Two Worlds Apart: Bridging the Gap Between Physical and Virtual Media for Distributed Design Collaboration

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ABSTRACT
A tension exists between designers' comfort with physical artifacts and the need for effective remote collaboration: *physical objects live in one place*. Previous research and technologies to support remote collaboration have focused on shared electronic media. Current technologies force distributed teams to choose between the physical tools they prefer and the electronic communication mechanisms available. We present Distributed Designers' Outpost, a remote collaboration system based on The Designers' Outpost, a collaborative web site design tool that employs physical Post-it notes as interaction primitives. We extended the system for synchronous remote collaboration and introduced two awareness mechanisms: transient ink input for gestures and a blue shadow of the remote collaborator for presence. We informally evaluated this system with six professional designers. Designers were excited by the prospect of physical remote collaboration but found some coordination challenges in the interaction with shared artifacts.

Keywords
computer-mediated communication, CSCW, tangible user interfaces, remote interaction, distributed awareness

INTRODUCTION

For three decades we have heard pundits tout the imminent arrival of the paperless office. However, paper remains a central artifact in professional work practices and use of paper is consistently increasing [19]. It is tangible, portable, readily manipulable, and easily editable [12]. In our previous studies into design, we found that pens, paper, walls, and tables were often used for explaining, developing, and communicating ideas during the early phases of design [15]. Designers prefer these tools because they are flexible, immersive, easily sharable, and calm.

Many designers we have spoken with work in collaborative teams at multiple locations. When working with their remote colleagues, they are forced to choose between the physical tools they prefer and the electronic communication mechanisms available. The designers felt that consensus-building was vital to their work process. It becomes very important to establish deep relationships, especially when participants have different backgrounds [1]. However, it is more difficult to build relationships without a sense of physical presence.

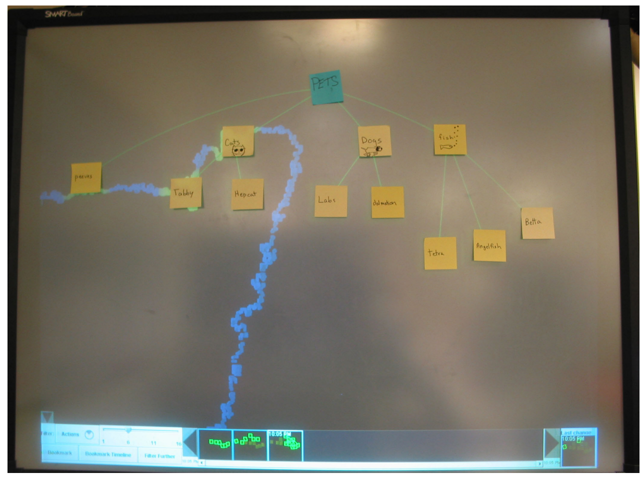

Figure 1: A view of one board in the Distributed Designers' Outpost setup.

Our remote collaboration system (Figure 1) extends the Designers' Outpost [9], a collaborative web site design tool that employs physical Post-it notes as interaction primitives. Users have the same fundamental capabilities with the Outpost system as with paper and whiteboards. Users create new objects by writing on Post-it notes and adding them to the electronic whiteboard, and organize information by physically moving Post-it notes around on the board. Paper in the physical world becomes an input device for the electronic world. A rear camera mounted inside the board captures the location of notes, detecting when notes are added, removed, or moved. A front camera captures the contents of the physical notes so that electronic counterparts can be displayed by means of a rear-mounted projector that outputs electronic information back onto the board surface in the physical world. This structured electronic capture of paper-based designs offers a several compelling advantages. In this paper, we show how structured capture enables fluid remote collaboration. Our previous research has shown how capture also provides the

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Figure 2: Our remote system running on two SMART Boards. Notes that are physical in one place (see left) are electronic in the other (at right). The Outpost history bar [10] at the bottom shows previous states of the board.

ability to transfer the information to other digital tools [9] and increased control over versioning and history [10].

To better support remote collaboration, we introduce an interaction paradigm where objects that are physical in one space are electronic in the other space, and vice-versa (see Figure 2). This paradigm has the potential to enable more fluid design among distributed teams, but must also overcome the problems of maintaining awareness between distributed groups.

