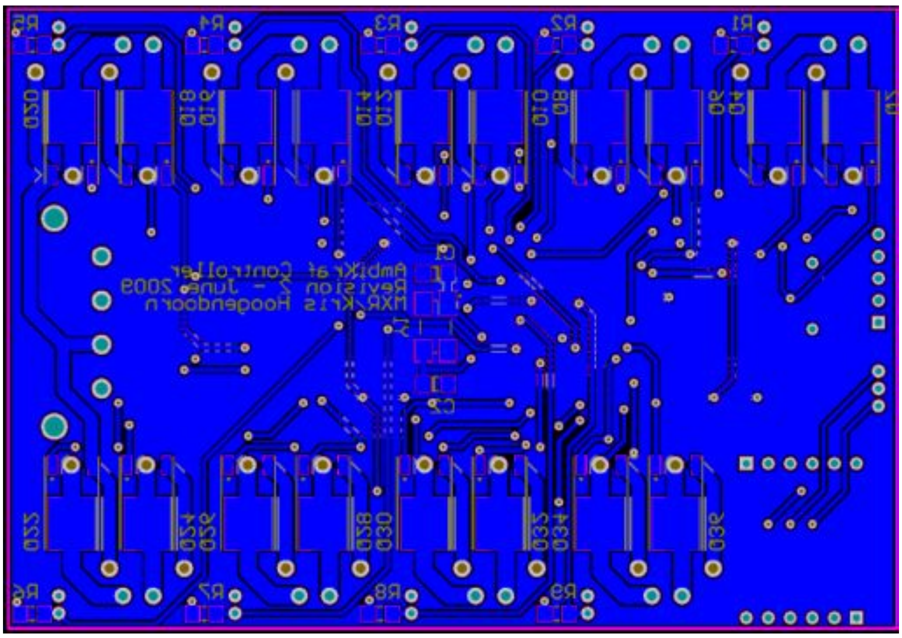


(b) Bottom Level Schematic with repeated modules

Figure 1: Version 1 : Schematic for driving 9 2.5cm x 2.5cm Peltier elements

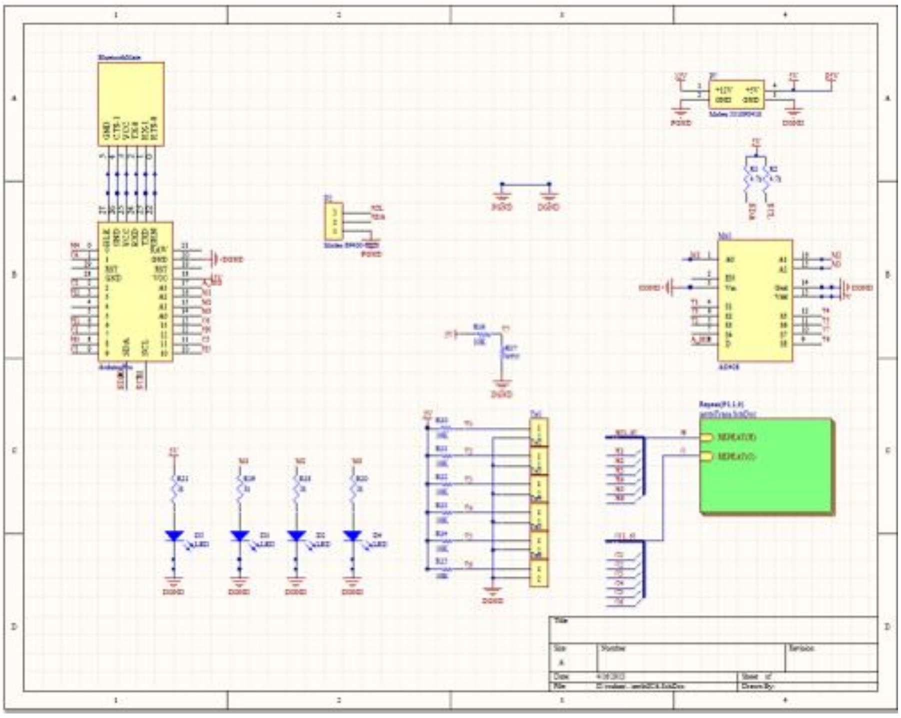


