Robust Projected Displays for Ubiquitous Computing

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1 Introduction

We believe projectors are currently the best technology for creating very large displays that are flexible, affordable, and easy to configure and deploy. Such displays have numerous applications in ubiquitous computing: generating a shared display for a spontaneous hallway meeting, placing a hidden display on a breakfast table behind a box of cereal for the private notification of an important message, or covering the front of a classroom with an interactive whiteboard. Recently there has been an explosion of interest in projector-based displays, and in particular on the use of vision technology for automated calibration and compensation [7]. Some representative examples are the Office of the Future project [9], the Everywhere Displays Projector [8], and using a projector to make one object look like another [3].
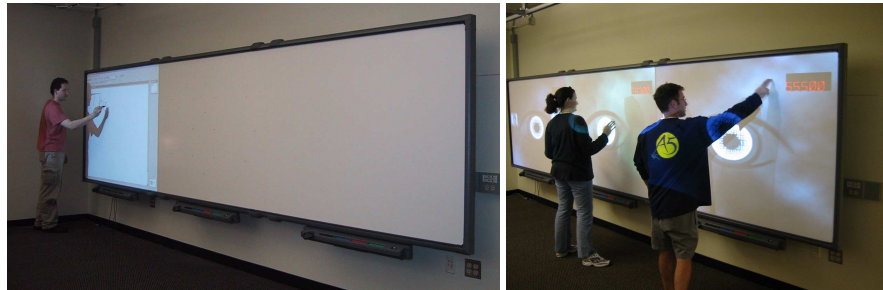

Fig. 1. The BigBoard at the Georgia Institute of Technology. Projection technology is the only feasible method for providing computer output over the entire 17.5 by 4.5 foot surface of this electronic whiteboard.

Most of this work has assumed that the display region lies on a single planar surface that has an unobstructed view of a single projector. Our research has focused on the development of multi-planar displays and on the use of redundant projection to obtain

robustness to shadows and occlusions, thereby supporting interaction with the display by the user. In particular, we have developed:

- Methods to automatically detect and calibrate multiple planar surfaces, resulting in a multi-planar display.
- Methods to interactively specify and control the projection region.
- Techniques to compensate for occlusions using vision sensing to control multiple redundant projectors.
- Evaluation of the usability of this new display technology.

2 Creating Multi-Planar Displays

To truly place a display anywhere, anytime, a projection system must be able to locate positions in the environment suitable for projection without manual intervention. Our recent research allows a projector/camera system to detect planar surfaces in the environment to create a projected display that incorporates multiple flat surfaces simultaneously. Configurations of walls and desktops in office and home settings naturally create juxtaposition of multiple flat surfaces, often at right angles to one another. In order to auto-calibrate for more than one display surface, we must recover multiple projector-to-surface homographies in such a way that the local geometric relationships between surfaces are preserved.
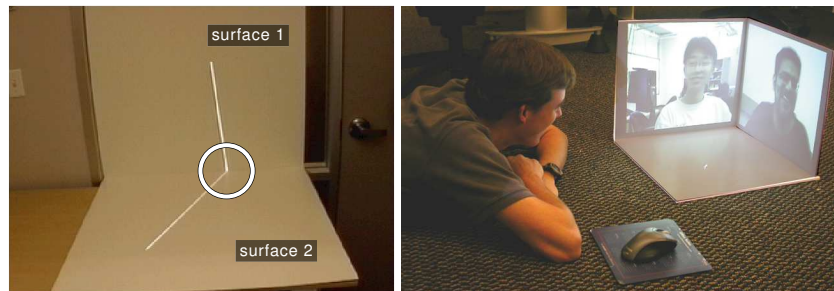

Fig. 2. Uncalibrated structured light is used to identify boundaries between adjacent planar surfaces in the camera image (left). Such displays can be used to display multi-dimensional data (such as 2 orthogonal views of a 3-D dataset) or simply as separate displays (right).