We present and evaluate two mechanisms for awareness: transient ink input for gestures and a blue shadow of the remote collaborator for presence. The transient ink is a pen-based interaction technique for conveying deictic (pointing) gestures. Users mark up the board to suggest changes or relationships without permanently cluttering the workspace. Transient ink is displayed on both boards for a few seconds, then fades away. The mechanism for presence awareness is a blue shadow that represents the location of the remote participants with respect to the shared workspace. Users of the system can get a sense of the locations and intentions of remote collaborators without needing their physical presence.

The Designers' Outpost was originally a single location interface. We extended Outpost to communicate between two remote hosts. The shared communication consists of user actions (e.g., adding and moving notes) augmented with remote awareness information (a vision-tracked shadow of the remote users and transient ink).

RELATED WORK

Our work draws from two areas: tangible interfaces and distributed media spaces for remote interaction.

Tangible User Interfaces for Remote Collaboration

Wellner's DigitalDesk [23] is a seminal example of a desk that supports paper as an input device. It uses ceiling-mounted cameras to track paper documents and the user's hands on a physical desktop, and a ceiling-mounted projector to electronically display data onto the desk and the paper. The DoubleDigitalDesk [23] extends this augmented paper input paradigm to a pair of networked DigitalDesks. Content can be either physical (drawn on paper by one of the users) or virtual (information that is projected, such as remote content.) The DoubleDigitalDesk enables a user to electronically view and copy her remote colleague's physical content. The Desk does not allow her to move or delete this remote content. DoubleDigitalDesk also allows for spatial content selection, but objects have no semantic distinctive identity. Each object and awareness cue has a distinct internal representation in Outpost. As such, this information can be edited and displayed separately. Our mediation techniques and stronger semantic representation of content enable users to delete and move remote physical content. Lastly, while the Desk is intended as a pair-ware system, Outpost explicitly supports multiple users at each location.

Collaborage [14] is a computer-vision system that captures paper information arranged on an ordinary wall, enabling it to be electronically accessed. These pieces of paper are tagged with glyphs, a type of 2D bar-code. The electronic capture of paper information enables remote viewing (e.g., a web page view of a physical in-out board), but not remote interaction. Distributed Outpost provides for two way interaction and also offers awareness cues.

InTouch [5] provides an identical set of cylindrical rollers to participants at two different locations. The networked rollers behave as though they are physically connected. This system provided a shared mechanism for synchronous awareness of touch. InTouch's compelling aesthetic experience encouraged us to explore richer awareness mechanisms for our design tool.

Reznik and Canny's Universal Planar Manipulator (UPM) [18] provides a view of the future where physical objects can be controlled remotely. The UPM is a rigid, horizontal plate which vibrates in its own plane and moves generic objects placed on it as a result of friction. However the technology is not yet mature enough to support large numbers of objects, and our system is based on vertical as opposed to horizontal surfaces.

Distributed Media Spaces

Over the last decade, there has been compelling research in distributed media spaces for visual collaboration tasks, such as shared drawing through electronic whiteboards. These researchers found, as we have, an interest by users in collaborating on design artifacts from different places. Clearboard [8] and VideoWhiteboard [21] are pair-ware systems that integrate visual drawings with video presence on a single display. Clearboard users draw on a glass board. The board is augmented with a live video projection, giving the appearance of "looking through the glass" at the remote participant's drawing, face, and upper body. The glass board and video camera setup is duplicated at each end. VideoWhiteboard works in a similar fashion, however, the video image is the shadow of a standing remote user's body. Both of these systems use a direct video feed, cleverly aligned, to transmit both the drawing and presence information.

While the data transmission in these systems is a raw video feed, Distributed Outpost has a structured representation of the content. Its computer vision algorithms locate physical objects and users' shadows, building an internal representation of this content and awareness feedback. This semantic understanding of the information allows for more flexibility in presentation. For example, in Distributed Outpost the awareness display can be removed, modified in color, or shown as an outline only. Distributed Outpost provides more control over changes to content, allowing objects to be erased or moved without affecting the rest of the display. In addition, all of the advantages carry over to Outpost's design history and ability to transition to other tools.

Several other researchers are investigating interaction techniques for large electronic display surfaces [20], the combination of these surfaces with physical objects [6, 17], and multimodal interaction with paper [12, 13].

Our research goal is to bring together tangible user interfaces and distributed media spaces to create and evaluate an application that supports an existing design practice.

INTERVIEWS AND FIELDWORK INFORMING DESIGN

Previous fieldwork and design studies [2, 15] have found that designers often need to collaborate with colleagues and clients who are not located the same office or even the same city.