(a) Top Layer

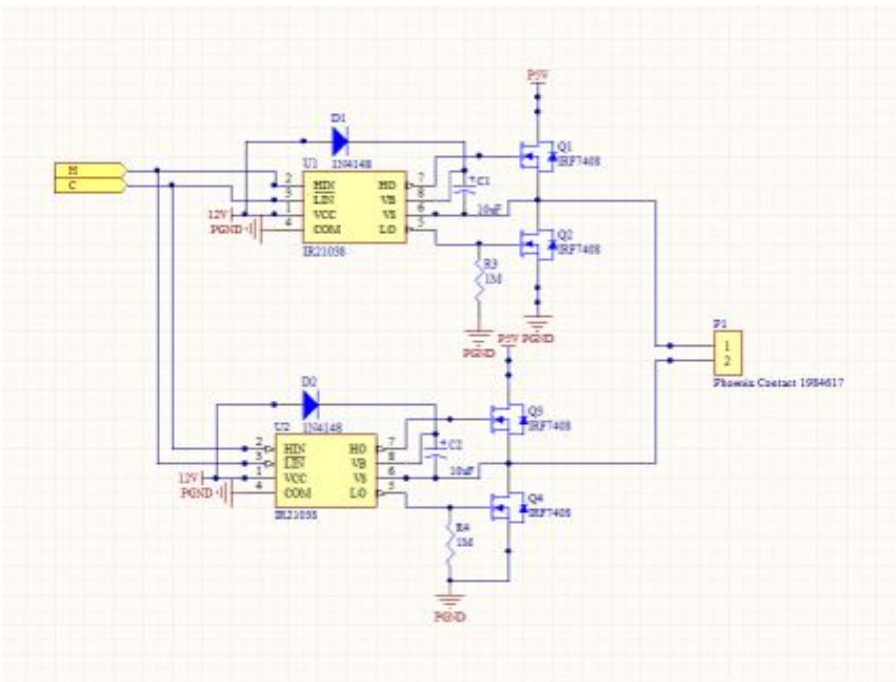


(b) Bottom Layer

Figure 2: Version 1 : PCB layout for driving 9 2.5cm x 2.5cm Peltier elements

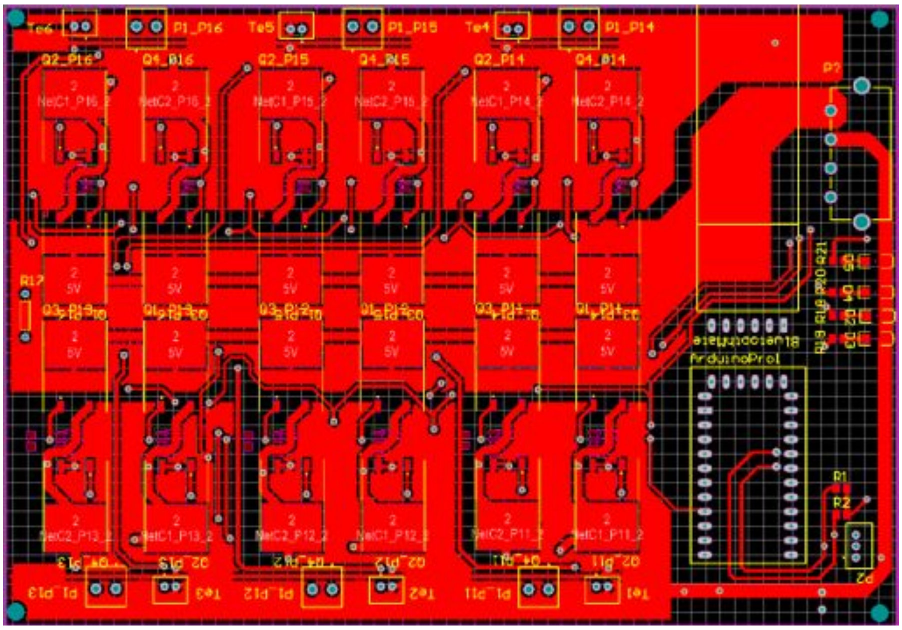


