The Everywhere Displays Projector:
A Device to Create Ubiquitous Graphical Interfaces

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Abstract. This paper introduces the Everywhere Displays projector, a device that uses a rotating mirror to steer the light from an LCD/DLP projector onto different surfaces of an environment. Issues of brightness, oblique projection distortion, focus, obstruction, and display resolution are examined. Solutions to some of these problems are described, together with a plan to use a video camera to allow device-free interaction with the projected images. The ED-projector is a practical way to create ubiquitous graphical interfaces to access computational power and networked data. In particular, it is envisioned as an alternative to the carrying of laptops and to the installation of displays in furniture, objects, and walls. In addition, the use of ED-projectors to augment reality without the use of goggles is examined and illustrated with examples.

1 Introduction

Ubiquitous computing envisions a world where it is possible to have access to computer resources anywhere and anytime to the data and services available through the Internet [1]. Since most of current software and Internet data is designed to be accessed through a high-resolution graphical interface, to truly ubiquitously compute today users need devices with reasonable graphical capabilities. This means carrying laptops everywhere, wearing computer graphics goggles, or installing monitors and displays on the surfaces of spaces and objects, such as desks, fridges, and entrance doors. Or, simply, to resign to the low-resolution displays of mobile phones or PDAs.

In this paper we explore an alternative approach to create ubiquitous graphical interfaces. Our idea is to couple an LCD/DLP projector to a motorized rotating mirror and to a computer graphics system that can correct the distortion caused by oblique projection. As the mirror moves, different surfaces become available to be used as displays. Also, we plan to employ a video camera to detect hand interaction with the projected image using computer vision techniques.

Our target is to develop a projection-based system that creates interactive displays everywhere in an environment by transforming a surface into a projected "touch screen." Such an *Everywhere Displays projector* can be installed, for example, on the ceiling of a space, to provide a generic computer interface to users in that environment (see Fig. 1).

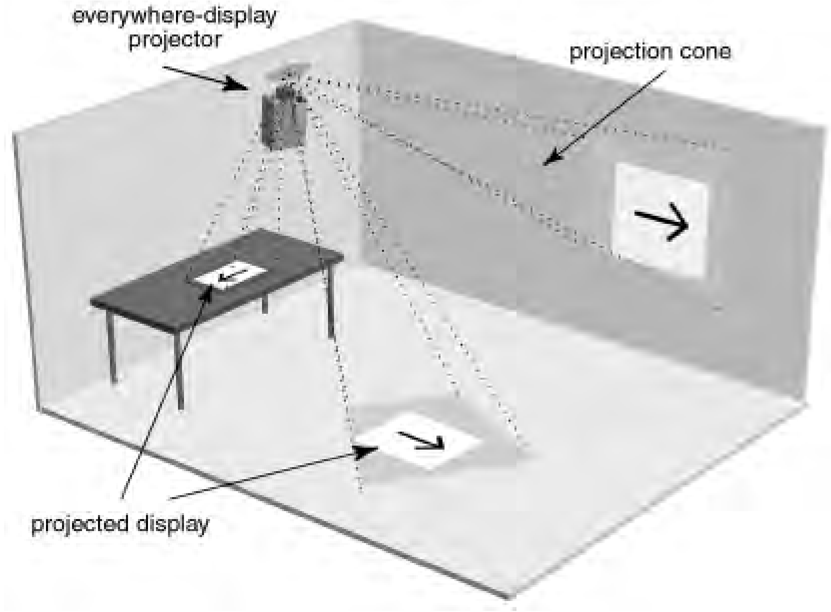

Fig. 1. Using the Everywhere Displays projector to create displays on different surfaces in an environment.

For example, an ED-projector can be installed in a meeting room and be used not only to project images on the walls but also to create individual displays for each of the participants of a meeting. Instead of today's meeting tables populated by bunkering personal laptops, a small set of ED-projectors can be shared by the participants to access their personal data, but easily reconfigured to allow teamwork. For instance, two people can be paired together to work on a sub-problem using a display projected in front of them while the other participants keep discussing the main themes using a display projected on the wall.

Moreover, ED-projectors have the ability to provide computer access in public environments without the risk of equipment being broken or stolen. Instead of carrying a computer, PDA, or phone everywhere, users can simply request a computer display, maybe by making a gesture to an overhead camera, and receive the projected image on a surface near their location. For example, an ED-projector in a store can transform pieces of white cardboard attached to shelves into interactive displays with product information. Unlike traditional kiosks, there is no need to bolt monitors and computers to the floor.