We brought six professional designers into our laboratory to provide feedback on Distributed Outpost. We first asked them to discuss their current remote collaboration practices. The designers described several important collaboration tasks including: consensus building, concept mapping, user focused design solutions, and defining project features, function, and interaction.

Current Experience: Working Remotely

Working with remote participants is a "nightmare," stated one designer. The designers expressed three primary frustrations with their current collaboration tools. First, they felt that their interactions with remote colleagues were impoverished. Second, they felt the tools well suited to collaboration (e.g., e-mail, telephone), were ill-suited to design. Finally, all of the designers in our study had developed ad hoc methods when designing with remote colleagues.

We found four ways they collaborated with remote team members.

1. Whiteboard, video, and e-mail: One group maintained their physical practice of using a whiteboard with sticky notes at a central office. Remote participants can view the screen though a video link, however, their participation is severely limited. Distributed workers send e-mail to the facilitator when they have input. Thus, they are totally reliant on the facilitator for their participation in the design session, and there is a time lag between their contribution and its visibility to the rest of the group. As a group member stated, "This makes it almost impossible to have active participation of remote participants."

2. Two whiteboards and videoconference: Occasionally both offices will have sophisticated videoconferencing technology. Designers work on two separate, manually synchronized whiteboards with Post-it notes. Each side has a remote controlled pan/tilt/zoom camera. The technology is adequate for viewing the distributed boards, and the resolution is high enough to view written text. However, there are significant pauses in the interaction while one side zooms the camera in to see a change, and there is trouble keeping the separate representations consistent.

3. Collocated meetings (and occasional conference call): Another group was limited to only generating ideas when they were collocated. Once the ideas were generated, the potential design was typed into a computer for sharing with the remote clients. When meeting with clients in a conference call, each person had their own paper printouts on which they recorded potential changes to the design. Later, these designs were synchronized by the designers in a discussion meeting to come up with the final design.

4. Visio and e-mail: Another participant developed designs alone with Microsoft Visio, a GUI diagramming tool. When it came time to collaborate, he would e-mail the document to another user, who would change it and e-mail it back. Some of his colleagues did not have this tool and thus worked on paper printouts and had him enter the changes into his document. This setup made real time collaboration impossible and added significant lag to the design process.

User Needs for Remote Collaboration

One of the largest problems we identified was a lack of shared workspace. For large, remote teams, it can be hard to maintain focus without a shared artifact to discuss. It is also difficult for remote users to gesture or convey spatial relationships when they do not have access to the items

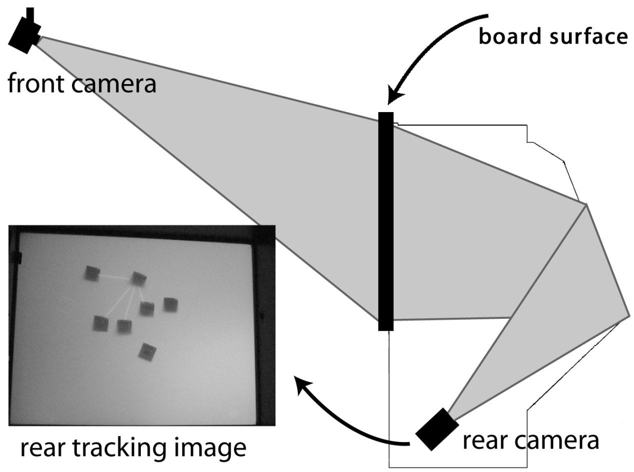

Figure 3. The two cameras used to track and capture user shadows and physical documents in Outpost.

under discussion. The formality and constraints of current technologies also interrupt the flow, making designing more difficult [11].

Many designers stressed the importance of establishing common ground with the people they worked with. "It's not the end, it's the means," one designer explained. Consensus is vital for moving forward in the project. When the participants have different backgrounds, it becomes especially important to establish deeper relationships.

The designers we interviewed found it was difficult to establish a rapport with distributed participants. They said that they felt disjointed from the people that they were working with remotely. Even with a sophisticated video conferencing setup, disjointedness was a problem. Latency, a lack of presence information, and out of sync artifacts remain barriers to effective collaboration.