(a) Top Level Schematic

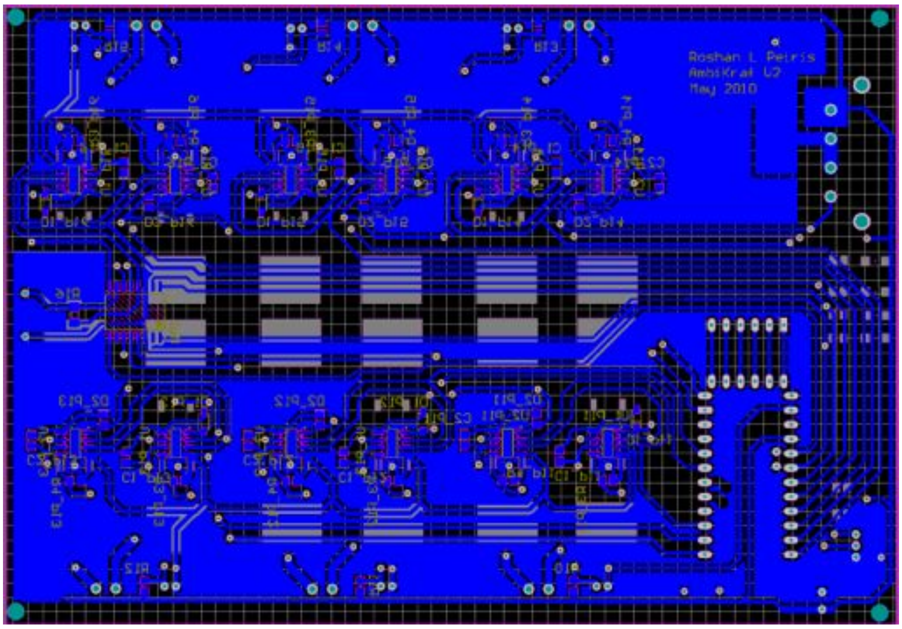


(b) Bottom Level Schematic with repeated modules

Figure 3: Version 2 : Schematic for driving 5 2.5cm x 2.5cm to 6cm x 6cm Peltier elements

