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electronic document. It may be possible to implement this with a single slot: why have a separate in-door and out-door? In Figure 4, the solid arrows indicate movements of documents by hand.

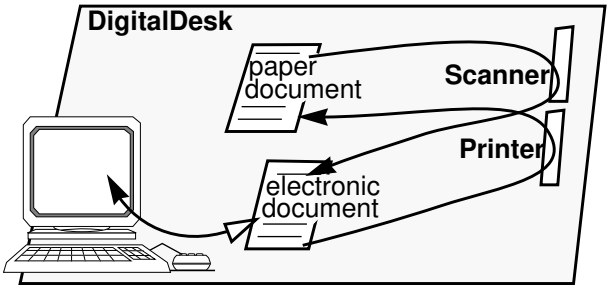

Figure 4. Moving documents through the desktop

This desktop could replace a conventional workstation, but some users may want to remain backward-compatible with the workstation style of interaction. The two can be integrated by allowing the user to drag electronic documents into the workstation by hand, and out of the workstation by mouse.

The mode of use thus encouraged by this system is for users to continuously move documents back and forth between the physical and electronic media, and to work on a document in both places, depending on which medium seems better suited to the particular task. Ideally, the user should hardly be aware of where the document is. The physical and electronic desktops complement and enhance each other.

Conclusion

Today's electronic desktop is a kind of "virtual reality," quite separate from the physical desk of the user. A "computerized reality" approach to HCI, on the other hand, seeks to add computer functionality to physical objects and environments while allowing people to continue interacting with them as before. The DigitalDesk applies this approach to the desk, and attempts to merge the physical world of paper, pens and tape with the electronic world of the workstation. The DigitalDesk Calculator is an example that illustrates how merging these two worlds can improve the usability of a very simple and well-established application. The style of interaction enabled by a digital desk is different than mouse-based "direct manipulation," because users manipulate both electronic and physical objects by *touching* them with their fingers. This style of "tactile manipulation" makes possible new interaction techniques that offer important advantages over currently used techniques, but it does not preclude them. Tactile manipulation on a digital desk brings the desktop back to the desk top, and it offers advantages over conventional workstations that, in some settings, could render them obsolete.

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The author is very interested in comments from readers, particularly suggestions for specific applications that seem well suited to this technology.

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track of where the finger is, so it immediately zooms back out to find it. The result is that large, quick movements are followed less precisely than fine movements, but for pointing applications this seems acceptable.

Motion detection uses an image loop-back feature of the image processing board that allows the most significant bits of two images to be sent through a lookup table. This table is set up to subtract the two images, allowing very fast differencing of sequential frames. Current finger-tracking performance using a Sun 4/110 and an Itex100 image processing board is between 6 and 7 frames per second.

Obtaining a high contrast image

Simple thresholding is not adequate for obtaining an image suitable for character or finger recognition. In normal office lighting, the range of brightness on different parts of the desk varies greatly, so a simple threshold creates large patches of black and white. Another problem can be automatic gray balancing on the camera. This can cause a change in brightness in one part of the image to affect the values in all other parts. These problems were solved, however, by using a histogram-based adaptive thresholding method [Wall74, Cast79].

System architecture

One of the goals in this DigitalDesk implementation was to be able to run standard X Window applications using the finger as a pointing device. The system is implemented so that finger location and tapping information are sent through X in such a way that from the point of view of applications, these events are indistinguishable from those of the mouse. The system runs on two machines: a Sun 4/110 and a SPARCstation. This is because the image processing board plugs into a VME bus, while the projected LCD display plugs into an Sbus. Figure 3 illustrates how the software modules interface to each other and the hardware (note key in the bottom right corner). The system is implemented in C++ and C under SunOS and TCP/IP.