INTERACTION TECHNIQUES

Our system addresses designers' needs in two ways. We provide a unified workspace with support for spatial gestures between remote colleagues. We also provide presence and awareness mechanisms to help remote participants establish common ground. In supporting these requirements, we felt it was important to keep the physical interaction and maintain a calm interface, such as in AROMA [16].

Shared Workspaces and Transactional Consistency

Our system consists of a shared workspace though which groups of designers can interact. Several designers can participate at once when working with the board. The computer vision system supports simultaneous input of several Post-it notes.

A note is created by writing on a physical Post-it note and placing it on the board. When a local user *physically adds* a note to the whiteboard, the remote system *electronically displays* a photograph of that object (see Figure 2). The vision system's rear camera locates the note and the front camera takes the photograph (see Figure 3). The front

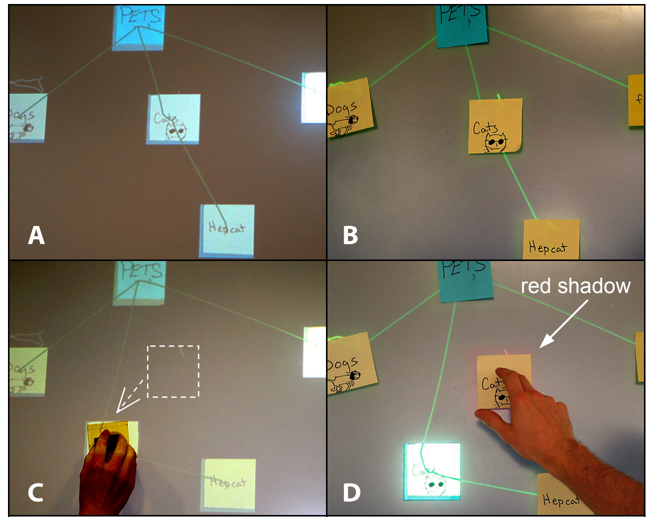

Figure 4: Moving a note: (A) and (B) show the remote and local views before the move. In (C), a remote user moves the electronic version of the 'Cats' note with the move tool. (D) shows the virtual 'Cats' note at the new location and the local user removing the out of date physical 'Cats' note (marked with a red shadow).

camera very rarely has problems with users occluding note pictures. When any user performs an action, both the local and the remote system are updated. Both teams can interact with any note, regardless of whether it exists as a physical object or remote analogue.

To delete a note, the user simply removes it from the board. To move a note, the user picks it up and places it in the new position. (Currently, the system does not recognize specific notes based on content and so it assumes that the note is the same if it is replaced within seven seconds.)

We would like for both teams to be able to edit and move all objects. When the objects are electronic (such as with links), this is easily facilitated. When the objects are physical (such as with Post-it notes), editing them from multiple sites introduces some difficulty. One option is to only allow the creator editing ability [14]; that is not very appealing.

We have taken an alternate approach. Post-it notes in Outpost cast electronic shadows as feedback to the user that the system is aware of their presence. When a note's physical state becomes transactionally inconsistent, the system casts a strong red shadow indicating to the user to remove the artifact (see Figure 4D). The red shadow identifies that the physical note is no longer an information handle to the virtual remote analogue. This feedback is lightweight; it provides awareness that the note is out of date, but does not require the user take any action.

We originally introduced the red shadow feedback in Outpost's design history system [10]. There, it identifies notes that are out of date with respect to time. Here, it identifies notes that are inconsistent with the remote users' board.

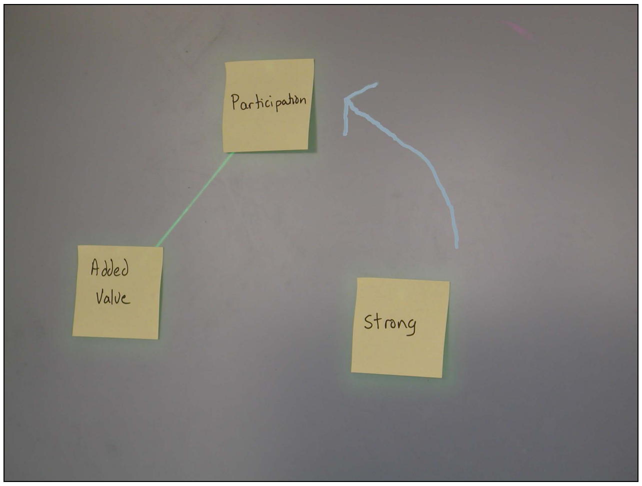

Figure 5: "Should *this* note be moved up *here*?" Transient ink is used to convey specific notes and spatial positions by a remote user. The arrow disappears after several seconds.