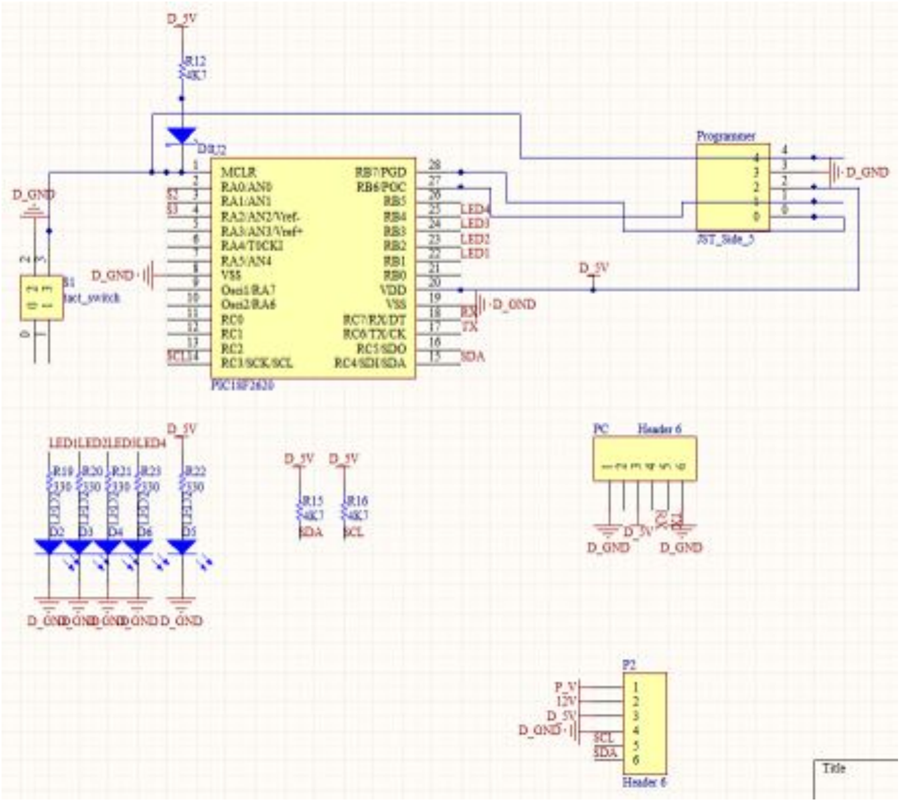


(a) Top Layer

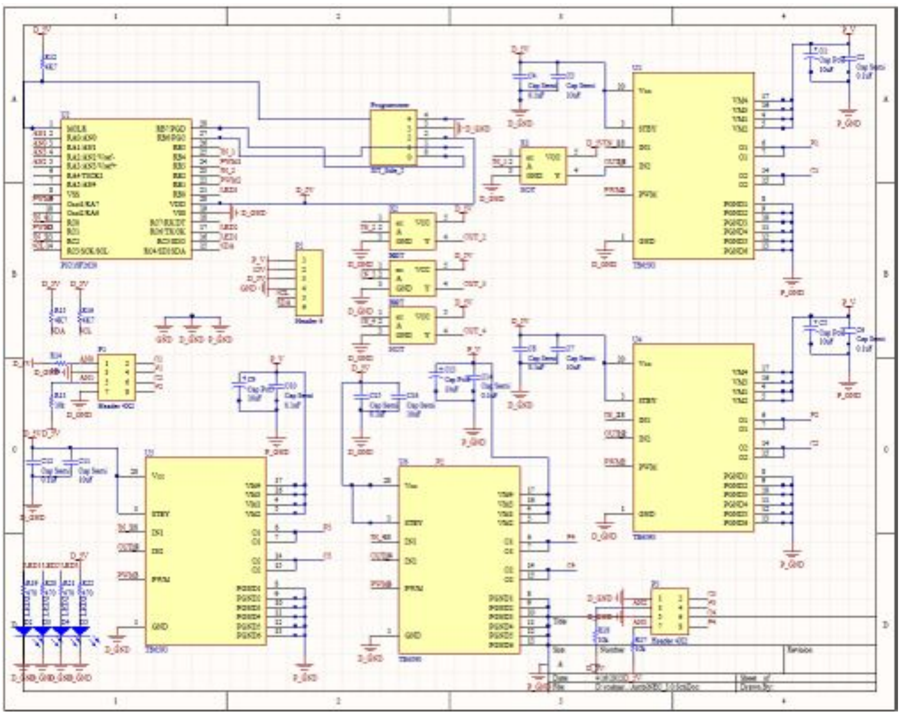


(b) Bottom Layer

Figure 4: Version 1 : PCB layout for driving 5 2.5cm x 2.5cm to 6cm x 6cm Peltier elements