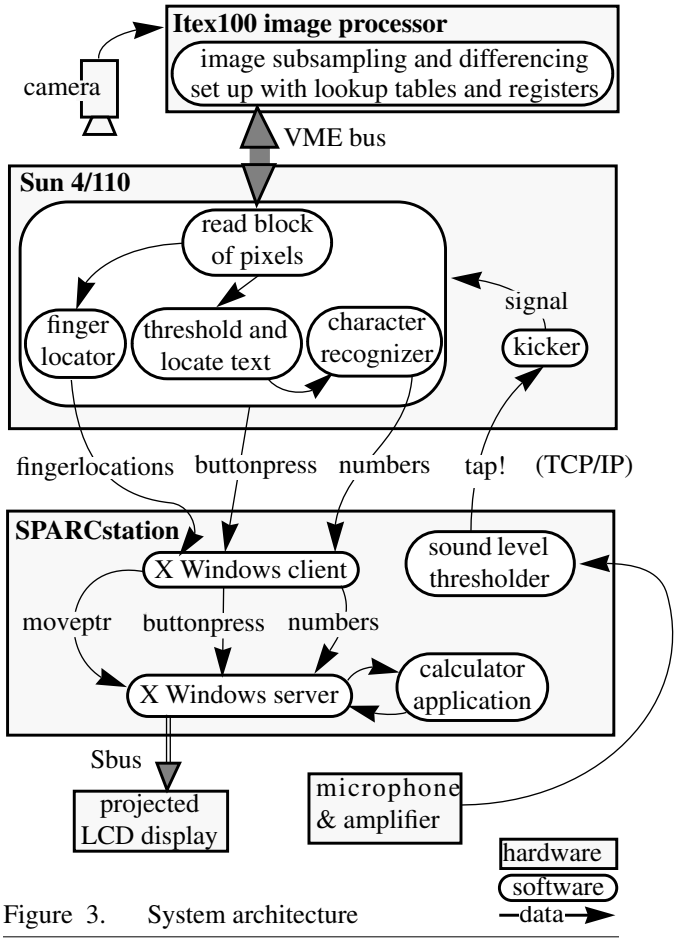

Figure 3. System architecture

Future Tactile Manipulation

The currently implemented DigitalDesk has only begun to explore the possibilities for tactile manipulation. This section describes some additional ways in which a DigitalDesk could be used. Although not yet currently implemented, the following examples illustrate the style of interaction that tactile manipulation might enable in the future.

Medium-independent tools

Fingers are not the only things that could be used in both the electronic and physical media on a DigitalDesk. Conventional desk tools can also benefit from being computerized when they are used on this desk if the tools are recognized by the system. An ordinary eraser, for example, can be made to erase electronic documents in addition to physical documents. A stapler could be used to attach electronic documents together, and a staple remover would detach them.

Moving between the paper and electronic worlds

Both electronic and paper documents can be dragged on the surface of a DigitalDesk with the hands. In order to further integrate the two sides of the desk it would be useful to have a “door” between them. This can be implemented with two slots on the side of the desktop. If the user drags an electronic document to one of the slots (a printer), then it comes out as a paper document. If the user drags a paper document to the other slot (a scanner), then it enters the desk as an

most clearly. An ideal system would have projection both from above and from below.

Tactile manipulation

A goal of the DigitalDesk is to apply computerized reality to the desk. This means that interactions on the DigitalDesk should be upwardly compatible with interactions on an ordinary desk, *i.e.* the old way should still work. The old way to interact with objects on the desk is to reach out and touch them. On a DigitalDesk, both physical and electronic objects can be manipulated by touching them. This is different from mouse-based "direct" manipulation (which is actually not direct at all). This is *tactile* manipulation. These interfaces are designed to work in the same way for both electronic and physical objects. The goal here is that when the user learns to do something with an electronic document, he or she can do the same thing to a paper document, and vice versa. Although this goal may never be fully achieved, it is the driving spirit of this research.

The DigitalDesk Calculator

The DigitalDesk Calculator is a prototype of a simple example that illustrates how an application might benefit from tactile manipulation. Informal and video-recorded observations [Harp91] indicate that people using desk calculators often enter numbers that are already printed on a piece of paper lying on the desk. Users have to manually copy the numbers into the calculator in order to perform arithmetic on them. Transcribing these numbers can constitute a large proportion of the keystrokes when using a calculator, and a large proportion of the errors.