In other words, we are proposing a shift in the display paradigm, which ceases to be regarded as a device to be installed in an environment, or carried along by a user and becomes a service provided by a space, like electric power or phone lines. But like any innovation, ED-projectors not only solve a problem but also create a new set of applications. For instance, if information about location and identity of objects in an environment is known, an ED-projector can be used as a device to augment reality without requiring users to wear goggles. It can lead a visitor to its destination in a

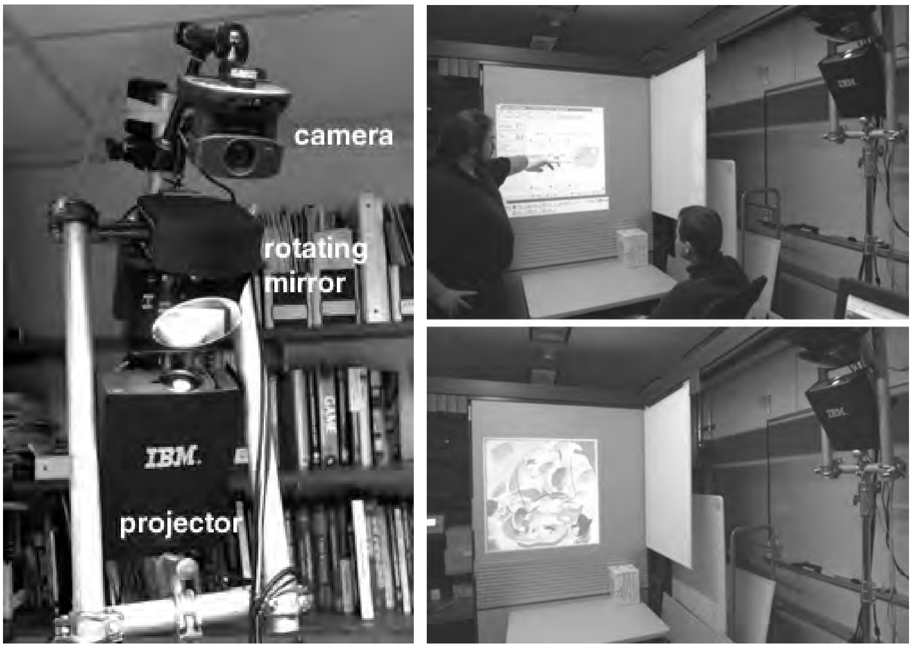

Fig. 2. Current prototype of the Everywhere Displays projector (left) and the projector being used in an office-like environment (right).

building by directly projecting arrows on the floor; or project information directly onto the objects being assembled in an industrial plant. The ED-projector enables a computer system not only to augment a physical space with information but also to "act" in that environment and its users by projecting light patterns and symbols on objects and people.

This paper describes our current prototype of the Everywhere Displays projector and the technological solutions used in its implementation. We also demonstrate applications for different scenarios and examine new interaction paradigms for human-computer interaction that might emerge from the pervasive use of ED-projectors.

2 The Everywhere Displays Projector

The *Everywhere Displays projector*, or simply *ED-projector*, is composed of an LCD/DLP projector and a computer-controlled pan/tilt mirror. The projector is connected to the display output of a host computer that also controls the mirror. The left-side picture of Fig. 2 shows a prototype of an ED-projector built with an off-the-shelf rotating mirror used in theatrical/disco lighting, connected through a DMX network to the host computer.

In the configuration shown in Fig. 2-left, the projector's light can be directed in any direction within the range of approximately 60 degrees in the vertical and 230

Fig. 3. Perception of contrast: global brightness (left); local brightness (middle); and a photomontage simulating the perceived contrast (right).

degrees in the horizontal. When positioned in the upper corner of a room (such as shown in Fig. 1), this prototype is able to project in most part of the two facing walls, half of the two adjacent walls, and almost everywhere on the floor.

Figure 2 also shows the current prototype of the ED-projector in use in an office-like environment. The top-right of Fig. 2 shows the ED-projector helping collaborative work. Notice the projector on the right upper corner of the picture and the angle of the rotating mirror used to direct the light onto the wall. The bottom-right picture of Fig. 2 shows the same surface being used to project the picture of an artwork as decoration for the room. Both photos were taken under normal office lighting conditions.

ED-projectors are feasible today due to the technical advances in two areas: video projectors and computer graphics engines. Current LCD/DLP projectors are able to create images that have enough contrast to be seen even when lights are turned on. Fast and cheap computer graphics engines are necessary to correct for the distortion caused by oblique projection. This and other implementation issues are discussed in the following sections.

2.1 Brightness and Contrast

Projecting images in a brightly lit room is possible because the human vision system perceives brightness and contrast locally. Consider a white wall in an environment with normal lighting: if no image is projected, subjects would describe the brightness of the wall as “white.” However, if a white and black pattern with sufficient brightness is projected on the same wall (typically 5 to 10 times brighter than the normal lighting), viewers perceive the white projected pattern as “white” and any neighboring area receiving only the ambient light as “black” [2].

