Augmented Reality: Linking real and virtual worlds
A new paradigm for interacting with computers

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ABSTRACT

A revolution in computer interface design is changing the way we think about computers. Rather than typing on a keyboard and watching a television monitor, Augmented Reality lets people use familiar, everyday objects in ordinary ways. The difference is that these objects *also* provide a link into a computer network. Doctors can examine patients while viewing superimposed medical images; children can program their own LEGO constructions; construction engineers can use ordinary paper engineering drawings to communicate with distant colleagues. Rather than immersing people in an artificially-created virtual world, the goal is to augment objects in the physical world by enhancing them with a wealth of digital information and communication capabilities.

KEYWORDS: Augmented Reality, Interactive Paper, Design Space Exploration, Participatory Design

INTRODUCTION

Computers are everywhere: in the past several decades they have transformed our work and our lives. But the conversion from traditional work with physical objects to the use of computers has not been easy. Software designers may omit small, but essential, details from the original system that result in catastrophic failures. Even the act of typing is not benign: repetitive strain injuries (RSI) due to overuse of the keyboard has become the major source of workmen's compensation claims in the United States and causes over 250,000 surgeries per year.

The "paper-less" office has proven to be a myth: not only are office workers still inundated with paper, but they must now handle increasing quantities of electronic information. Worse, they are poorly equipped to bridge the gap between these two overlapping, but separate, worlds. Perhaps it is not surprising that computers have had little or no impact on white collar productivity [8, 25]. The problem is not restricted to office work. Medicine has enjoyed major advances in imaging technology and interactive diagnostic tools. Yet most hospitals still rely on paper and pencil for medical charts next to the patient's bed. A recent study of terminally-ill patients in the U.S. concluded that, despite detailed information in their electronic medical charts, doctors were mostly unaware of their patients' wishes. Despite its importance, the electronic information all too often remains disconnected from the physical world.

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Augmented Reality addresses such problems by re-integrating electronic information back into the real world. The various approaches share a common goal: to enable people to take advantage of their existing skills in interacting with objects the everyday world while benefiting from the power of networked computing.

In this paper, I first describe the three basic approaches to augmenting real-world objects. I then describe our explorations with three recent projects which augment an extremely versatile object: paper. Rather than trying to replace paper documents with electronic immitations of them, we create "interactive paper" that is linked directly to relevant on-line applications. *Ariel* augments paper engineering drawings with a distributed multimedia communication system, *Video Mosaic* augments paper storyboards with an on-line video editing and analysis system and *Caméléon* augments paper flight strips by linking them to RADAR and other electronic tools to aid air traffic controllers. In each case, the goal is to create a smooth transition between paper used for real-world applications and the virtual world of the computer.

HOW TO "AUGMENT REALITY"

One of the first presentations of augmented reality appears in a special issue of *Communications of the ACM* , in July, 1993 [24]. We presented a collection of articles that "merge electronic systems into the physical world instead of attempting to replace them." This special issue helped to launch augmented reality research, illustrating a variety of approaches that use one or more of three basic strategies:

1. **Augment the user**
   The user wears or carries a device, usually on the head or hands, to obtain information about physical objects.

2. **Augment the physical object**
   The physical object is changed by embedding input, output or computational devices on or within it.

3. **Augment the environment surrounding the user and the object**
   Neither the user nor the object is affected directly. Instead, independent devices provide and collect information from the surrounding environment, displaying information onto objects and capturing information about the user's interactions with them.

Augment:	Approach	Technology	Applications
Users	Wear devices on the body	VR helmets Goggles Data gloves	Medicine Field service Presentations
Physical objects	Imbed devices within objects	Intelligent bricks Sensors, receptors GPS, electronic paper	Education Office facilities Positioning
Environment surrounding objects and users	Project images and record remotely	Video cameras, Scanners Graphics tablets Bar code readers Video Projectors	Office work Film-making Construction Architecture

Figure 1: Examples of augmented reality approaches, with relevant technologies and applications

Figure 1 gives examples of different augmented reality applications. Each approach has advantages and disadvantages; the choice depends upon the application and the needs of the users. The key is to clearly specify how people interact with physical objects in the real world, identify the problems that additional computational support would address, and then develop the technology to meet the needs of the application.