The DigitalDesk Calculator is projected onto the desktop, and the user can use it much like a regular electronic calculator. The projected cursor follows the user's finger as it moves around on the desktop. To enter a number, the user taps on the desired projected buttons. The advantage of this calculator over an ordinary calculator, however, is that it has an additional way to enter numbers. If the number to be entered is already printed on a piece of paper lying on the desk, the user can simply point at it with a finger or other pointer. In front of the user's finger is projected a rectangle that indicates what is being pointed to. When the user taps, the system reads the number with the camera, recognizes it, and treats it as though the digits had been typed into the calculator by hand. Feedback is provided by displaying the indicated numbers in the projected calculator.

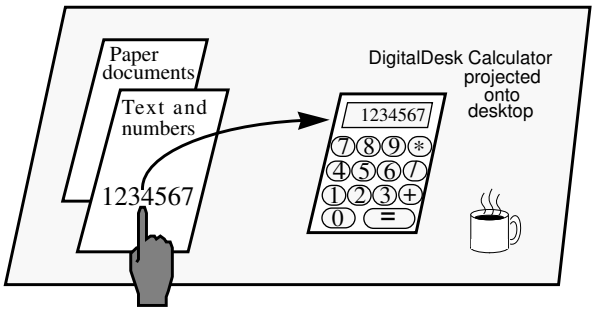

Figure 2. The DigitalDesk calculator

An example where this would be useful is when a price list for a variety of items is on the desk and cost calculations need to be made from these prices. Almost all the relevant numbers are already on the paper and can easily be input using this system. Tactile manipulation is used to physically drag the price list on the desk, and to electronically select the numbers. Much fewer keystrokes are required to perform the calculations than with a conventional calculator.

The current implementation only recognizes a single typeface, and the number must be somewhat isolated from the text. The system is therefore a prototype, not yet robust enough for real users, but it demonstrates the utility of the concept.

Implementation Issues

Processing images in real time

Response time is considered one of the chief determinants of user satisfaction with interactive computer systems [Baec87]. This is especially true for direct manipulation systems, VR systems, and it will also be true for a DigitalDesk. Sophisticated pattern matching algorithms can be used when there are no time limits, but this system should ideally be able to process every video frame, which means processing 25 or 30 frames per second. This requires either very fast special-purpose hardware, or techniques for minimizing the amount of processing required.

The current implementation uses simple image processing hardware. It initially subsamples the image of the desk surface and processes it at very low resolution to get an approximate location for the finger. Only then does the system scale to its full resolution in order to get a precise location, so only small portions of the image need to be processed. If the user moves too quickly, the system loses

that the camera is not only used to detect the position of the hands, but also to read portions of documents. The following sections describe the three key features of a DigitalDesk: using a camera to allow pointing with the fingers, reading paper documents on the desk, and projecting images onto the desk.

Using a camera to allow pointing with the fingers

The DigitalDesk aims to make electronic interactions on the desktop nearly identical to physical interactions. This requires manipulating objects with unencumbered hands, requiring an input technique such as image-based hand tracking. There are several problems with this approach to hand tracking [Stur91], but they fall into two main categories: performance limitations and occlusion. The performance problems are being solved as computer hardware improves, and occlusion of the fingers (by other objects and parts of the body) does not seem to be a significant problem in the context of desk work. Hands on a desk have a limited range of motion, and desk work is mainly two dimensional. Pointing at things on the DigitalDesk is much like pointing out things to another person. The finger works well when pointing to large objects, but for higher precision, as when pointing to a single character, it is useful to point with something like a pen to avoid ambiguity. The current implementation only allows a single pointer, but Krueger's VIDEODESK demonstrated a wide variety of additional single and multi-finger interaction techniques that could also be used.

A problem when observing the hands through an overhead camera is that it is difficult to determine exactly the moment when the user presses something. A pause in movement often occurs without a press being intended. This problem is solved relatively easily, however, by listening. A small snare-drum microphone is attached underneath the desk and its digitized signal is fed into the system. From this data, the system detects a tap. A more difficult problem is how to detect dragging. More sophisticated sound processing could be used or a second camera, but the easiest solution seems to be placing a touch pad in the surface of the desk. From a CR point of view, a digitizing tablet is not as effective in merging the electronic and physical desktops because it requires holding a special-purpose pointing device. The basic finger-following system can be used as an alternative pointing device for a conventional workstation, but the DigitalDesk does more than this.