Figure 3 exemplifies this mechanism in a situation where the ED-projector is used to create projected labels on white Styrofoam cups. The left picture of Fig. 3 shows the global brightness as “collected” by a photographic camera. In this picture, ambient light illuminates all the cups although the third cup of the top shelf also receives the projection of the pattern shown in the middle picture of Fig. 3. In the left image the

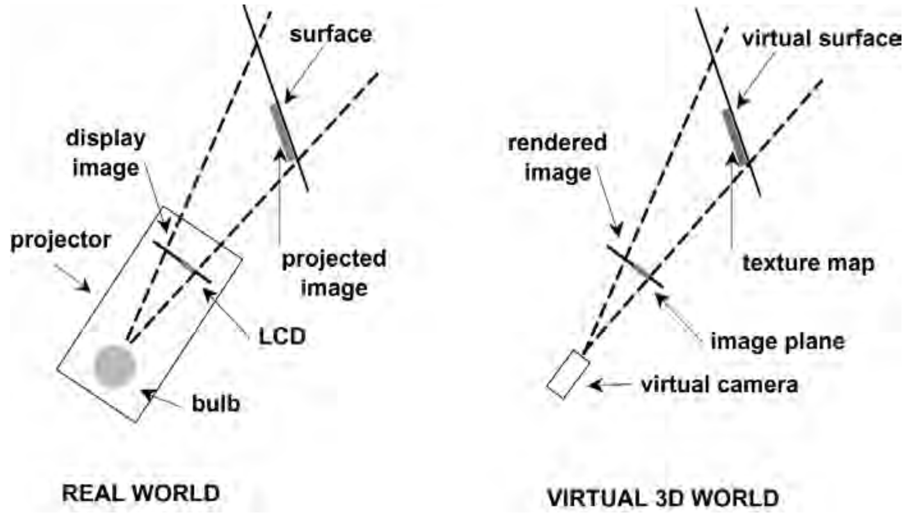

Fig. 4. Using a virtual computer graphics 3D world to correct the distortion caused by oblique projection by simulating the relationship in the real world between the projector and the projected surface.

projected pattern is barely visible because the photographic camera, unlike the human eye, equalizes the brightness globally. The camera takes in account the large black background of the shelf and compresses the range of brightness differences of the pattern projected on the cup into a few shades of white.

However, as shown in the middle of Fig. 3, there is enough local difference in brightness on the projected pattern to allow its clear perception if only local lighting is considered. In particular, notice that the black “OK” lettering corresponds to the white surface of the cup reflecting just the ambient light. Since human vision adjusts to local contrast, the resulting perceived brightness is more like the photomontage shown in Fig. 3-right where the projected pattern is clearly discernible.

Our first prototype employs a 1200 lumens LCD projector that has proved to have enough brightness and contrast to project images on the surfaces of an office room with the lights on. Although we have not conducted experiments to determine the perceived brightness and contrast, in typical home and office conditions a white pattern projected by our prototype is approximately 10 times brighter than its surroundings and, therefore, enough to create the illusion of contrast.

The second prototype we built employs a 3000 lumens LCD projector, enabling sharper contrast for most projected surfaces. In particular, the increase in brightness improved significantly the quality of images projected on horizontal surfaces such as tables and desks. Since such surfaces tend to be orthogonal to the sources of ambient light, the specular component of their reflected light is brighter than non-horizontal surfaces such as walls. However, with a 3000-lumen projector, even the extra brightness provided by the specular light is overshadowed by the projection light.

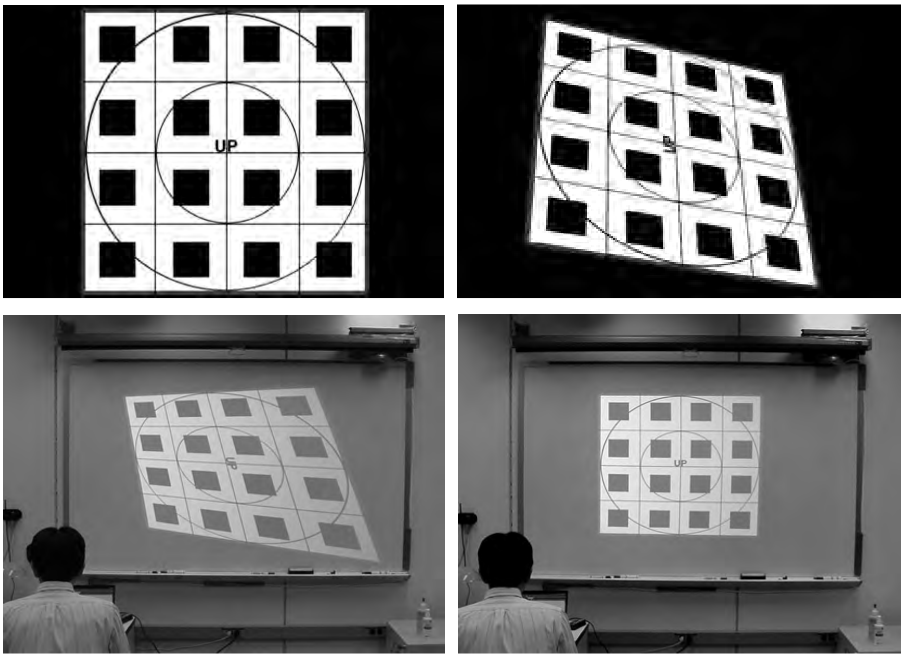

Fig. 5. Correction of oblique distortions: (left) the typical result of the oblique projection of a pattern on a surface; (right) the projection of the distorted pattern (top-right) creates a projected image free of distortion (bottom-right).