Augment the user

Beginning with the earliest head-mounted display by Sutherland in 1968 [21], researchers have developed a variety of devices for users to wear, letting them see, hear and touch artificially-created objects and become immersed in virtual computer environments that range from sophisticated flight simulators to highly imaginative games. Some augmented reality researchers have borrowed this "virtual reality" technology in order to augment the user's interactions with the real-world. Charade [2] involves wearing a data glove to control the projection of slides and video for a formal presentation. Charade distinguishes between the natural gestures a user makes when just talking or describing something and a set of specialized gestures that can be recognized by the system, such as "show the next slide" or "start the video".

Some applications are designed to let people get information by "seeing through" them. For example, an obstetrician can look simultaneously at a pregnant woman and the ultrasound image of her baby inside [1]. A video image of the woman, taken from a camera mounted on the helmet, is merged with a computer-generated ultrasound image that corresponds to the current position of the live image. A similar approach enables plastic surgeons to plan reconstructive surgery [4]. The surgeon can simultaneously feel the soft tissue of a patient's face and examine a three-dimensional reconstruction of bone data from a CAT scan that is superimposed on the patient's head. KARMA, the Knowledge-Based Augmented Reality for Maintenance Assistance, [6] lets a repair technician look through a half-silvered mirror and see the relevant repair diagrams superimposed onto a live video image the actual device being repaired. The system tracks the viewer and the components of the device being repaired in real-time and

calculates how best to present the information. These applications require tight coupling between the electronic images and particular views of the physical world. The problem of "registering" real-world objects and precisely matching them to the corresponding electronic information is an active area of research in augmented reality.

Augment the object

Another approach involves augmenting physical objects directly. In the early 1970's, Papert [19] created a "floor turtle", actually a small robot, that could be controlled by a child with a computer language called Logo. LEGO/Logo [20] is a direct descendant, allowing children to use Logo to control constructions made with LEGO bricks, motors and gears. *Electronic bricks* contain simple electronic devices such as sensors (light, sound, touch, proximity), logic devices (and-gates, flip-flops, timers) and action bricks (motors, lights). A child can add a sound sensor to the motor drive of a toy car and use a flip-flop brick to make the car alternately start or stop at any loud noise. Children (and their teachers) have created a variety of whimsical and useful constructions, ranging from an "alarm clock bed" that detects the light in the morning and rattles a toy bed to a "smart" cage that tracks the behavior of the hamster inside.

Another approach is "ubiquitous computing" [23], in which specially-created objects are detected by sensors placed throughout the building. *PARCTab*s fit in the palm of your hand and are meant to act like post-it notes. The notebook-sized version acts like a scratch pad and the *Liveboard*, a wall-sized version, is designed for collaborative use by several people. A related project at Xerox EuroPARC [17] uses Active Badges (from Olivetti Research laboratory, England) to support collaborative activities, such as sharing documents, and personal memory, such as triggering reminders of important or upcoming events or remembering people or meetings in the recent past.

Augment the environment

The third type of augmented reality enhances physical environments to support various human activities. In Krueger's Video Place [7], a computer-controlled animated character moved around a wall-sized screen in response to a

person's movements in front of the screen. Another early example was Bolt's "Put That There" [3], in which a person sits in a chair, points at objects that appear on a wall-sized screen and speaks commands that move computer-generated objects to specified locations. Elrod and his colleagues [5] use embedded sensors to monitor light, heat and power in the building, both to make the environment more comfortable for the occupants when they are there and to save energy when they are not.

