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Abstract

As computing has moved off the desktop, visualization research in interaction, computer graphics and usability has become more interdisciplinary. In this paper we focus on our work in two areas. We describe self-configurable and scalable displays using ad-hoc clusters of enhanced *self-contained* projector units. Then, we discuss the development of *multi-user* touch-sensitive screens that support collaborative applications for projector-based displays.

1 Introduction

Traditionally projectors have been used as static devices, mostly for presenting content to a passive audience. Over the past decade, ideas for novel uses of projectors have developed significantly, so that they can now be used as part of systems that actively sense the environment. Meanwhile, emerging technologies such as sensor networks or cluster computing are blending multiple different devices into a single vast pool of resources. Can we similarly use intelligent projectors to create a pervasive information display infrastructure? The research challenge is how to create *Plug-and-disPlay* projectors. We describe our effort in creating self-contained projector systems that are aware of their surroundings via built-in sensors. The projectors can respond to the display context. Single units can recover 3D geometric and photometric information about the environment. Multiple, possibly heterogeneous, units can work in clusters and discover the topology. Such projectors allow self-configuring, seamless and large-area support for interaction, display or augmentation.

While the display systems are evolving, mouse-like touch-sensitive user interaction efforts for large format displays are primarily limited to mode where only a single user is active at a time. This baton-passing metaphor is limiting for collaborative applications where multiple users may want to simultaneously manipulate the visualization. We have developed a hardware solution to detect and measure multiple touch locations. In addition the system can identify the corresponding user for the touched screen location. The multi-user touch sensitive screen is based on a low-cost grid of radio transceivers embedded in the display surface. We describe our efforts in several collaborative applications that exploit the multi-user touch sensitive screen.

Such aware projectors and collaborative interfaces will work flexibly in a variety of situations, communicate with other entities and harmoniously make use of available resources.

2 Aware Projectors

Projectors are getting smaller, brighter, and cheaper. The evolution of computers is suggestive of the ways in which projectors might evolve. As computers evolved from mainframes to PCs to handheld PDAs, the application domain went from large scientific and business computations to small personal efficiency applications. Computing has also seen an evolution from well-organized configurations of mainframes to clusters of heterogeneous, self-sufficient computing units. In the projector world, we may see similar developments – towards portable devices for personal use; and a move from large monolithic systems towards ad-hoc, self-configuring displays made up of heterogeneous, self-sufficient projector units. The most exploited characteristic of projectors has been their ability to generate images that are larger in size than their CRT and LCD counterparts. But the potential of other characteristics unique to projector-based displays is less well investigated. Because the projector is decoupled from the display (i) the size of the projector can be much smaller than the size of the image it produces, (ii) overlapping images from multiple projectors can be effectively superimposed on the display surface, (iii) images from projectors with quite different specifications and form factors can be easily blended together, and (iv) the display surface does not need to be planar or rigid, allowing us to augment many types of surfaces and merge projected images with the real world.

What components will make future projectors more intelligent? We consider the following elements essential for geometric awareness – sensors such as camera and tilt-sensor, computing, storage, wireless communication and interface. Note that the projector and these components can be combined in a single self-contained unit with just a single cable for power, or no cable at all with efficient batteries. Figure 1 illustrates a basic unit. This unit could be in a mobile form factor or could be a fixed projector.

The unit can communicate with other devices and objects to learn geometric relationships as required. The ability to learn these relationships on the fly is a major departure from most existing projector-based systems that involve a pre-configured geometric setup or, when used in flexible environments, involve detailed calibration, communication and human aid. Even existing systems that use a simple planar homography and avoid complete calibration require some Euclidean information on the screen (e.g., screen edges or markers) or assume the camera is in the ideal sweet-spot position.