2.2 Correcting for Oblique Projection Distortion

When projection is not orthogonal to the projected surface, the projected image is distorted. In fact, as shown in Figs 1 and 2, in most cases the ED-projector is used to create displays on surfaces that are not orthogonal to the projection direction. To correct the distortions caused by oblique projection and by the shape of the projected surface (if not flat), the image to be projected must be inversely distorted prior to projection. In general, this distortion is non-linear and is computationally expensive to correct, involving the selective compression and the expansion of the original image.

We have developed a simple scheme that uses standard computer graphics hardware (present now in most computers) to speed up this process. Our method relies on the fact that, geometrically speaking, cameras and projectors with the same focal length are identical (as observed in [3, 4]). Therefore, to project an image obliquely without distortions it is sufficient to simulate the inverse process (i.e., viewing with a camera) in a virtual 3D computer graphics world.

As show in Fig. 4, we texture-map the image to be displayed onto a virtual computer graphics 3D surface identical (minus a scale factor) to the real surface. If the position and attitude of this surface in the 3D virtual space in relation to the 3D virtual camera is identical (minus a scale factor) to the relation between the real surface and the projector, and if the virtual camera has identical focal length to the projector, then the view from the 3D virtual camera corresponds exactly to the "view" of the projector (if the projector was a camera). Since projectors do the inverse of viewing, i.e., they project light, the result is a projection free of distortions.

In practice we use a standard computer graphics board to render the virtual camera's view of the virtual surface and send the computed view to the projector. If the position and attitude of the virtual surface are correct, the projection of this view compensates the distortion caused by oblique projection or by the shape of the surface. Of course, a different calibration of the virtual 3D surface must be used for each surface where images are projected in an environment.

An example of the results of the process is depicted in Fig. 5. In a typical situation of oblique projection, the pattern shown in the top-left is projected without any correction, resulting in the bottom-left image of Fig. 5. After calibration of the virtual 3D surface and camera parameters, the projection of the rendered image (top-right) creates a projection free of distortion (bottom-right).

So far we have experimented only with projecting on planar surfaces. The calibration parameters of the virtual 3D surface are determined manually by simply projecting the pattern shown in Fig. 5 and interactively adjusting the scale, rotation, and position of the virtual surface in the 3D world, and the "lens angle" of the 3D virtual camera. This process typically takes between 10 to 20 minutes but we are currently working on its automation using techniques similar to [5].

Another simple technique to correct for distortion on planar surfaces is simply to distort the texture to be projected by a homography [6]. In this case, calibration is obtained by interactively grabbing with the mouse each corner of the projected pattern and moving it to the desired location on the surface. Alternatively, the homography can be embedded to the graphics board projection matrix [3]. Unlike the previous approach, homographies work only for planar surfaces.

2.3 Focus

We currently use a LCD projector where focus and zoom parameters can be remotely controlled by computer commands issued through the serial port. However, another problem with oblique projection is that it is not possible to put all areas of the projected image simultaneously in focus. Fortunately, current commercial projectors have a reasonable depth of focus range, enough to maintain decent focus conditions in most cases. We have succeeded in projecting on surfaces with up to 30 degrees of inclination in relation to the projection axis without significant degradation of focus. However, the problem becomes more severe as the distance between the projected surface and the projector decreases.

2.4 Display Resolution

One problem with the techniques described above to correct oblique distortion is that it creates displays with resolutions that are smaller than the projector's resolution. As can be seen in Fig. 5, the distortion correction process has to fit an irregular

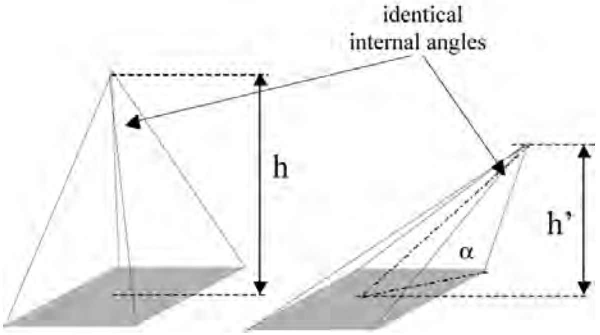

Figure 6. Change of volume for identical internal angles.

quadrangular into the 4:3 viewing area of typical displays. The result is that a considerable amount of display area is lost in the process.