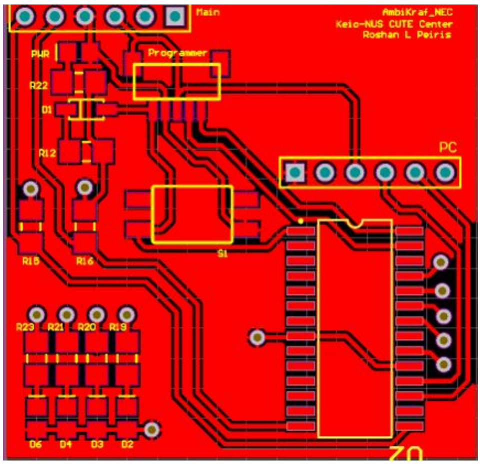


(a) Master circuit to drive cascaded pixelated display

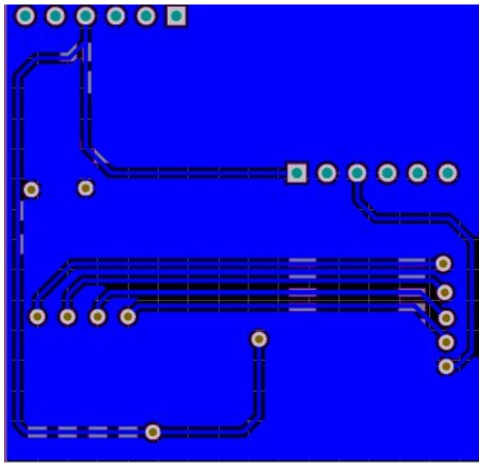


(b) Schematic for driving 4 Peltier modules (can be cascaded)

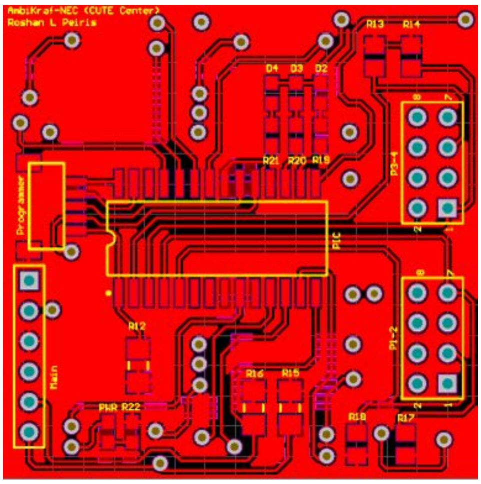
Figure 5: Schematics for pixelated display of 4 2.5cm x 2.5cm Peltier modules