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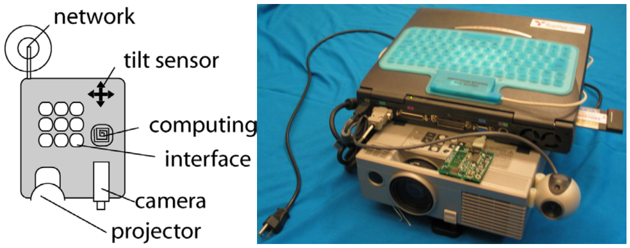

Fig. 1. *Self-contained intelligent projector unit, which c communicate with other units via both, light and RF, to lea geometric relationships and topology. (a) Components of a sing unit and (b) our prototype with a single external cable for power.*

3 Intelligent Self-organizing Projector Clusters

We have recently presented the ideas and algorithms to create a self-configuring ad-hoc display network, able to create a seamless display using self-contained projector units and without environmental sensors [Raskar et al 2003]. We call them *iLamps*. Our approach to ad-hoc projector clusters is inspired by work on grids such as ad-hoc sensor networks, traditional dynamic network grids, and ad-hoc computing grids or network of workstations (NoW, an emerging technology to join computers into a single vast pool of processing power and storage capacity). Research on such ad-hoc networks for communication, computing and datasharing has generated many techniques, which could also be used for context-aware 'display grids'.

From a geometric point of view, existing multi-projector display systems are based on the notion of one or more environmental sensors assisting a central intelligent device. This central hub computes the Euclidean or affine relationships between projector(s) and displays. In contrast, our system is based on autonomous units, similar to self-contained computing units in cluster computing (or ubiquitous computing). In the last four years, many authors have proposed automatic registration for seamless displays using a cluster of projectors. We improve on these techniques to allow the operation without environmental sensors and beyond the range of any one sensor. We also extended the cluster-based approach to second-order display surfaces, curved quadric surfaces such as cylinders and spheres.

In the proposed approach, each individual unit senses its geometric context within the cluster. This can be useful in many applications. For example, the geometric context can allow each projector to determine its contribution when creating a large area seamless display. Multiple units can also be used in the shape and object-adaptive projection systems for projector-based augmented reality.

This approach to display allows very wide aspect ratios, short throw distance between projectors and the display surfaces and hence higher pixel resolution and brightness, and the ability to use heterogeneous units. An ad-hoc cluster also has the advantages that it (a) operates without a central commanding unit, so individual units can join in and drop out dynamically, (b) does not require environmental sensors, (c) displays images beyond the range of any single unit, and (d) provides a mechanism for bypassing the limits on illumination from a single unit by having multiple overlapping projections. Figure 2 shows an example.

Similar to computing units in a computing cluster, projector units can dynamically enter and leave a display cluster, and the alignment operations are performed without requiring significant pre-planning or programming. This is possible because (a) every unit acts independently and performs its own observations and calculations, in a symmetric fashion (b) no Euclidean information needs to be fed to the system (such as corners of the screen or alignment of the master camera), because tilt-sensors and cameras allow each projector to be geometrically aware. In contrast to our approach, systems with centralized operation for multi-projector display quickly become difficult to manage.

The ideas of the display cluster provides geometric underpinnings for a new generation of projectors – autonomous devices, easily adapting to operation within a cluster, and adaptive to their surroundings.

4 Multi-user Touch Sensitive Interaction

While the display systems are evolving, mouse-like touch-sensitive user interaction efforts for large format displays are primarily limited to mode where only a single user is active at a time. The use of multiple mice in a collaborative environment is particularly problematic. It can be challenging for users to keep