Because the DigitalDesk needs to read documents in addition to tracking the hand, it cannot rely on having a bright white background, as VIDEODESK and the Mandala system do. It must be able to distinguish the hand from documents and clutter appearing on the desk. The main distinguishing characteristic of hands is that they move, so finger-following is currently accomplished by using image differencing to perform motion detection. Although changes in the image occur for other reasons than moving hands, this technique is reasonably accurate.

Reading portions of documents on the desk

A great deal of information comes to us as printed matter. The "paperless office" predicted in the 70's never happened. In fact, the market for business paper has continued to grow faster than the general economy [Xero91]. Paper is cheap, very high resolution, portable, universal, and you can spread it out all over your desk. A computerized desktop ought to be able to access some of this paper-based information electronically. A natural way to input a page or less of text into a computer is to point at the text with a finger. This is how we show text to another person, and it is much simpler than using a scanner, no matter how small. One difficulty is that the finger sometimes obscures some of the characters. Other difficulties, such as poor lighting, are discussed below in the section on implementation issues. A greater problem, however, is the low resolution of standard video cameras. One approach to this problem, taken by a related project at EuroPARC [Newm91b], is to simulate a high resolution camera by manually pre-scanning documents then using the low resolution camera image to look up the corresponding scanned document. The system described in this paper does not require pre-scanning because it uses multiple cameras, some of which are zoomed in very close to the desk. A wide angle view is used to track the finger, but a close-up view is used for character recognition. In the long run, high definition television and advances in cheap, integrated digital cameras will make this approach more economical than it is today.

Projecting images on the desktop

Projection provides similar capabilities to using a large flat display screen, but it has the advantage that computer-generated images can be superimposed on paper documents. A problem with overhead projection is shadows; for example, one cannot lean over to look at a projected image too closely. In practice, however, this has not yet proved to be a problem. Another issue with projection is the brightness of the room. The projector used in these experiments works quite well with the room's normal fluorescent lights, but a bright desk lamp makes the display unreadable. The same would be true of direct sunlight, so this limits the desk's usability in some settings. One last problem with projection is that not all surfaces make good screens. The projection area should be white in order to see the projected images

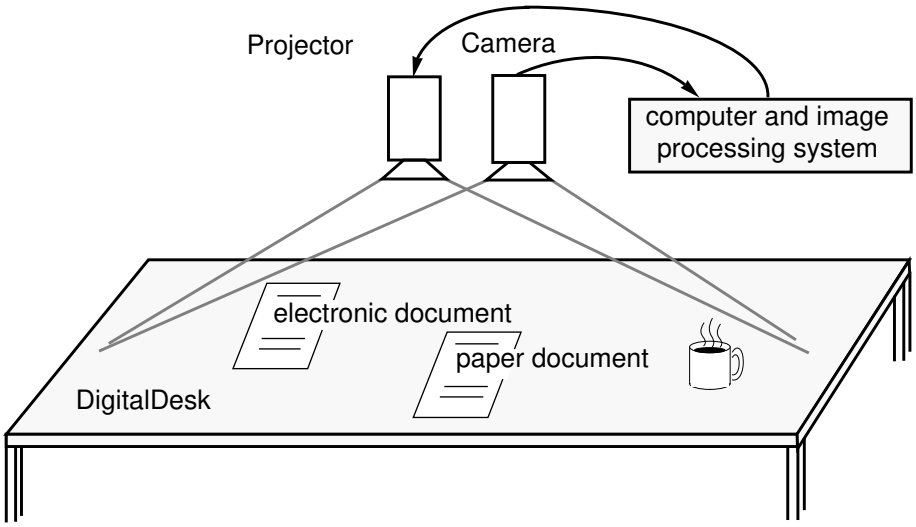

Figure 1. A DigitalDesk system

to enter a new world to use these systems. Instead, they continue to interact with familiar objects almost as before, but the computer adds new functionality.