A remote user could do two things to make a physical note transactionally inconsistent: delete the note or move the note. If the note is deleted, the faint recognition shadow is replaced with a red shadow (see Figure 4D). The local user could remove the note to dismiss the shadow or re-post the note if they disagreed with its removal. When a note is moved, a red shadow displays behind the out-of-date physical note and a virtual note appears in the new position (see Figure 4). The local user could then remove any physical note with a red shadow.

When a note is virtual, the physical handles are missing, and must be replaced with electronic controls. In this case, a note context menu is available for deleting notes, and the physical move tool is available for moving the notes as described in [9].

Desktop Outpost

When an electronic SMART Board and camera setup is not available, Distributed Outpost will work on a PC type setup such as a rear projected display on a digital desk with a Wacom Graphire pen tablet or ordinary mouse. It is possible to add notes with a tap and draw on them with the stylus tool. Links can be added by drawing a line between two notes. Erasing and moving ink and links is supported with the stylus button.

Although the setup is not ideal and the tangible advantages of Outpost are not available, users can still work with the notes using pen-based design interaction. This setup is more cost effective and flexible for remote participants with limited resources.

Transient Ink for Deictic Gestures

One of the challenges of sharing a workspace still remains: how to convey deictic gesture. After the idea generation phase, designers find it important to organize, group, and link information. Organizing ideas into a coherent structure is an important stage in the design process. Physical layout is used to convey conceptual relationships.

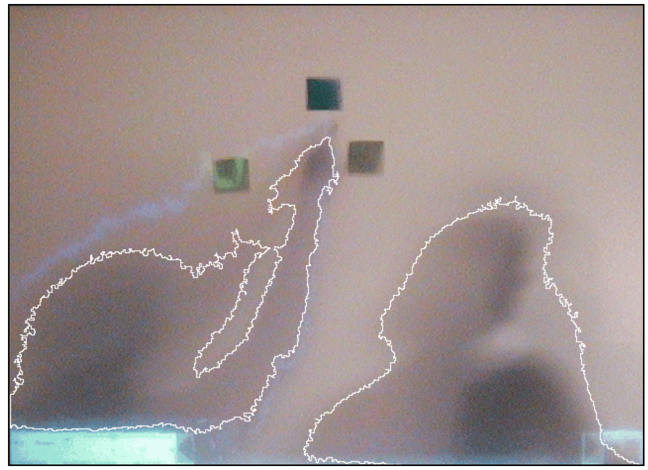

Figure 6. The view from the rear camera. The calculated borders of the shadows are drawn in white, on top of the raw pixel input.

When remote users do not have access to the board, it is difficult for them to understand what their local colleagues are communicating or to express their opinions on relationships. It can even be difficult to specify which note they are talking about.

When users would like to draw their collaborators' attention to a particular spatial position or artifact, they need some way to convey this deictic gesture. We found that a simple remote pointer did not convey enough information. For this reason, we developed transient ink as a richer interaction technique for enabling distributed users to convey deictic information to each other. This is similar to the technique described in [22], which conveyed a transient pointer to a remote site. However, our technique has richer interaction. It conveys an ink stroke rather than a pointer, and it allows multiple simultaneous strokes.

Users draw electronic transient ink on the board with the red stylus tool (see Figure 5). The ink is rendered on both displays for a few seconds, and then it fades away. This allows users to convey relationships, suggest links, and point to notes without committing their changes and permanently cluttering the board.

When using the board interface, a specific stylus is used to select transient ink instead of regular ink and link creation. From the desktop setup, it must be selected from a pie menu. In addition to transient ink as a mechanism for conveying gesture, we provide vision-tracked shadows of people to help provide a rough idea of remote collaborators' locations around the board.

Distributed Presence

A sense of presence is important to developing a working relationship with remote colleagues. However, the designers we interviewed did not feel that the currently available videoconferencing and audioconferencing technologies provide a sufficient sense of presence to establish a rapport.