In our prototypes we employ 1024x768 XVGA projectors. However, due to the loss of display area created by the distortion correction process, we have observed that the obtained resolution corresponds approximately to VGA, i.e., 640x480 pixels. This estimation takes in account that in the process of rendering the distorted image some pixels of the original image are compressed into single pixels of the projected image.

Other factors also influence the perceived resolution, among them the angle of projection and the texture of the projected surface. In the case of extreme angles of projection (<20 degrees), we have observed in some cases that while the center of the image is in focus, the area near the edges are somewhat blurred. This blurring is less visible if the projected image has less detail. Similarly, projecting onto textured surfaces such as carpets introduces a high frequency spatial component on the visual field, contributing to decrease the perceived resolution because of interference patterns. We are currently starting research aiming to determine how much perceived resolution is lost when projecting on surfaces of different colors, specular components, and textures.

2.5 Obstruction and Glare

Unlike LCD displays, the use of projectors as graphical displays face the problem of having the projected image being obstructed by people or moving objects in the environment. This was, in fact, one of our major concerns in the start of this project. However, our experience has shown that obstruction is far less common than we anticipated, particularly when the projector is positioned in the upper corner of a room (as shown in Fig. 1). Although we initially tried to position the projector on the center of the ceiling, the corner placement proved to be much more effective, mainly because in this situation the projection cone tends to be closer to the wall and therefore less prune to be intercepted by human beings.

Another reason for the relative lack of obstruction is the fact that oblique projection cones are smaller than orthogonal projection cones. To see this, consider the two projection cones C and C' with identical bases and internal angle (i.e., lens configuration) and heights h and h', as shown in Fig. 6. Since the loci of all vertices of pyramids of equal base and internal angle is a sphere[1], it's easy to see that the $h' = c.h.\sin\alpha$, where c is a constant smaller than 1 that depends on the geometry of the orthogonal pyramid C.

Since the volume of the pyramid is proportional to the product of the area of the base B by the height of the pyramid, $V = 1/3B.h$, we obtain that the volume of the two pyramids are related by:

$$V' = V.c.\sin\alpha$$

For instance, if the angle of oblique projection α is 30 degrees, the volume of the oblique pyramid is less than half the volume of an equivalent orthogonal pyramid. Since the projection cones of oblique projections are smaller than those of orthogonal projections, we should expect a similar reduction in the likelihood of obstruction.

Similarly, the positioning of the projector on the ceiling, above human heads, contributes decisively to avoid glare and direct staring to the bulb of the projector. Again we see here a benefit of oblique projection that allows this placement of the projector on the ceiling. Although most commercial projectors today have some mechanical or electronic device to correct for keystoning (typically less than 10%), this correction does not allow the positioning of the projector sufficiently high to avoid glare. In the office-like experimental setup of our environment, however, glare happens only in very unusual situations such as when the user is sitting on the floor.

3 Making the ED-Projector Interactive

The current prototypes of the ED-projector include the functionality to project on different surfaces a 512x512 portion of the interactive desktop display of the host computer. The user can interact in real-time with this projected desktop using mouse and keyboard.

We are now starting to explore the interaction with the projected surface without the need of users having to manipulate input devices. In other words, we would like to have the projected display behaving as if it was a "touch screen," making the ED-projector a system easily usable in public spaces or in hazardous environments. The goal is to have the user interact by moving her hand over the projected surface, as if the hand was a computer mouse (see Fig. 7); and by moving the hand rapidly towards the surface, to generate a "click" event. We are currently investigating the use of a pan/tilt video camera that is controlled by the computer so it has a complete view of the projected surface (depicted in Fig. 2, installed on the top of the ED-projector).

To track the position of the hand over the surface, we are considering the development of variations of the traditional background subtraction techniques used in computer vision [7]. However, unlike those cases, we have a situation where the

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[1] This is the 3D equivalent of the known geometric property that for any two distinct points on a circumference, all triangles formed by the two points and one third point belonging to the arc between them have internal angles of the same size.

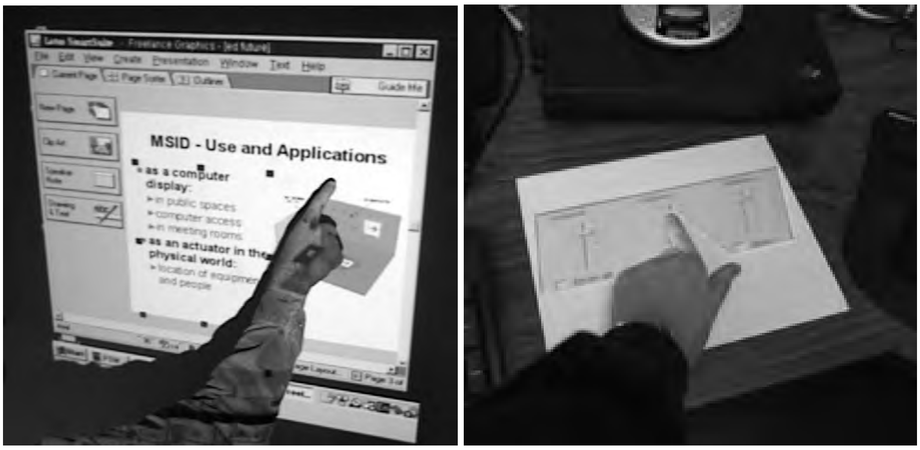

Fig. 7. Examples of interaction with the projected display by hand.