Many existing systems are examples of computerized reality. At the University of Cambridge Computer Laboratory and Rank Xerox EuroPARC, for example, several systems use Active Badges [Want90] to detect peoples' movements throughout the buildings: Pepys [Newm91a] automatically creates a diary of daily activities for badge wearers, and BirdDog [OShe91] changes its display depending on who is in the room. The rooms in these buildings have added functionality without requiring people to use them differently. Other devices that preserve a familiar interface while enhancing it with electronic features are musical instruments such as computerized keyboards, guitars and drums. Head-up displays [Wein91] create CR because instead of *replacing* what the user sees, they enhance it by superimposing a computer-generated image onto the real world. This approach to HCI has great advantages over the VR approach. Familiar tools are still usable as before, because CR interfaces are designed to be upwardly compatible with our interfaces to ordinary real-world objects. More examples of CR being developed at Xerox PARC are described in [Weis91].

Today's workstation requires the user to abandon the familiarity of the physical desk and enter the virtual world of the electronic desktop. Instead of VR, this paper applies CR to the desk. It describes a prototype DigitalDesk which attempts to merge the physical and electronic desktops into one. It does not use the desktop *metaphor* because it is *literally* a desk top. With this desk, we can begin to explore interaction techniques that could significantly change the way users interact with and think about computerized desktops.

The DigitalDesk

The DigitalDesk is an ordinary desk and can be used as such, but it has a few extra capabilities. A video camera is mounted above the desk pointing down at the work surface. This camera's output is fed through a system that can detect where the user is pointing, and it can read portions of documents that are placed on the desk. A computer-driven projector is also mounted above the desk, allowing the system to superimpose electronic objects onto paper documents and the user's work surface [See Figure 1].

This system shares some features of the VIDEODESK, by Myron Krueger [Krue83, Krue84]. Krueger's system consists of a light table with a video camera pointing down on it. Behind the table is a screen with the user's silhouette and various graphical objects that the user can interact with. The Mandala system [Vinc90] also uses a video camera to let a person control a musical performance using his or her entire body instead of just the hands. The DigitalDesk differs from these systems in that feedback is projected back onto the desk instead of on a separate screen. Another difference is

The DigitalDesk Calculator: Tactile Manipulation on a Desk Top Display

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Abstract

Today's electronic desktop is quite separate from the physical desk of the user. Electronic documents lack many useful properties of paper, and paper lacks useful properties of electronic documents. Instead of making the electronic desktop more like the physical desk, this work attempts the opposite: to give the physical desk electronic properties and merge the two desktops into one. This paper describes a desk with a computer-controlled camera and projector above it. The camera sees where the user is pointing, and it reads portions of documents that are placed on the desk. The projector displays feedback and electronic objects onto the desk surface. This DigitalDesk adds electronic features to physical paper, and it adds physical features to electronic documents. The system allows the user to interact with paper and electronic objects by *touching* them with a bare finger (digit). Instead of "direct" manipulation with a mouse, this is *tactile* manipulation with a finger. The DigitalDesk Calculator is a prototype example of a simple application that can benefit from the interaction techniques enabled by this desktop. The paper begins by discussing the motivation behind this work, then describes the DigitalDesk, tactile manipulation, and the calculator prototype. It then discusses implementation details and ends with ideas for the future of tactile manipulation.

Keywords: user interface, interaction technique, display, input device, workstation, desk, desktop.

Introduction

Many of us work at a desk, and an important part of desk activities involve "paper pushing," or the manipulation of paper documents. Although paperwork on the desk and electronic work on the workstation are often related, the two activities are quite distinct. Interaction techniques in the two environments are very different, and mastering one does not help master the other. Given the amount of time we spend at work, the quality of this desk interface makes up an important element in our quality of life. The conventional outlook for computerized desktops is that personal workstations are destined to evolve into faster machines with integrated 3D graphics and full-motion audio/video. More and more functionality is expected to migrate onto these super-workstations and off the conventional paper pusher's desktop. This paper presents an alternative.

Advances in digital technology are enabling computers to sense and synthesize many aspects of our environment. This has been exploited in the field of human-computer interaction (HCI) primarily through the study of virtual reality (VR), where users can interact with completely synthesized worlds using, for example, 3D head-mounted displays and data gloves [Rhei91]. Even the traditional workstation is a limited sort of virtual reality, where the world resembles a desk work surface adorned with windows, icons and menus.

Computerized reality

But what about the *real* world? Some computer applications exploit the familiar world, not by simulating it electronically, but by enhancing it. Instead of virtual reality, these systems create *computerized* reality (CR). Users do not have