The Digital Desk [22] uses a video camera to detect where a user is pointing and a close-up camera to capture images of numbers, which are then interpreted via optical character recognition. A projector overhead projects changes made by the user back onto the surface of the desk. For example, the user may have a column of numbers printed on a particular page. The user points to numbers, the digital desk reads and interprets them, and then places them into an electronic spreadsheet, which is projected back onto the desk. Using his fingers, the user can modify the numbers and perform "whatif" calculations on the original data (figure 2).
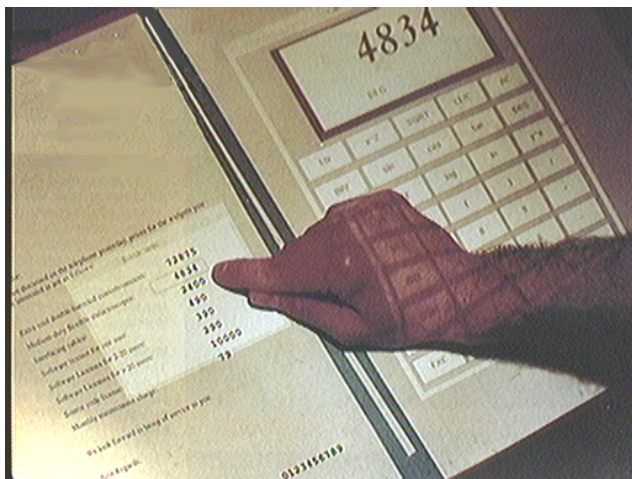
Figure 2: A user points to a column of numbers printed on a paper document and then uses an electronic calculator projected on the desktop.

In [15], we describe a set of applications that interpret information on paper along different dimensions: numbers can be calculated, text can be checked for spelling or translated into a different language, two-dimensional drawings can be turned into three-dimensional images, and still images can become dynamic video sequences. In all of these examples, the user can see and interact with electronic information without wearing special devices or modifying the objects they interact with.

INTERACTIVE PAPER
Paper is an extremely versatile object, used for many purposes in a variety of different ways. Yet, once written on or printed, the information on paper is essentially static. The user can erase pencil marks and make new annotations with a pen, but usually, once paper is printed, it stays the same. If we want to modify information via the computer, we must return to the computer screen, make the changes, and print out a new version. The result is that many computer users keep two parallel filing systems, one for their electronic documents and another for their paper documents. The two are often related, but rarely identical, and it is easy for them to get out of sync. Many software application designers understand this problem and have tried to replace paper altogether, usually by providing electronic versions of paper forms. While this works in some applications, for many others, users end up juggling both paper and electronic versions of the same information.

We have been exploring a different approach: Instead of replacing the paper, we augment it directly. The user can continue to take advantage of the flexibility of paper and, at the same time, manipulate information and communicate via a computer network. The next section describes three applications of "interactive paper". We are not simply interested in developing new technology. In each case, we began with observations of how people use a particular type of paper document in a particular use setting. We then use participatory design techniques to develop a series of prototypes that link the paper to relevant computer software. The goal is to take advantage of the unique benefits of both paper and electronic forms of information, creating a new style of user interface that is lightweight and flexible, computationally powerful, and enhances users' existing styles of working.

Ariel: Blueprints that talk to the net
We studied the work practices of a group of construction supervisors working on the Storebaelt bridge in Denmark (the world's longest suspension bridge). Our original goal was to provide them with a sophisticated multimedia communication system that would let them talk to one another and share information. We discovered that they must deal with thousands of engineering design drawings as they manage and inspect the work of the bridge contractors. Yet on any given week, they only use four or five drawings.

Another important discovery was that, although they all have computers in their offices, they rarely use them, except occasionally for email mail and writing reports. Instead, they travel constantly from their offices to the bridge pylons in the waterway and back to the pre-fabrication sites and administrative offices on shore. The supervisors much prefer the convenience of paper drawings, especially since they can easily make informal notes and sketch ideas for design changes. These informal changes are extremely important: as many as 30% of the changes made are never transferred to the on-line system. Thus the paper drawings are the most accurate record of the actual design of the bridge.