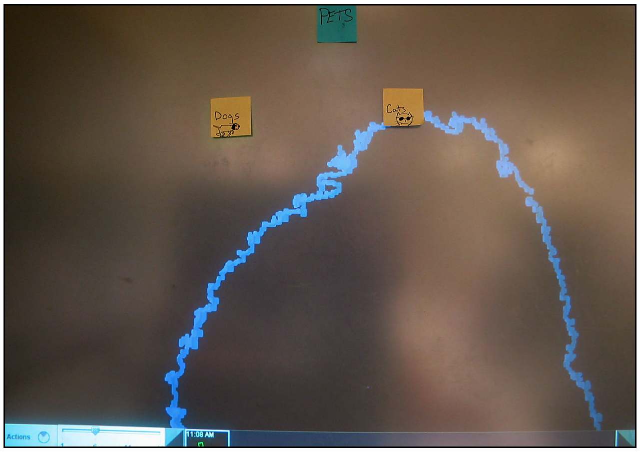

Figure 7: Our distributed awareness mechanism. A blue shadow outline in the background represents a remote collaborator.

Our presence shadow is inspired by Clearboard [8] and VideoWhiteboard [21]. The seamless interaction paradigm put forth in these systems is particularly appropriate to support awareness for our system. It is important that the presence mechanism be calm and non-distracting, allowing designers to focus on the task.

We extended the rear camera's vision processing, used for detecting notes, to detect peoples' shadows on the board (see Figure 6). As a person casts a shadow on the board, we determine if it is the appropriate size and darkness for a person. If so, the vision system calculates the shadow boundary. If more than one person is working at the board (as in Figure 6) the awareness will show multiple shadows.

An early version of the remote awareness, used for the feedback session, displayed a translucent blue oval based on the center point, width, and height of the detected shadow. However, the designers found that this did not provide enough detail.

The current presence visualization is a stylized shadow outline of the remote users, displayed on the background of the design surface (see Figure 7). This shadow conveys the remote users' presence, gesture, and location in a lightweight fashion.

All content and presence information is sent using sockets over IP, unlike prior work [8, 21], which required a video link. We decided to present a shadow instead of a live video image of the user because the latter would disrupt the interaction with physical notes. Our goal was to subtly display and communicate information that is not part of the user's primary foreground task.

SOFTWARE INFRASTRUCTURE

Our remote collaboration system extends the Designers' Outpost. Outpost was built using the SATIN toolkit [7], which employs a command object system. A command object [3] represents a change between two states. For example, adding a note, removing a note, adding ink, adding links, and adding transient ink are all command objects.

Data Transfer

The system works as a peer-to-peer system; both endpoints replicate their commands, sending the corresponding command objects to the opposite endpoint. Each object has a unique global identification tuple, composed of its creator's hostname and an integer corresponding to its position in the local command queue. This identifier is used to refer to objects between hosts. We modified the SATIN command queue so that when a command is executed, it is also marshaled for serialization over the wire, and sent to the remote host. Because most of the changes were made at the toolkit level, other SATIN-based applications can benefit from this infrastructure with minimal application-level change.

Outpost designs are serialized to files as XML documents. We use the same XML serialization scheme for network communication. The connection between the machines is socket based. Users have the option of connecting to different remote hosts, or not connecting at all if they wish to work alone.

At present, photographs of notes are stored as JPEG files on a networked file server. They are accessed as needed over the file system by the hosts. This could easily be modified to use a web server to support collaboration between distinct organizations.

Vision and Tracking

Our vision system is written in C++ on top of OpenCV [4], a highly optimized library of computer vision and image processing primitives. The original Outpost vision tracking system used the rear camera to track notes [9]. We extended this to find shadows of people using the system.

The system processes the image using spatial and temporal filtering, corrects for perspective distortion, and computes a running average of the expected background image.

We construct three thresholded difference images. Possible pixels from added notes are found by subtracting the current frame from the expected average image. Potential shadows are found the same way. They have a lower threshold than for notes, because a person's shadow from standing in front of the board is not as dark as the shadow cast by a note stuck directly onto the board. Potential removed notes are found by subtracting the expected average image from the current frame.

At this point we segment the binary images using a connected-components algorithm. The found elements expected to be notes are subjected to size and shape restrictions using an expectation maximization algorithm before being classified as notes. The person objects are also subjected to size restrictions of 0.5% to 40% of the board.

The vision system runs as a separate process, passing events (e.g., `Add [x, y, θ, ID]`, `Remove [x, y]`, `AddPerson [x, y, w, h]`) to the local Outpost UI through a socket network connection.

