Pulp-Based Computing: A Framework for Building Computers Out of Paper

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Abstract In this paper, we describe a series of techniques for building sensors, actuators and circuit boards that behave, look, and feel like paper. By embedding electro-active inks, conductive threads and smart materials directly into paper during the papermaking process, we have developed seamless composites that are capable of supporting new and unexpected application domains in ubiquitous and pervasive computing at affordable costs.

Keywords: Paper, smart materials, composites, ubiquitous computing, sensors, actuators, collocated input/output.

1 Introduction

Before the advent of computers, paper was the substrate of choice for storing, organizing and transmitting information. Its durability, coupled with the versatility of the printing press, became a pivotal force in the cultural, economic and scientific developments that permeate most of our life. Despite claims that flexible and non-emissive display and input technologies will eventually render paper obsolete, the technologies haven't matured enough to fully replace books, newspapers, or notepads [2]. Moreover, these technologies usually overlook the material qualities and interaction affordances that are at the core of paper's versatility. Paper sheets can be bent, folded, shredded, recycled, stapled and written on at a very low cost and without the need for software upgrades or everlasting battery supplies. Building upon this potential, we have developed electronic paper composites, which combine traditional papermaking techniques with the interaction possibilities of smart materials.

2 Paper Composites

A composite material is a combination of two or more materials that have different physical or chemical properties, but together yield unique characteristics, while retaining the strengths and particularities of its constituent elements. This fabrication process provides a rich array of possibilities for engineers and designers, since the number of material combinations is practically unlimited and can be specifically customized for each design requirement. Today, applications for composite materials range broadly, from the fabrication of bricks to the design of highly specialized aircrafts used in extremely demanding environments [8]. Similarly, paper companies and designers are taking advantage of composite techniques to develop rubberized paper surfaces, improve foldability, and develop sheets that are tear resistant and waterproof, pushing the boundaries of what paper can do.

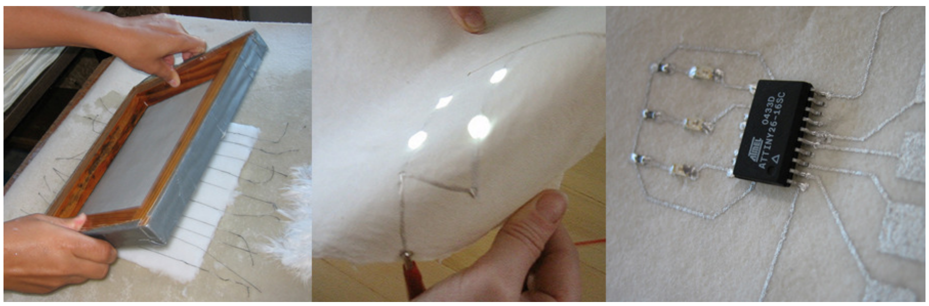

Fig. 1. Left: paper and conductive threads composite; center: flexible paper display; right: paper-based printed circuit board (*PPCB*).

By embedding electro-active materials into paper during the papermaking process, it is possible to create sensors and actuators that convey the affordances and tactile qualities of paper, while leveraging the potential of ubiquitous computers. Moreover, since this approach amalgamates an object's substrate with its internal electronic components, we can create truly seamless collocated input and output interfaces

3 Papermaking

Papermaking can be broken down into 3 steps: preparation of the fibers, sheet formation, and drying. Initially, natural or recycled fibres are broken down and converted into pulp (a concentrated mixture of fibres suspended in liquid). Secondly, the pulp is further diluted with water and drained through a fine-mesh moving screen to form a fibrous web. This web is then pressed and dried into a continuous sheet of paper that can take any shape and consistency.

Whereas industrial papermaking processes are highly mechanized and produce large quantities of paper, its handmade alternatives are laborious and time consuming activities. However, handmade paper allows for an inclusion process, where a physical object can be permanently embedded in between two individual paper sheets which are then compressed, drained and set to dry. By silk screening and encapsulating electrically active inks in between sheets, it is possible to create an electronic paper "sandwich" which is resilient and inseparable from its embedded object [3]. Rather than simply depositing ink on a sheet's surface, which is prone to chipping and breaking [4], our process encapsulates the ink particles in-between wet paper sheets. When the sheets dry and shrink, they compress the inks, keeping them protected from external stresses. The result are sensors and actuators that are more resilient, reliable and electrically insulated from the outside.