We were interested in giving supervisors improved access to critical information as well as to each other. Rather than designing yet another unused program for the supervisor's desktop computer, we decided to use an augmented reality approach. Ariel [11,14] lets the engineering drawings themselves became the interface to the computer. We developed a series of prototypes in collaboration with the engineers, to explore different interfaces and functionality. Figure 3 shows the first prototype, developed in Unix.
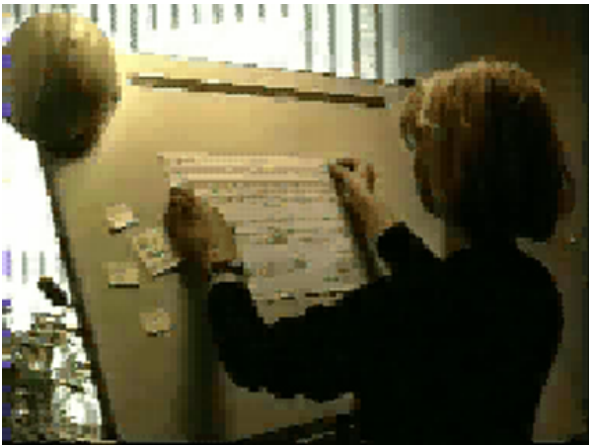
Figure 3: The first prototype of Ariel (Unix) uses an A0 sized graphics tablet to capture annotations and commands from the user, and projected information back onto the tablet.

When the supervisor wants to connect the drawing to Ariel, she simply places it onto the desktop. Ariel identifies the drawing via a bar-code (figure 4) and uses a tiny video camera to capture the position of a light pen and a hand-held scanner to capture hand-written notes. We experimented with various mechanisms for registering the exact location of the drawing with respect to the graphics tablet. The most successful version involved asking the user to point to each of the four corners of the drawing (after identifying it so Ariel would know the correct size). Ariel then adjusts the electronic image of the drawing to correspond to the actual size of the paper drawing.

Figure 4: Identifying the drawing via a barcode reader.

Ariel uses a portable video projection panel to display computer images and interactive menus onto the drawing. Figure 5 shows the MacIntosh interface, in which the user can make hypermedia annotations, indicated by "hotspots" to add audio, video or text notes, in addition to the ones written in pencil. Projection of computer images onto the paper drawing can occasionally be confusing. One solution is to place a piece of plain white paper over areas of the

drawing, to make it easier to see the projected information. By placing a small led in the corner of the paper, we create a "real" as opposed to a "virtual" window, that Ariel can track as it is moved around the drawing.
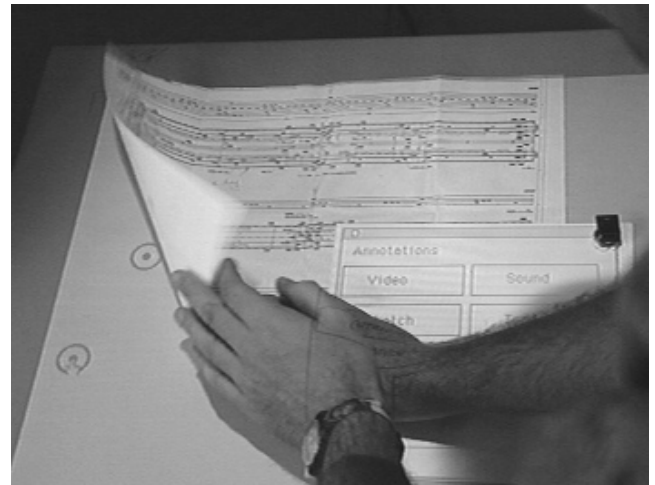
Figure 5: (Macintosh interface) Movable hotspots, indicating annotations, are projected onto the paper. The user can move a paper "window" anywhere on the surface; Ariel detects it via the red led in the corner.