The projector displays a series of horizontal and vertical lines that are observed by the camera. A line that crosses multiple surfaces appears as several line sections (Figure 2-left). Our system makes no assumptions about the angles other than that they are large enough to produce a visible discontinuity in a projected line. We fit a line to each section, intersect these lines and connect the intersections to determine the precise boundary (in the camera image) between each pair of adjacent surfaces. After finding the planar regions we use line correspondences to obtain a mapping from the projector

to each surface. These mappings are refined so that common points along boundaries match, allowing an image to be dragged between surfaces without visual discontinuities [1,2]. Previous work in this area required the use of an expensive laser range-finder [16].
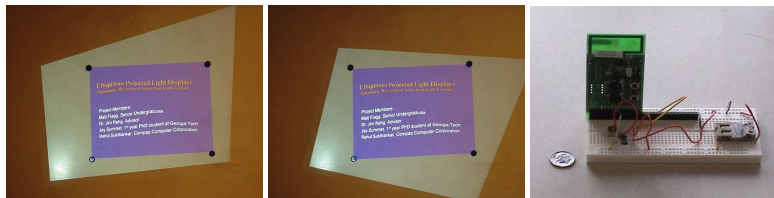
3   Interactive Control of Projected Displays

Fig. 3. Users can position fiducials such as poker chips to indicate a desired display location (left, center). A hardware sensor which can locate itself within a projectors' frustum (right).

In some cases, a user would like to be able to interactively specify the portion of a wall or desk which should be used for a display. We have found that by using four fiducial markers on a display surface a user can easily specify the desired display area. Since walls tend to be light colored, we have found that any small dark target, such as a poker chip, can serve as a fiducial which can be recognized and tracked via a camera [10].

Alternatively, we have built a microprocessor based sensor board which can locate itself within a projection frustum by detecting specially coded patterns of light, and radio its location back to the computer controlling the projector.[1] Such a sensor board could be built into a "magic-wand" that the user could use to mark out the corners of a display. A similar system with four sensors integrated into the corners of a projection surface has been used to create a mobile self-calibrating display surface [6].

4   Virtual Rear Projection

Front projection technology, in which projectors are located in the same space as the users, is currently the most economical way to create large flexible displays. However, front projection suffers from the drawback that the projected light can easily be occluded by a user or object which moves between the display and the projector. Rear projection solves this problem, but is much more expensive[2] and commonly results in immobile displays. Additionally, rear-projection is infeasible when attempting to co-opt

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[1] See http://www.cc.gatech.edu/~summetj/movies/bw-locate320.avi for a video demonstration.

[2] In addition to the cost of the display surface and its installation, the projection area behind the screen costs an average of $77 (USD) per square foot in an office building[17].

existing surfaces for display. For these reasons, we must solve the problem of occluders which may shadow some or all of the display.

The key idea behind our approach is illustrated in Figure 4 (left). Redundant overlapping projectors provide multiple paths of light to each point on the display surface. A vision system detects light paths that are blocked by the user or other occluding object and switches the light to an unobstructed path. This is done on a per-pixel basis in real-time using an alpha mask for each projector. This accomplishes both the elimination of shadows from the display and the removal of projected light from the user's body [14].

We have investigated several ways to detect occlusions, such as 1) a single camera watching the display surface for shadows [12,11], 2) multiple cameras detecting the occluders using a form of spatial background subtraction [4], and 3) the use of infrared light and camera. The Metaverse lab has also worked on the shadow elimination problem, but their system only eliminated shadows [5], while other work using infrared light and camera to remove light projected on the user's body [15] did not address the elimination of shadows. Our solution is nearing the speed required for interactive systems, currently operating at 10Hz.[3] We are working on sensing technologies which detect users as they are about to block the optical path of projectors and switch illumination to unblocked secondary projectors ahead of the occlusion in a pro-active manner.

Empirical studies of users working with front projection, virtual rear-projection, and rear-projection displays indicate that users prefer virtual rear projected displays over traditional front projection. Additionally, users working with front projected displays exhibited clear coping behavior when shadows would occlude the display. Participants using VRP displays did not exhibit these coping behaviors and behaved exactly as participants using rear projected displays [13].

5   Conclusion

We have demonstrated that computer vision can be combined with multiple redundant projectors to create flexible, large scale interactive displays. In addition, we have described a new type of multi-planar display and demonstrated the ability to interactively

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[3] See http://www.cc.gatech.edu/~summetj/movies/vrp-IR.avi for a video.

Fig. 4. Overhead diagram of a switching virtual rear projection system (left). As an occluder (the user) blocks one projector (center), the secondary projector begins to fills in the shadow (right). Footnote 3 provides a URL to download the video from which the center and right images were taken. The video illustrates the system's capabilities much better than static images.

control the display area. We believe this new technology has the potential for broad impact on ubiquitous displays.

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