PRELMINARY USER FEEDBACK

We had six professional designers visit our lab. We asked them to come prepared to design a web site of their own choosing. We had one group of three, one group of two, and one single user come in and use the system. Each session lasted 1.5 to 2.5 hours. First, we orally interviewed them about their current remote collaboration practices. Then, we gave a brief introduction to the remote system and had them use the system to design their site. Designers were generally enthusiastic about the system's potential to improve their work.

Due to the technical constraint of having only one full Outpost board setup, the groups worked with one Outpost Board connected to a VisionMaker digital desk. The input for the digital desk was an input-only Wacom Graphire pen tablet. One of the participants used a mouse instead of a Wacom Tablet. Although we recognize the importance of audio to distributed collaboration, the current implementation has no audio support. This is not a major drawback as a conference call can easily provide multi-user audio support. For our feedback sessions, the board and the desk were located in the same room. The participants were allowed to speak to each other but unable to see each other because of a curtain.

During the sessions, users input ideas using physical Post-it notes for concepts and styluses for linking and annotation. They were able to access transient ink by using a specific stylus tool. The rear camera tracked their shadow location. The board users were able to see the blue oval "shadow" that they were transmitting to the remote participant, but there was no shadow of that participant available to them.

The Digital Desk side had no cameras, and thus was set up to run Desktop Outpost. The digital desk users were seated in front of the slanted desk. Users could input notes and write on them using the Wacom stylus. Although their location was not tracked, they could see the shadows representing the people working at the board. Transient ink was available to them as an option through a pie menu accessed with a right click.

Qualitative Feedback

The users were very enthusiastic about the shared workspace. They felt that it would increase the value of working sessions with team members and clients. They appreciated seeing their colleagues' input in real time. They were also impressed with the fluid mobility of data and flexibility of location. They felt it improved their collaboration, as spatial relationships were visible in real time to everyone. One designer mentioned that she preferred Distributed Outpost to the whiteboard and videoconferencing setup because Outpost digitizes the information for later use, and there is no pause in the work for zooming and panning of videoconferencing cameras. They liked the flexibility of the notes, and being able to collaborate and throw out ideas quickly.

Users also liked the concept of transient ink. One designer especially liked this concept because he could show relationships between elements without committing to the interaction. Designers found with Outpost's functionality made it easy to make changes and communicate their intent to others. About half of the participants found the transient ink useful; the others did not use it during the test. As one user commented, one may as well make marks with ordinary ink and then erase them. However, one of the participants rated the transient ink as being more important in remote collaboration than voice.

Half of the users found the presence awareness shadow compelling. They felt it was vital to provide a frame of reference for the remote participant. They could thus make references to data objects with an understanding of how the remote person viewed them. They felt this gave a better understanding of participation from the remote site.

Areas for Improvement

Although the users seemed generally enthusiastic about the potential of the system, there were some coordination problems. With a physical Post-it note, it is clear when two co-located people wish to move or edit the artifact at the same time. With Distributed Outpost, there are no restrictions on who can change or edit notes. So conflicts can occur, although they were fairly infrequent and easily corrected.

Even though the remote shadow was designed to be unobtrusive, some designers found that it was a bit jumpy and distracting. They would have liked to see a smoother motion so they could attribute human characteristics to it. For example: showing hesitation, acceleration, "things that one can translate into feelings." They also wanted more detail than the oval shadow provided.

Overall, the designers we interviewed were enthused by our system and felt the concepts would be helpful in increasing the interactivity of their remote design collaboration. Our design studies also showed that audio was very important to communication. We plan to integrate this into our system. We also plan to improve the quality of the shadow by presenting a more detailed and smoother representation. In future we would like to evaluate this system over the long term in a pair of distributed design offices that regularly collaborate with each other.

CONCLUSIONS

We have presented Distributed Designers' Outpost, a remote collaboration system supporting designers' need for both physical artifacts and distributed collaboration. Our remote system provides a shared workspace where the participants can edit any object, regardless of where it was created. We presented two novel awareness mechanisms: transient ink input for gestures and a vision-tracked stylized shadow for presence. Six professional designers provided feedback about the system, and were enthusiastic about its potential to support their current practices and increase their ability to work in distributed teams.

Computers have been instrumental in allowing us to communicate quickly with people all over the world. However, we lose some of the advantages of meeting face to face. Hopefully this work will help to bridge the gap between the virtual and physical worlds and help remote teams to work more comfortably and effectively.

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