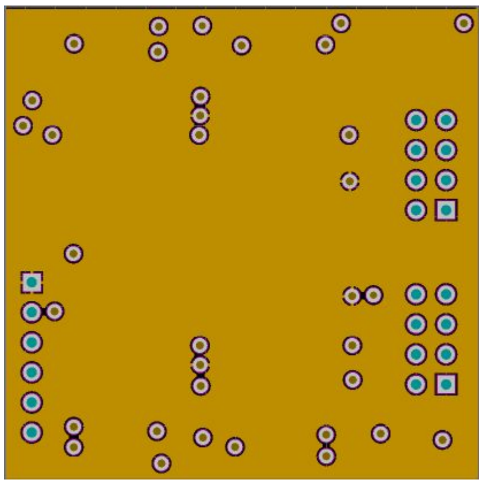
(a) Master Top Layer



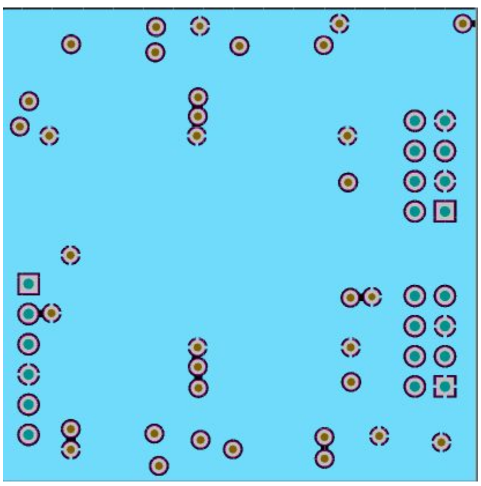
(b) Master Bottom Layer



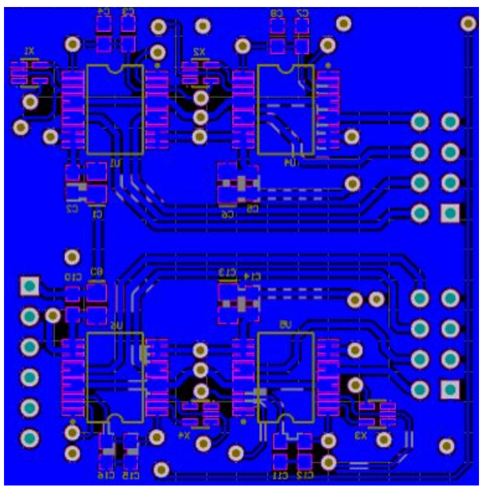
(c) Peltier Driver Top Layer



(d) Peltier Driver Layer 2

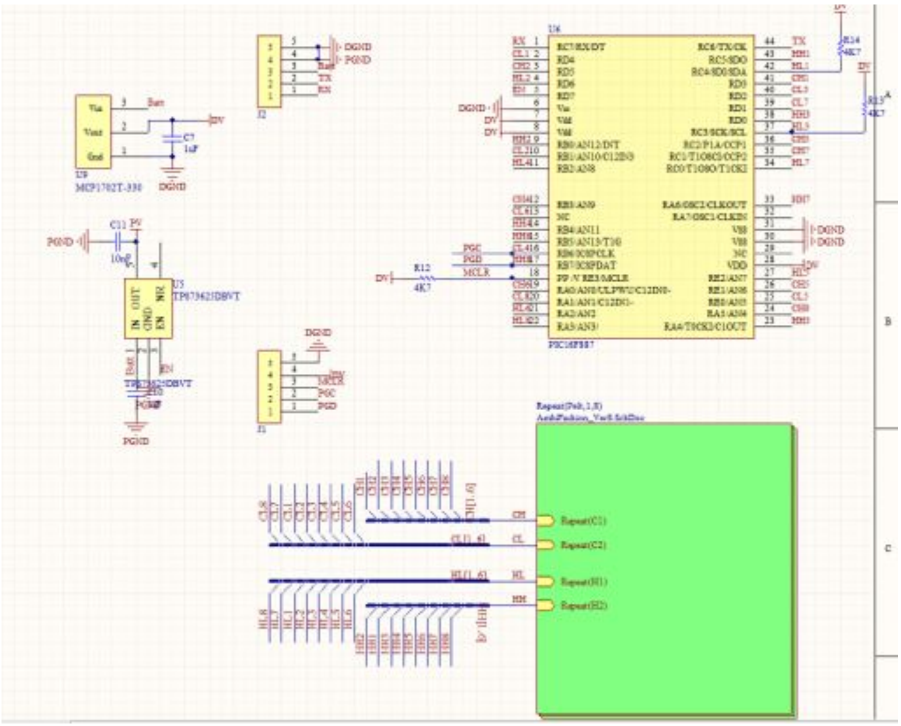


(e) Peltier Driver Layer 3

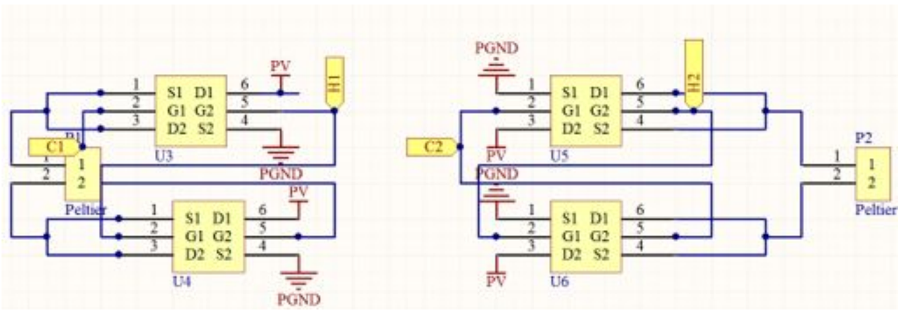


(f) Peltier Driver Bottom Layer

Figure 6: PCB Layers of Master Circuit and Peltier Driver Circuit for cascadable pixelated display of 4 2.5cm x 2.5cm Peltier modules