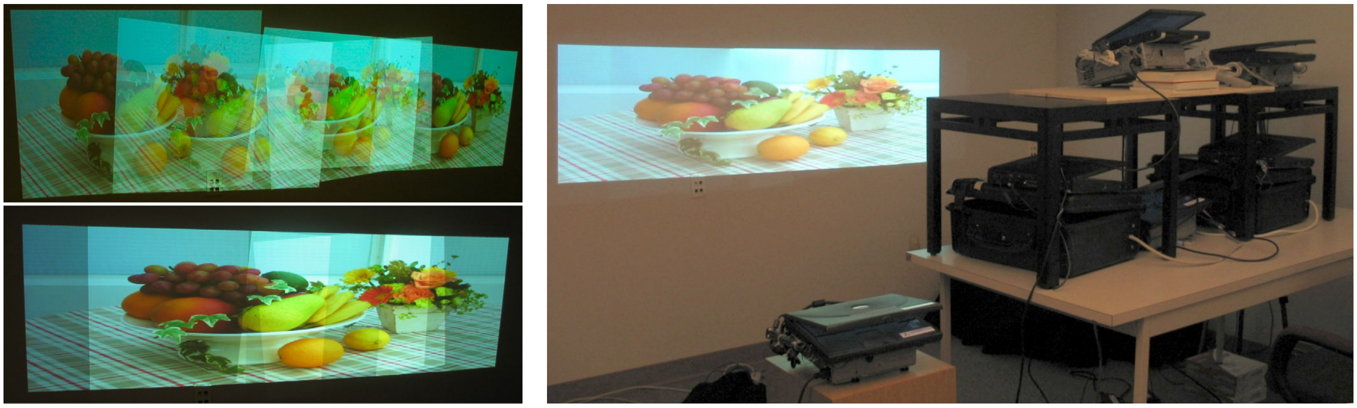

Figure 2: *Application of self-configuring projectors in building wide aspect ratio displays. Every unit is self-contained. We use a modified global alignment scheme based on local pairwise relationships. This replaces existing techniques that require the notion of a master camera and Euclidean information for the scene. Left-top: Uncorrected projection from each of the five projectors; Left-bottom: Registered images; Right: Setup of self-contained units and seamless display.*

track of one pointer on a large surface with lots of activity. Keeping track of many mice is nearly impossible. This leaves users physically pointing at their virtual pointers to tell other users where they are. Also, relying on a separate physical device keeps us from utilizing the natural human tendencies of reaching, touching and grasping.

Using a large touch-screen as the table surface would seem to be an answer, but existing touch technologies were inadequate. Most allow only a single touch and do not identify users. While schemes have been developed where users take turns [Inkpen et al, 1997], we wanted the interaction to be simultaneous and spontaneous.

Unlike electronic whiteboards or other vertical touch systems, the tabletop nature of our display creates a problem: people tend to put things on tables. With a pressure-sensitive surface, foreign objects create spurious touch-points causing single touch systems to malfunction.

Optimally, we would like a multi-user touch surface to have the following characteristics:

- Multipoint: Detects multiple, simultaneous touches.
- Identifying: Detects which user is touching each point.
- Debris Tolerant: Objects left on the surface do not interfere with normal operation.
- Durable: Able to withstand normal use without frequent repair or re-calibration.
- Unencumbering: No additional devices should be required for use – e.g. no special stylus, body transmitters, etc.
- Inexpensive to manufacture.

We have developed a technology at MERL called DiamondTouch, which meets all of these requirements [Dietz and Leigh, 2001].

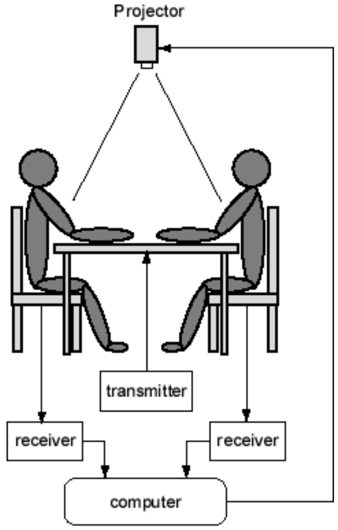

Figure 3: *The multi-user DiamondTouch works by transmitting signals through antennas in the table. These signals are capacitively coupled through the users and chairs to receivers, which identify the parts of the table each user is touching. A computer can then use this information in the same way as mouse or tablet data.*

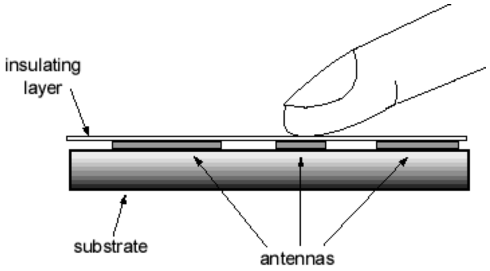

Figure 4: *A set of antennas is embedded in the tabletop. The antennas are insulated from each other and from the users.*

DiamondTouch works by transmitting a different electrical signal to each part of the table surface that we wish to uniquely identify. When a user touches the table, signals are capacitively coupled from directly beneath the touch point, through the user, and into a receiver unit associated with that user (Figure 3). The receiver can then determine which parts of the table surface the user is touching.