projected background changes significantly and abruptly over time. To overcome this problem, we are exploring two alternatives: the use of two synchronized cameras in a stereo configuration as in [8] and a method based on the estimation of the projected background of the image.

The second method explores the fact that although the projected background changes, what is being projected is known to the system. Therefore, if the patterns of light reflection are known for the projected surface, it is possible to estimate how the projected image will look like when seen by the camera. In other words, we are investigating whether we can calculate the expected background based on the surface reflectance characteristics (together with the camera influence on them) and the image being projected.

The detection of "clicking" events seems to be quite more complicated. To detect a fast movement of a hand or finger towards the projected surface, we need some estimation of the distance of the hand to the surface. Although we plan to experiment with stereo vision to solve this problem, we are considering a simpler scheme based on the measurement of the width of the shadow created by the hand. As seen in Fig. 7-left, the obstruction of the projected light by the user's hand creates a black shadow, in this case to the left of the hand. As the hand gets closer to the surface the shadow decreases in width, especially in the area near the fingers. Our plan is to track the size of this shadow and use it to estimate the hand-surface distance.

A word of caution has to be made about using DLP projectors with standard video cameras. Since DLP projectors project each RGB separately, capturing the projected image with a camera normally results on images showing only one or two of the light components. The only way to overcome this problem, it is necessary to synchronize it with the projector and to increase the exposure time of the camera so it integrates all color components.

4 Using ED-Projectors in Ubiquitous Computing

The ED-projector is a generic input/output device that has been designed for use in multiple applications. These applications can be basically classified in two classes. The first class corresponds to the creation of interactive displays that provide computer access from surfaces of objects, furniture, walls, floor, etc. The second class of applications deals with typical augmented reality applications: the ED-projector can be used to point to physical objects, show connections among them, attach information to objects, and to project dynamic patterns to indicate movement or change in the real world. This section covers the applications in ubiquitous computing; the next section explores the uses of ED-projector as a tool to augment and affect reality.

4.1 Ubiquitous Access to Computational Resources and Information

The ED-projector is a tool that can create a high-resolution graphical interactive display to access computational resources, personal information, and the web. In this regard, it can be seen as a device that realizes the aspirations of ubiquitous computing [1] without the encumbering carrying of laptops or wearing of video-goggles. Since it can be installed on the ceiling of environments, it does not require the use of batteries or wireless links, eliminating two key problems of current laptops. And, unlike PDAs and phones, it does not require a change in most of today's interaction paradigms since it can provide access through a high-resolution (VGA, at least) display.

Fig. 8 depicts an example where a desktop application is moved around a room, being available in different surfaces that correspond to different uses of computer access. First, the display is laid on a desk, then moved onto a whiteboard, and finally projected on the wall besides the whiteboard. Notice that the display, in this last position, can be easily consulted while the users are scribbling on the whiteboard.

Similar applications can be created for professional environments such as hospitals where space is tightly constrained and there are restrictions on what can be carried by people. For example, a single ED-projector in an infirmary can provide on-demand computer access to nurses and doctors, freeing them from carrying laptops around. In another scenario, ED-projectors can substitute TV sets in patient rooms: although they can still be used to project TV images on the wall, they also enable computer access to data and communications from the patient's bed, without any need to move and connect equipment in the vicinity of the patient.

4.2 Collaborative Work

Video monitors, LCD screens, and PDAs are designed for individual use of computers. The only tool currently easily available for collaborative work with computer applications are LCD projectors, normally mounted on rooms to project on one of the walls, creating a "stage" effect for presentations. This configuration is

Fig. 8. The ED-projector moving a desktop application to the top of a table, to a whiteboard, and to a wall on the side of the whiteboard.

awkward for collaborative work since it creates a single point of attention and distracts people from looking at each other.

There has been a significant amount of HCI and design work to provide computer access to tables (for some examples, see [9, 10]). The ED-projector is clearly a device that enables this kind of interactive work, with the advantage that the resource can be easily moved to walls, adjacent tables, etc., allowing easy reconfiguration of a meeting space for different functions and teamwork styles.

Similarly, ED-projectors can be used in school classrooms. Instead of having a row of workstations with video monitors, the teacher can use ED-projectors to reconfigure the classroom for individual, group, or whole class activities. In day-care centers and kindergartens the device enables the use of walls and floors for education and entertainment, with the advantage of no infant contact with heavy or breakable objects.