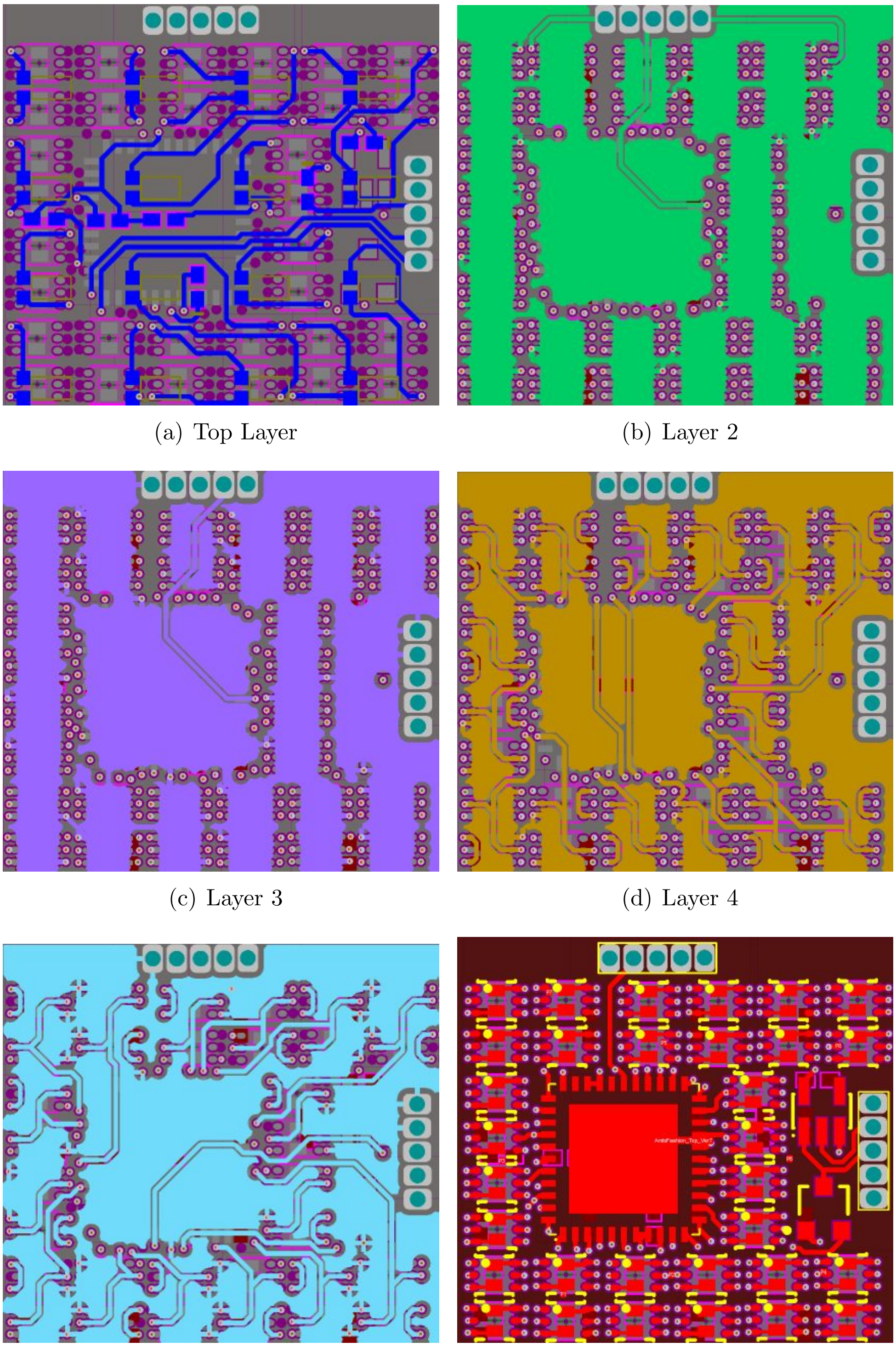


(a) Top Level Schematic



(b) Bottom Level Schematic with repeated modules

Figure 7: Schematic for driving 16 miniature Peltier elements



(a) Top Layer (b) Layer 2

(c) Layer 3 (d) Layer 4

(e) Layer 5 (f) Bottom Layer

Figure 8: 6-Layer PCB layout for driving 16 miniature Peltier elements (2.5cm x 2.2 cm)