The table surface is a constructed with a set of embedded antennas, which can be of arbitrary shape and size. The antennas are thin pieces of an electrically conductive material, which are insulated from each other. Since the coupling of signals to the users is done capacitively, the antennas are also insulated from the users, and the entire table surface can be covered by a layer of insulating, protective material as shown in Figure 4. Each antenna extends over a single area of the table to be unambiguously identified: the system cannot tell where on the antenna a user touches, just that the user touches that antenna. A transmitter unit drives each antenna with its own signal that can be distinguished from the signals of the other antennas. Users are capacitively coupled to their receivers through their chairs, and the receivers are connected back to the transmitter through a shared electrical ground reference.

When a user touches the table, a capacitively coupled circuit is completed. The circuit runs from the transmitter, through the touch point on the table surface, through the user to the user's receiver and back to the transmitter. This multi-user touch sensitive display is a natural fit for many types of collaborative applications.

5 Collaborative Displays

In this day and age of high technology, there is still an important role for face-to-face collaboration. Many meetings are on the road, and may be spontaneous events with no a priori planning. Flat, horizontal surfaces are natural for people to meet around and collaborate on. Figure 5 (a), reproduced from [Edwards et al 2002], shows two people sitting face to face at a table in the airport collaborating through their two laptops. However, the laptop screens are oriented toward their owners, and are difficult for the collaborator to view. Wouldn't it be more natural if their collaborative materials were simply laid out on the tabletop! Ad hoc, spontaneous collaborations are often seen around work places, in waiting areas at airports and train stations, as well as in cafes and lounges. People use flat, horizontal surfaces as the basis of their collaboration, with the ancillary support of tools such as laptops, PDAs, and paper documents. We present one potential

Fig. 5. *(a) Collaboration at an airport (reproduced from [Edwards et al 2002]) (b) Collaboration via a DiamondTouch interface around an UbiTable*

application of the low-cost DiamondTouch display to allow multi-user collaboration. The project, called UbiTable, exploits design space of tabletops as scrap displays [Shen et al, 2003].

The goal of the UbiTable project is to provide efficient walk-up setup and fluid UI interaction support on horizontal surfaces. We wish to enable spontaneous, unplanned, collaboration where the participants share contents from their mobile devices such as laptops and PDAs. We draw technological underpinnings from peer-to-peer systems [Edwards et al 2002], ad hoc network protocols (such as 802.11 ad hoc mode, or Bluetooth), and existing authentication and encryption methods. Our focus is on design solutions for the key issues of (1) a model of association and interaction between the mobile device, e.g., the laptop and the tabletop, and (2) the provision of three specific shades of sharing semantics termed Private, Personal and Public. This is a departure from most multi-user systems where privacy is equated with invisibility. Figure 5 (b) shows the current UbiTable setup. Note that UbiTable also provides a variety of digital document manipulation functions, including document duplication, markup, editing, digital ink for drawing and annotation. The elaboration of these functionalities is out of the scope of this paper.

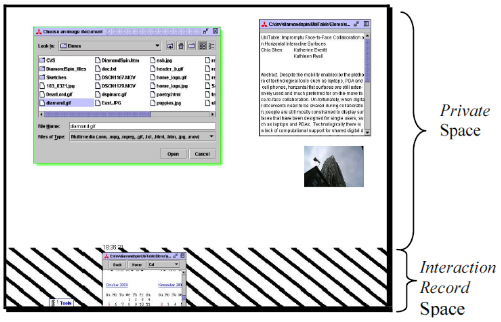

Fig 6. *Screenshot of Laptop A*

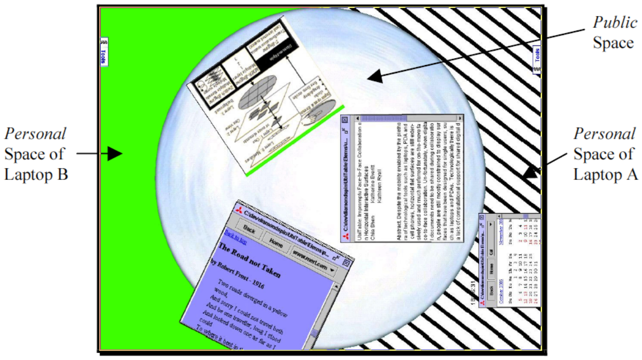

Fig. 7. *Screenshot of UbiTable tabletop*

5.1 Design and Usage

The guiding principles, supported by the observational data, in the design of UbiTable are:

1. Shared scrap display: (a) Simple walk-up utility for collaboration setup. (b) Easy and visible association between users, documents, and laptops. (c) Fluid content movement between laptops and the tabletop.
2. Separation of privacy from visibility: (a) A well defined gradient of three sharing semantics, Private, Personal and Public. (b) Shared interaction, with equal input capability to public documents, but owner controlled document distribution and replication.

Our goal is to provide an easily accessible scrap table that supports sharing of documents and ad hoc collaboration while maintaining user control over documents and gradations of privacy and visibility.

UbiTable is designed for easy walk-up usage. At the same time, people collaborating around the table will temporarily own the table during their usage session. That is, the table can serve as a true scrap display device. Thus, we must provide means for people to feel secure while putting their content onto the table. Figure 6 shows the UbiTable application screen on the laptop and Figure 7 is the UbiTable display on the tabletop. All interactions with the tabletop are done naturally by touching the table. When a laptop is connected to the table, an icon appears on the tabletop that represents this particular laptop. To associate the laptop with the side of the table adjacent to her, the user drags her laptop's icon into the side area of the tabletop.

Most current desktop multi-user systems provide a binary notion of public and private data. Things in the shared space are equally visible and accessible by others, while private data is neither visible nor accessible to others. In most cases, private data is kept on one's own desktop or laptop, or viewed with special private viewing device [Russell and Gossweiler, 2001][Yerazunis and Carbone, 2001]. Observations of people collaborating around a table with physical artifacts (such as paper documents) show well-understood social protocols defining semi-private personal documents. These documents may be shared later in the meeting.

As shown in Figure 6, the display on the laptop is divided into two regions, Private and Interaction Record. The tabletop display consists of a shared public circular region in the middle, and two to N Personal regions at the edges. Figure 7 shows a tabletop with two Personal regions, one at each side. We use color or pattern as a visible means to indicate identity and ownership. The color or pattern of a user's laptop Interaction Record space matches that of the side of the table designated as his Personal space. For example, as shown in Figures 6 and 7, the laptop with striped display Interaction Record background is associated with the striped Personal side of the tabletop. Documents display an ownership bar of their owner's pattern across their top. When a user touches a document on the tabletop display, a shadow of his color or pattern appears around the document.

Our research on interactive surfaces is in some sense complementary to the peer-to- peer network, data transport, and security services that services such as Speakeasy [Edward et al 2002] offer. Ubi-Table addresses the issues of shared workspaces on horizontal surfaces, and the semantics of private, personal and public data access and exchange. Speakeasy can be used as our underlying ad hoc peer-to-peer discovery protocol and network service infrastructure.

6 Conclusion

We have discussed two main directions in intelligent and collaborative displays. They are based on data projectors for image formation and multi-user tabletop surfaces for interaction.

Projectors are showing the potential to create new ways of interacting with information in everyday life. Desktop screens, laptops and TVs have a basic constraint on their size – they can never be smaller than the display area. Hand-helds such as PDAs are compact but the display size is too limited for many uses. In contrast, projectors of the near future will be compact, portable, and with the built-in awareness that will enable them to automatically create satisfactory displays on many of the surfaces in the everyday environment.

Despite the mobility enabled by the plethora of technological tools such as laptops, PDA and cell phones, horizontal flat surfaces are still extensively used and much preferred for on-the-move face-to-face collaboration. Technologically there is a lack of computational support for shared digital document access, browsing, visualization and manipulation on horizontal surfaces. We have described a robust, low-cost hardware solution called DiamondTouch and presented an examination of the design space of tabletops used as scrap displays. In the future such methods can address the visual accessibility vs. the electronic accessibility of documents, an issue that is critical to ubiquitous environments.

Acknowledgements

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