Every drawing contains information about the author of the drawing and other responsible individuals. Ariel lets the user take advantage of this information to establish live video connections with people at other Ariel sites, via a media space (figure 6). The supervisor can also send multimedia mail and look at annotations made by her colleagues.
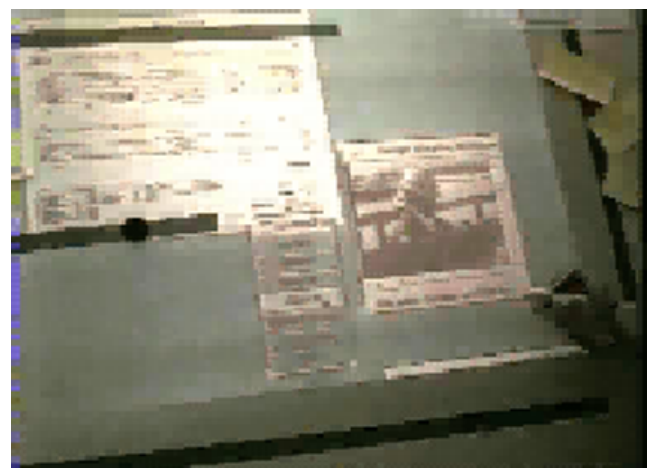

Figure 6: Users can access a media space and communicate with others at different locations on the bridge.

The main advantage of using engineering drawings as the interface is that they are never "down"; they always work. Yet with Ariel, these same drawings provide a simple and effective interface to a sophisticated distributed multimedia network, with all its capabilities for information exchange.

Video Mosaic: Interactive paper storyboards

Film makers and video producers use paper storyboards to organize and illustrate the flow of a movie or video. Storyboards usually consist of a series of "shots", each containing a "best frame" or sketch of a representative image from a motion sequence, the corresponding dialog or voice-over, and notes about the shots or scene (figure 7).
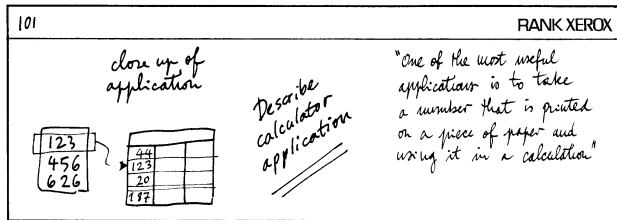

Figure 7: An example of an informal storyboard, with a sketch of the video to the left, a description of the shot in the middle, and the subtitles to the right.

Although on-line video-editing systems have been available for over a decade, most people continue to use paper storyboards: they are portable as well as easy to read, annotate and exchange with others. On-line video systems make it easy to search for text strings and see the action; but suffer from limited screen real estate and are not very portable. (Even with lap-top computers, it is still easier to read storyboards on paper.)

Video Mosaic [12] explored ways of linking paper storyboards to an on-line video editing system I originally developed at MIT, called EVA [9]. Storyboards consist of a series of elements, each with a video clip, subtitles and commentary about the shot. The printed version of a storyboard element includes an identification code, an image of the "best" frame, the text of the subtitles and a snapshot of any relevant hand-written notes. The user can manipulate the individual segments of a paper storyboard, reordering, editing and annotating them as desired. The user maintains the flexibility of the paper storyboard, while gaining access to on-line editing facilities for creating new versions of the video. Figure 8 illustrates the basic layout of Video Mosaic, with a closeup camera (or handheld scanner) for detecting precise information, a wide-angle camera for detecting the position of individual storyboard elements (via a light pen or barcode reader) and a projector (or embedded monitor) for displaying information to the user.

We developed Unix and a Macintosh prototypes to explore different user interface styles. The Unix version (figure 9) uses optical character recognition to identify the storyboard element and the user commands (via "paper buttons"). For example, a user might decide to edit together three particular video clips. She picks up the relevant storyboard elements (figure 10), places them one at a time under the video camera, tapping once to tell the system to identify that element. She then places a paper button with the word "play" on it and taps. The corresponding video sequence plays in a video monitor embedded in the desk.
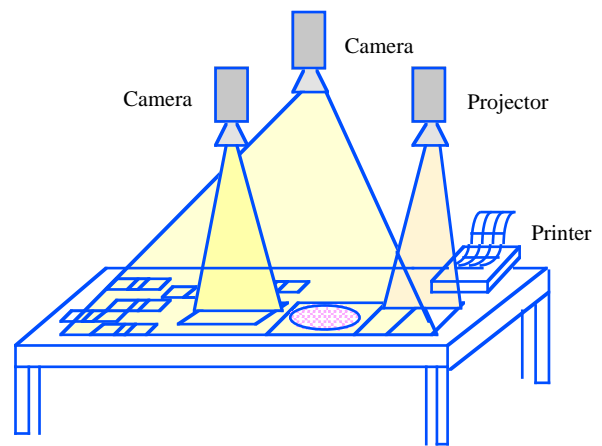

