
ThermoTouch: Design of a High Dynamic (Temperature) Range Thermal Haptic Display

Sven Kratz

FX Palo Alto Laboratory
3174 Porter Drive
Palo Alto, CA, 94304, USA
kratz@fxpal.com

Tony Dunnigan

FX Palo Alto Laboratory
3174 Porter Drive
Palo Alto, CA, 94304, USA
tonyd@fxpal.com

Abstract

We describe a novel thermal haptic output device, *ThermoTouch*, that provides a grid of thermal pixels. Unlike previous devices which mainly use Peltier elements for thermal output, ThermoTouch uses liquid cooling and electro-resistive heating to output thermal feedback at arbitrary grid locations. We describe the design of the prototype, highlight advantages and disadvantages of the technique and briefly discuss future improvements and research applications.

Author Keywords

thermal, haptic, interactive surface, tactile

ACM Classification Keywords

H.5.m [Information interfaces and presentation (e.g., HCI)]:
Miscellaneous; []

Introduction

There has been significant research interest in thermal-haptic output on interactive displays for a long time. For instance, researchers have explored the simulation of different material properties [3, 4, 6] on an interactive surface. Other projects have focused on using thermal output to as an additional channel to convey information [8], for use as a non-visual channel in mobile devices [9, 10]. The effect of ambient factors such as user clothing [2] or weather conditions [1] have also been studied.

Paste the appropriate copyright statement here. ACM now supports three different copyright statements:

- ACM copyright: ACM holds the copyright on the work. This is the historical approach.
- License: The author(s) retain copyright, but ACM receives an exclusive publication license.
- Open Access: The author(s) wish to pay for the work to be open access. The additional fee must be paid to ACM.

This text field is large enough to hold the appropriate release statement assuming it is single spaced in a sans-serif 7 point font.

Every submission will be assigned their own unique DOI string to be included here.

Peltier Elements

Peltier elements make use of the Peltier effect to convert electrical current to heat. The Peltier effect occurs at the junction between two conductors. Dependent on the voltage polarity, one side of the junction heats up while another side cools down. This is the reason why Peltiers can be used in-situ both for heating and for cooling applications.

The prototypes used by the previously mentioned research were all devices with a single point of thermal output. However, there has been recent work [5, 7] which discussed prototypes that provide a 2D grid of thermal output “pixels”.

Peltier elements:

- have limits to how fast they can change their output temperature. A high temperature switching speed would be beneficial when using the haptic display for, e.g., dynamic scenes or video content.
- have limits on the temperature range (hot and cold limits) they can be set to, based on. the current temperature of their hot side. Thus, obtaining very low temperatures often requires active cooling of the hot side.
- are energy inefficient. There is significant loss involved at when converting electrical current to hot or cold output. Thus large grids of Peltier elements may consume a lot of power.
- are relatively expensive, so the cost of scaling them to very large output grids may be high.

In face of the limitations of Peltier elements, we propose a novel approach based on water cooling and electro-resistive heating. We foresee that our system will overcome the previously discussed limitations: it will have a higher temperature change speed, a higher range of “displayable” temperatures and be more efficient than a Peltier-based solution.

Apart from the advantages in the technical specifications, the setup we propose is also more scalable than those based on Peltier elements. Resistors are relatively cheap passive devices that can convert electrical input energy to heat with 100 % efficiency. Resistors can even be constructed easily from a thin conductor wire, or as implemented by us, be printed directly onto a PCB as a copper

trace.

Water has a very high thermal capacity, and is thus very well suited for cooling applications. Water cooling is in use in machines ranging from internal combustion engines to nuclear power plants. The basic liquid cooling cycle is very simple and thus highly scalable: pump coolant from a reservoir to the place where heat needs to be removed, then pump coolant to a heat exchanger to remove the excess heat in the coolant, and then re-introduce coolant to the coolant cycle or the reservoir.

ThermoTouch Technical Design

Unlike previous thermal-haptic devices, ThermoTouch uses liquid cooling and electro-resistive heating to provide thermal feedback. The basic design of ThermoTouch consists of a PCB which is printed with grid of copper heating coils, which allows the application of heat or cold at any grid location by controlling the electrical current passing through the coil at that specific location.

To enable cooling, when current to a heater coil at a grid location is switched off, the PCB is placed on top of a cooling manifold. A pump circulates liquid coolant through cooling equipment and through the manifold. The coolant is used to extract excess heat from the grid when cooling is desired. By balancing the cooling effect of the manifold with heat input from the heating coils in the grid, arbitrary temperatures can be set at any point on ThermoTouch’s grid. Figure 1(a) shows a side view of the PCB and cooling manifold assembly and Figure 1(b) shows a render of component assembly.