4 Pulp-Based Computing Architecture

We have developed several distinct underlying technologies, which combined can provide the framework and instigate the development of a paper-based computing platform.

Embedded Off-The-Shelf Components The first technique consists of embedding off-the-shelf sensors, actuators and Integrated Circuits into paper sheets. We have specifically experimented with piezo-microphones, SMD LEDs, vibrating motors, photovoltaic cells and bend sensors. This approach takes advantage of existing hardware interfaces which are already optimized to account for electric variations, such as long term drift, hysteresis or non-linearity, and, since the components are electrically independent from the paper substrate, they suffer no relevant interference.

Bend Sensor We have also developed a paper sheet that can sense bend in two dimensions (x,y) by infusing carbon resistive ink in between two layers of paper. Instead of silk screening resistive ink on top of a dry sheet of paper, we printed it on a pressed wet sheet and covered it with a second layer, forming one single double-layered sheet. In the case of a book, this approach allows us to measure variations in resistance and detect when pages are being flipped without additional electronic components that could interfere with the textural and visual qualities of the book. Moreover, it prevents the resistive ink from chipping or cracking upon stress, which would dramatically reduce the sensor's lifespan.

Speakers and Collocated I/O The same silkscreening and inclusion technique was used to print spirals of conductive ink on the surface of paper sheets. By oscillating a current flow through this spiral, it's possible to create a controlled magnetic field which can vibrate the paper fast enough for it to produce an array of audible frequencies. Sound quality from a paper speaker is somewhat limited; but this restriction might not hinder applications where a broad frequency range is not a priority, such as interactive postcards or wallpapers that can provide relevant information to users. The same speaker spiral can concurrently function as an antenna for touch and proximity sensing when its capacitance is compared against RC variations caused by the interference of an external stimulus, such as a human hand. By intercalating sensing with actuation, the paper sheet becomes a true collocated input and output substrate. Additionally, by combining matrices of conductive and resistive inks, it is possible to detect touch on paper two-dimensionally, in a similar fashion to how the antenna design of a laptop's touchpad works.

Kinetic Paper We also experimented with a Nitinol and paper composite. Nitinol is a shape-memory alloy that, once treated to acquire a specific shape, can indefinitely remember its geometry. When current is applied to small strands of Nitinol embedded into paper, a sheet can physically deform and bend to acquire new shapes, or relax and return to its default shape. Future applications for this technology are innumerous, ranging from self assembling boxes to customizable wall dividers and tangibles interfaces that can adapt to use and context [6]. Present limitations are found in the fact that Nitinol needs to be heated to change shape which, in the case of resistive heating, consumes a lot of power.

Interface and Logic Finally, to unite all of these elements into a cohesive interactive system, we printed complete circuit boards and electrical buses with conductive ink. We also embedded conductive threads into paper, which present the same electrical profile as wires, but can withstand greater physical stress without permanent damage. Finally, microcontrollers, which need to be in-circuit programmed, were embedded and attached to an external hardware programmer through connecting pads left exposed on the outside surface of the paper.

5 Future Applications and Conclusion

By combining these techniques with different methodologies for sensing and communication, this technology can evolve into new and unexpected application domains in ubiquitous and pervasive computing, where electronic components that hold the physical and tactile properties of paper might be necessary. Moreover, the fabrication process is cheap, simple to replicate at a small or large scale and uses a largely recyclable material, providing a scalable and sustainable alternative for current electronic manufacturing practices. Some of the future applications which we are currently considering for this technology include: a collocated I/O paper sheet for constructing reconfigurable and interactive spaces; cardboard boxes that can display information about their content, weight, and overall strain; and sheet music that plays sounds with the touch of a pen.

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