Figure 8: Diagram of Video Mosaic layout

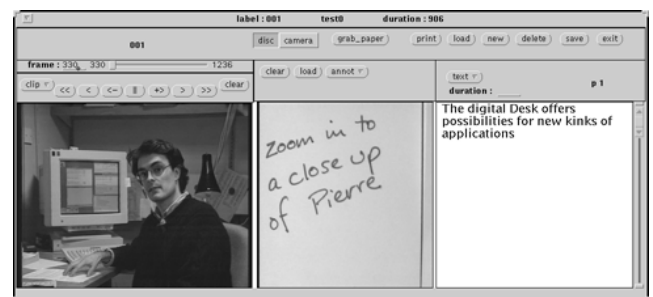**Figure 9: Unix version of Video Mosaic**
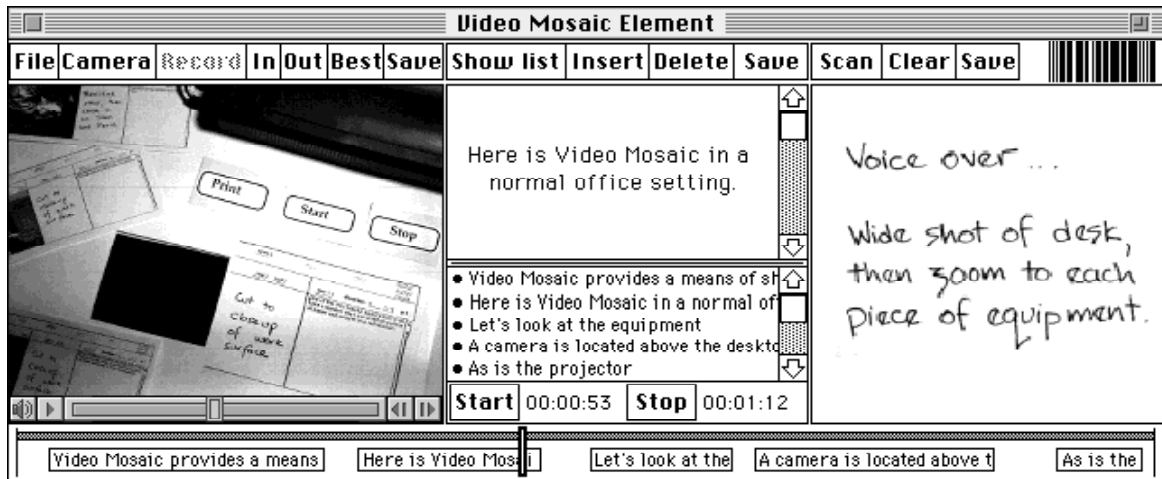

Figure 10: A Unix storyboard element.

Figure 11: Macintosh storyboard element.

Figure 11 shows a closeup of a storyboard element from the Macintosh version of Video Mosaic (figure 12). This version is significantly easier use: each storyboard element has a barcode printed in the corner and a menu of possible commands is projected onto the desktop. The user passes the barcode over the desired storyboard and points to the desired command. A video camera detects the red light emitted from the bar code pen and performs the relevant command on the selected video elements. The same projector projects the corresponding video onto the desktop. User annotations can be recorded either with the overhead camera or with a small, hand-held scanner.

Figure 12: Macintosh version of Video Mosaic.