In the following we will further detail the cooling, heating and control logic design of ThermoTouch.

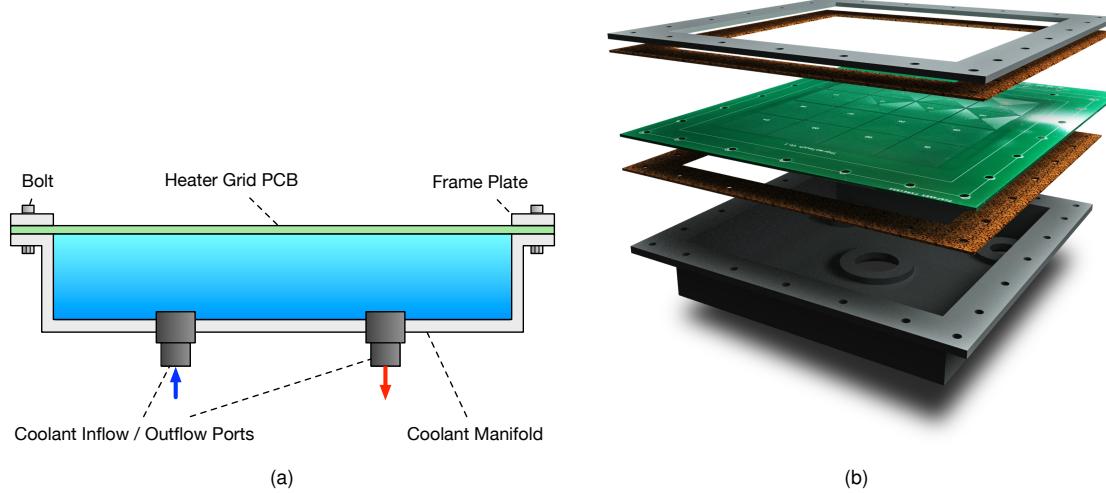


Figure 1: (a) Schematic of heater PCB and cooling manifold assembly. (b) Rendering of the PCM and manifold assembly.

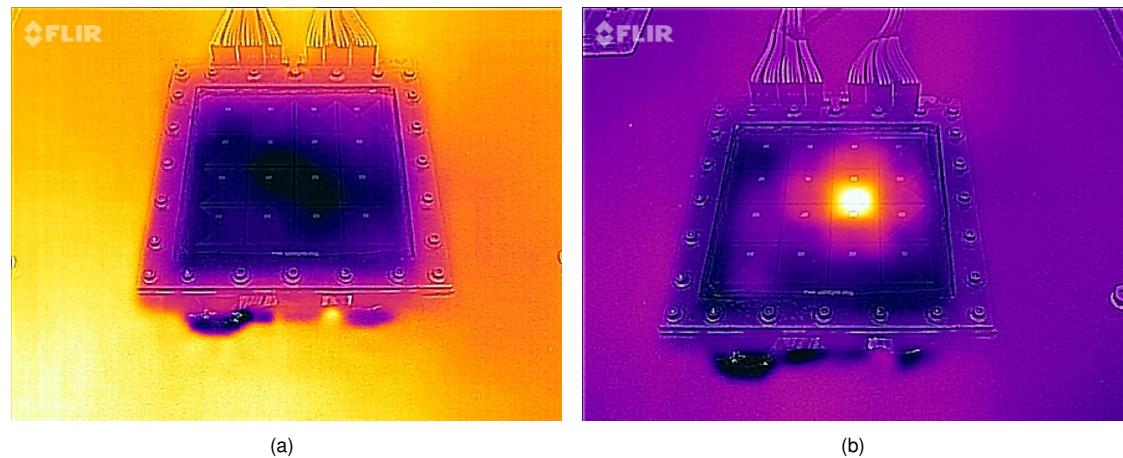


Figure 2: (a) Thermal image showing prototype in a cold state. (b) Thermal image showing one grid cell heated up.