There are many other similar applications in professional activities where teamwork is needed. Typical examples are surgery rooms, today crowded by arrays and arrays of bulk monitors displaying information and video imagery, and monitoring vital signs. A set of ED-projectors seems to substitute such configuration with the advantage that vital information can be easily brought in close proximity to nurses and physicians for detailed inspection or interaction.

4.3 Computer Access in Public Spaces and Hazardous Environments

The ED-projector can also be used to provide computer and information access in spaces where traditional displays can be broken or stolen, or create hazardous conditions, such as in public spaces or areas subject to harsh environmental conditions. Examples of spaces in the first category are waiting areas of transportation facilities such as subway stations and airports. The ceiling mounting of the ED-projector protects it against vandalizing, while the mirror allows easy change on where information is projected. This last feature is particularly important for this kind of environment where the cost of installing or reconfiguring equipment tends to be very high.

We also envision the use of ED-projectors in factory areas where normal electric devices are not allowed due to the potential risk of sparks, or simply because the environment itself contains hazardous elements to computers (such as water). The ED-projector can be encased in glass or other transparent material and still be able to create a useful display on such areas.

Another example of a "hazardous" environment is a home kitchen. By installing an ED-projector, and without the risk of spills, falls, or short-circuits, the kitchen user can access information, watch TV or surf the web, follow recipes, or simply set and control cooking time.

4.4 Bringing Computer Access to Disabled People

The ED-projector also permits an interactive display to be brought to the proximity of a user without requiring the user to move. In particular, the ED-projector can facilitate the access and use of computers by people with locomotive disabilities. For instance, it can project an interactive display on the sheet of a hospital bed without creating the risk of patient contact with any device. The patient, in this case, can interact with the display by simply using his hand and use it to search for information, call doctors and nurses, or to obtain access to entertainment.

5 Augmenting Reality with ED-Projectors

Ubiquitous computing research tends to focus on the issue of how computer resources can be spread through physical environments so computer and network access become seamless. However, an important consequence of embedding computers to physical environments is that it becomes easier to connect the computer to functions and knowledge that are specific of that space. A computer installed on the wall of a library is a natural candidate to manage the information about the books in that space, where they are located, and even how people are using them.

All this information about the environment can be provided to users. For instance, if the computer in the library knows where the books are located, it can help a user to find them. So far such applications have been explored in the context of augmented reality, mostly through the use of semi-transparent goggles [11, 12]. However,

Fig. 9. Augmented reality applications of Everywhere Displays: (1) an electronic phone directory is projected close to the phone; (2) the database corresponding to a file cabinet is accessed directly from the top of the cabinet; (3) a localization system points to the position of an object; (4) a notification of the arrival of an urgent e-mail is silently projected on the wall; (5) an emergency sign projected on the floor directly points to the nearest exit.

goggles not only are heavy and cumbersome, but they also require the fast and accurate tracking of the user's head to be effective.

We are exploring the use of the ED-projector in such environments. Unlike in previous works with static projectors [9, 10, 13], the rotating mirror expands the reach of projector to almost the entire room. It also enables the augmented reality image to follow an object around an environment (as long as there is a mechanism to track it). In the rest of this section, we examine augmented reality scenarios using the ED-projector.

5.1 Bringing Information to a Physical Location

Most applications of augmented reality are concerned with the virtual attachment of information to places and objects in the real world. Among such applications, we have been experimenting with the ED-projector to bring information to the physical location where the information is used or needed.

Figure 9.1 shows a simple example where a phone directory is projected close to a phone device, so it becomes easy to search and inspect information about the person a user needs to call. In an ideal situation, the simple act of picking up the phone could trigger the display of the directory on that surface. Figure 9.2 exemplifies another situation where a database application accessing a list of files is projected on the top of the file cabinet that contains those files. In this situation, the user can search the computer database using any kind of complex query, obtain and refine answers, and use the results to find the corresponding files in the cabinet.

5.2 Navigation, Tagging, and Localization of Resources

ED-projectors are ideal devices to support user navigation through an environment. For instance, by installing an ED-projector in a corridor it is possible to project information on any wall, door, or area in the floor. Moreover, if the intent is to provide directions for visitors, an ED-projector-based system has the advantage that no device needs to be given or worn by the visitor. Fig. 9.5 shows an example application where the projector is used to signal the direction of an emergency exit on the floor.

In a physical environment where the position of objects or components is known to the computer, it is possible to use an ED-projector system to visually point to an object's position or to tag it with relevant information, without requiring the user to wear or carry any kind of device. Fig. 9.3 shows an example where the ED-projector responds a verbal request for the position of an object (a digital camera) by directly pointing to the location of the object in the room. The system could follow by displaying a checkout list near the object that would allow the user to update the information about the item just by touching the projected checklist. Similarly, information about the digital camera or instructions for its use could have been displayed on the same area.