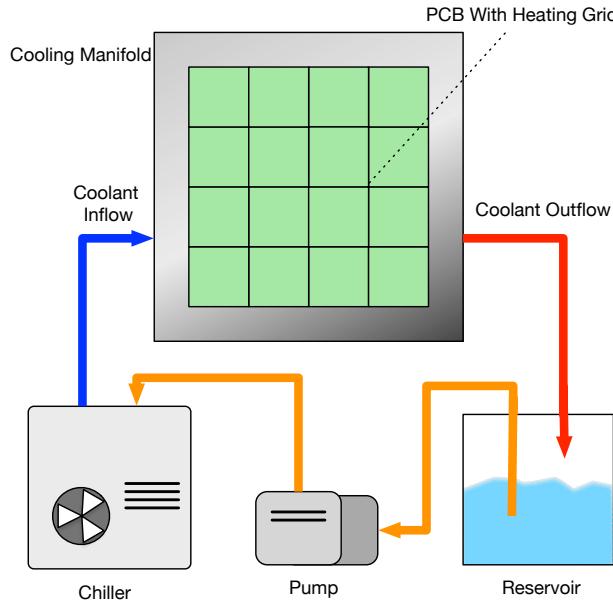


Figure 3: This figure shows the coolant flow through the components of ThermoTouch's cooling system.

Cooling Design

ThermoTouch uses water cooled to a temperature of 3° Celsius as liquid coolant. Water is pumped from a water reservoir containing 4 l of water to an aquarium chiller unit, which is used to cool the water. The outlet of the chiller unit is connected to the input port of the cooling manifold. To evenly disperse coolant, the manifold has 4 coolant outlets arranged in opposite corners. Outflow from the coolant outlets is piped back to the reservoir, where the cooling cycle begins anew. Figure 3 shows a graphical representation of the cooling system flow cycle.

Heater Grid Design

For heating, we designed a PCB printed with a grid of copper heating spiral. The copper traces for each spiral are printed in 5 mil (0.127 mm) traces. The copper strength of the PCB is 1.5 oz per foot (457.73 g/m^2). The distance between each spiral is also 5 mil. This results in a total electrical resistance for each heating spiral of around 10Ω . Thus, at a voltage of 20 V each heating cell is capable of putting out 40 W in heat. Figure 4 shows the PCB.

Control Design for Heating Grid

Whereas the cooling system as it currently is implemented is static and its properties cannot be modified while it is running, the heating grid needs to be actively controlled during operation. Each cell in the Heating Grid has an associated MOSFET (metal-oxide-semiconductor field-effect transistor) that switches current onto that cell's heater spiral. As our current prototype is a 4×4 grid of heating cells, we use a total of 16 MOSFETs to drive the cells. Since we require fine-grained control of the current switched to the heater cells in order to regulate different temperatures, we use a PWM controller shield to drive the gates of the MOSFETs. Finally, an Arduino Microcontroller board is used to implement control logic and send commands to the PWM controller shields via an I2C bus connection. The Arduino can communicate with a PC via USB so that interactive applications can make use of ThermoTouch.

Current Prototype and Functionality Demonstration

We have mounted the current ThermoTouch prototype into an industrial service cart which also supports all supporting components for the cooling system and a 600W power supply to drive the heating grid. Figures 5 and 6 show the current prototype's thermal-haptic top surface and the associated "plumbing" below the manifold for the cooling system.

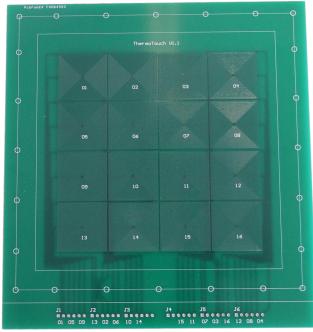


Figure 4: The PCB imprinted with the heater spiral grid.

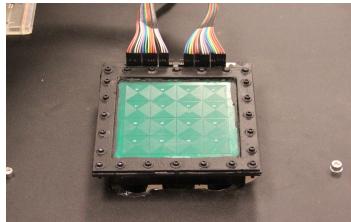


Figure 5: The top of the ThermoTouch prototype with the heater grid PCB.



Figure 6: Side view of the prototype showing the associated plumbing and devices of the cooling system.

To demonstrate the thermal output capabilities of our prototype, we took images of the prototype using a thermal camera. Figure 2(a) shows the prototype in a cooled down state. When applying current to a specific heat cell, we can observe a very distinct and localized heat signature, as shown in Figure 2(b).

Limitations and Advantages

Our approach to thermal haptic output obviously has some advantages. The general setup is more complex than solutions using Peltier elements, as it requires an external cooling system. Thus, ThermoTouch is best for fixed or semi-movable deployments, where portability is not an important design goal. Current thermal control is open loop, i.e., there is no direct temperature feedback from the touch surface. However, we believed that acceptable temperature control can be obtained by creating an input power / temperature control model through careful measurement of the device temperature at different power settings. We plan to incorporate temperature sensors in future and larger versions of ThermoTouch, where one localized control model may not be sufficient to obtain a uniform temperature output. A further limitation is that ThermoTouch currently does not support any input (i.e., touch detection). Touch detection could be implemented through external tracking (e.g., a depth camera), or, more elegantly, using capacitive sensing through the heater coils. We intend to provide visual feedback by using a projector to project video content onto the Thermal grid.

We believe the major advantage of ThermoTouch is the relative ease of scaling the design to very large thermal output grids. We intend to develop table or wall-sized versions of ThermoTouch in the future. At scale, we believe that ThermoTouch will be vastly more cost-effective than approaches using Peltier elements and consume less power.

We also intend to conduct technical experiments to determine the exact speed at which the ThermoTouch grid cells can change temperature. We believe that we can gain advantage here due to the efficiency of electro-resistive heating and the high thermal capacity of water coolant.

Conclusion and Future Work

We have described the technical implementation of a novel thermal haptic output device, which can output thermal feedback on a grid of “thermal pixels”. We introduced a novel approach to creating thermal output using water cooling and electro-resistive heating and have discussed advantages and disadvantages of the technique.

In the future, we wish to deploy ThermoTouch to enable novel media experiences using thermal feedback. We also intend to explore research questions on thermal haptic output. For instance, we are interested in finding a control model that keeps the perceived temperature of the device constant for the user, as previous work has shown that users adapt to new temperature levels after some time and then lack the sensation of a relative temperature difference.

References

- [1] Martin Halvey, Graham Wilson, Stephen Brewster, and Stephen Hughes. 2012. Baby it's cold outside: the influence of ambient temperature and humidity on thermal feedback. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 715–724.
- [2] Martin Halvey, Graham Wilson, Yolanda Vazquez-Alvarez, Stephen A Brewster, and Stephen A Hughes. 2011. The effect of clothing on thermal feedback perception. In *Proceedings of the 13th international conference on multimodal interfaces*. ACM, 217–220.
- [3] H Ho and LA Jones. 2004. Material identification using

- real and simulated thermal cues. In *Engineering in Medicine and Biology Society, 2004. IEMBS'04. 26th Annual International Conference of the IEEE*, Vol. 1. IEEE, 2462–2465.
- [4] Shuichi Ino, Shunji Shimizu, Tetsuro Odagawa, Mitsuru Sato, M Takahashi, T Izumi, and T Ifukube. 1993. A tactile display for presenting quality of materials by changing the temperature of skin surface. In *Robot and Human Communication, 1993. Proceedings., 2nd IEEE International Workshop on*. IEEE, 220–224.
 - [5] Kumiko Kushiyama, Tetsuaki Baba, Kouki Doi, and Shinji Sasada. 2010. Thermo-Pict neo. *Proceedings of SIGGRAPH 10* (2010), 1–1.
 - [6] Hendrik Richter, Doris Hausen, Sven Osterwald, and Andreas Butz. 2012. Reproducing materials of virtual elements on touchscreens using supplemental thermal feedback. In *Proceedings of the 14th ACM international conference on Multimodal interaction*. ACM, 385–392.
 - [7] Kensuke Takada, Kyoko Higurashi, Tatsuhiko Suzuki, Misako Ota, Tetsuaki Baba, and Kumiko Kushiyama. 2009. Temperature design display device to use peltier elements and liquid crystal thermograph sheet Thermo-Pict. In *SIGGRAPH'09: Posters*. ACM, 27.
 - [8] Reto Wettach, Christian Behrens, Adam Danielsson, and Thomas Ness. 2007. A Thermal Information Display for Mobile Applications. In *Proceedings of the 9th International Conference on Human Computer Interaction with Mobile Devices and Services (MobileHCI '07)*. ACM, New York, NY, USA, 182–185. DOI: <http://dx.doi.org/10.1145/1377999.1378004>
 - [9] Graham Wilson, Stephen Brewster, Martin Halvey, and Stephen Hughes. 2012. Thermal icons: evaluating structured thermal feedback for mobile interaction. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services*. ACM, 309–312.
 - [10] Graham Wilson, Martin Halvey, Stephen A Brewster, and Stephen A Hughes. 2011. Some like it hot: thermal feedback for mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2555–2564.