Unlike systems based on goggles, it is possible to have similar applications in public spaces. As shown in Fig. 10, a ED-projector can be used in a store to provide information about specific items, help people to find products, point to special promotions and sales events, and even provide entertainment for small children. All that is required is a set of white or light-colored surfaces where the information is to be projected.

5.3 Affecting People

The ED-projector can also be used as an actuator device to affect the people occupying a physical environment. If the system has information about the position of people, it can project light patterns that indicate possibilities or constraints to their movements and actions. For example, the projector can create an "electronic doormat" that helps the control of a line of people. It can indicate, directly on the floor, that the user should not move ahead by projecting, for instance, a red line. If the user keeps moving, the red line can follow him, and maybe increase in size or blink to stress the required human response.

Another application is the delivery of notification of important events to people, anywhere, and without the disruptive use of sound. Figure 9.4 shows a simple example of an e-mail notification being displayed on a wall close to where a user is working. Of course this scenario is only feasible if the identity, position, and head attitude of the user is known.

In many ways, the ED-projector is one of the first devices that allow a computer system to seamlessly act on the physical world we inhabit. It creates a harmless "robotic arm" of light that can affect people in multiple ways. Although sound and speech have been explored in the past as computer actuators in physical spaces, the

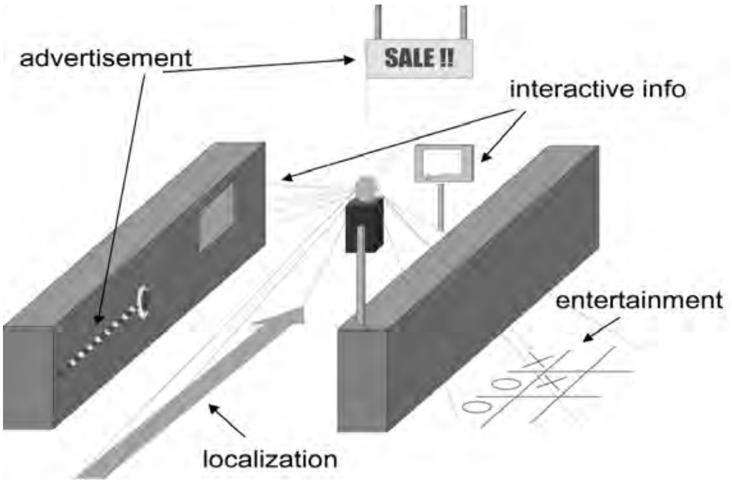

Fig. 10. Example of use of the ED-projector in a store.

ED-projector is unique in its possibilities of creating local, pinpointed ways for a computer to act on people.

6 Conclusion and Future Work

The main purpose of this paper is to present the ED-projector, a device consisting of a rotating mirror deflecting the light of a LCD projector. Although building on the previous research on interactive projected surfaces [9, 10, 14, 15], we believe that the introduction of the rotating mirror produces a very unique device. First, it allows a single I/O device to have multiple uses in the same environment and to dynamically create new displays as needed. An ED-projector can provide computer access to a user in one moment, project a notification of e-mail arrival in the next, and, in the case of an emergency, be used to direct people to exits. Second, an ED-projector creates a simple way for a computer to act on the objects and people in a physical environment, truly integrating computer actions to the real world.

The basic components for building an ED-projector are easily available. We have shown in this paper that the technology for correcting for oblique projection problems is simple and easy to implement. More research is needed, however, to make the calibration of the projector a simple process and certainly a lot more on the vision-based system for hand interaction with the projected image. Those problems, however, seem to be within the scope of currently known vision techniques.

The most exciting research is, in our view, on the new paradigms of human-computer interaction afforded by the concept of everywhere displays. Here we are proposing a scenario where ubiquitous computing happens without carrying displays around or installing them on furniture and walls. Unlike most of the current thinking that looks into devices that can be carried by users, we are suggesting that graphical interactive displays can be a service provided by a space.

While initially we are expecting to support the current desktop paradigm, there is no reason to confine interaction to a rectangular frame like current monitors are forced to do. A possible avenue to explore is to consider the tangible interaction paradigm proposed by Ishii [16], but realize it without wiring or modifying the objects used for interaction. For example, a paper cup on a table can be easily transformed into a volume dial by simply projecting a scale around it with a "volume" label and responding to any rotation of the object by a user.

Finally, what kinds of collaboration can happen between human beings and computer in the moment that computers have the ability to point and affect objects and people in the real world? Kitchens and stores are particularly exciting scenarios to explore these novel concepts. We can also see situations, such as the control of a line of people mentioned above, where computers become devices able to act on people in the physical world. We are planning to explore further all these new paradigms for human-computer interaction that appear as a result of the introduction of ED-projectors in real environments.

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