The techniques we developed for Video Mosaic proved useful for reading lengthy reports containing video clips. Normally, we prefer to read text on paper. But if the text contains video clips, it is necessary to read the document on-line. Video Mosaic allowed us to print a paper version of the document in which each still image has an identification number (or barcode). When activated, the related video clip plays on the monitor next to the desk. Video Mosaic illustrates how to merge paper storyboards or documents containing video with a variety of on-line video editing functions, taking advantage of the best elements of each.

Caméléon: Augmented paper flight strips

Caméléon [12] addresses a very different kind of problem. The current air traffic control system uses a combination of RADAR and paper flight strips to track the progress of each plane. Controllers annotate the flight strips to highlight problems, remind themselves to do things and to communicate the status of each plane to other controllers (figure 13).

Figure 13: Air traffic controllers working together at the Paris (Athis Mons) en route control center. Note that two controllers are simultaneously annotating different paper flight strips at the same time.

Although various on-line tools are being developed to help controllers handle the ever-increasing traffic loads, much of the information they need remains in hand-written form on the paper flight strips. The most common solution for developers of new technology is to remove the flight strips and replace them with electronic versions presented on a computer monitor. Unfortunately, this overloads the controller's visual channel and makes it more difficult for them to handle the planes.

We decided to try a different approach: rather than replacing the strips, we would augment them. We began with a four-month ethnographic study of a team of controllers at the Paris en route control center, emphasizing how they interact with paper flight strips. We found that annotations serve a variety of functions (figure 14).

Figure 14: Annotated paper flight strips

Controllers write for themselves, for each other and as a legal record of decisions made. Only a subset of these annotations need to be interpreted by the computer. We can take advantage of the existing layout of the strips and the agreed-upon ways of annotating them. For example, one section of the strip is devoted to the "exit level" of an airplane. The next sector (of the air space) is already recorded, as is the planned exit level.

We engaged in a year-long participatory design project, exploring different techniques for capturing information written on the strips, presenting information to the controllers and tracking the strips themselves. Figure 15 shows a prototype in which the plastic flight strip holder has been modified to contain a resistor.

Figure 15: Modified paper strip holder containing a resistor.

A frame with metal contacts on the sides (figure 16) detects the level of resistance (unique to each strip holder). The system can then tell which strip is located in which position on the stripboard. This frame is placed on top of a graphics tablet, which captures the annotations made by the controller.
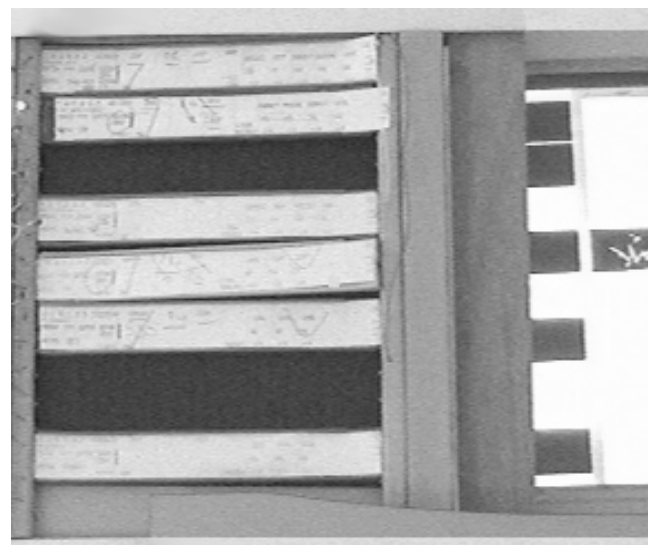

Figure 16: Caméléon stripboard that detects the position of paper flight strips, with a graphics tablet to capture text annotations and a touch screen to display relevant information.

A touch-sensitive screen adjacent to the stripboard displays information about each strip. For example, if another controller wishes to suggest a new flight level, it appears on the screen adjacent to the relevant strip. The controller can underline the level if she agrees, write a new one or click on the "telephone" icon to discuss it further. The controller can also generate commands, such as tapping once on a particular strip to see it highlighted on the RADAR, or twice to see route and other information (figure 17).
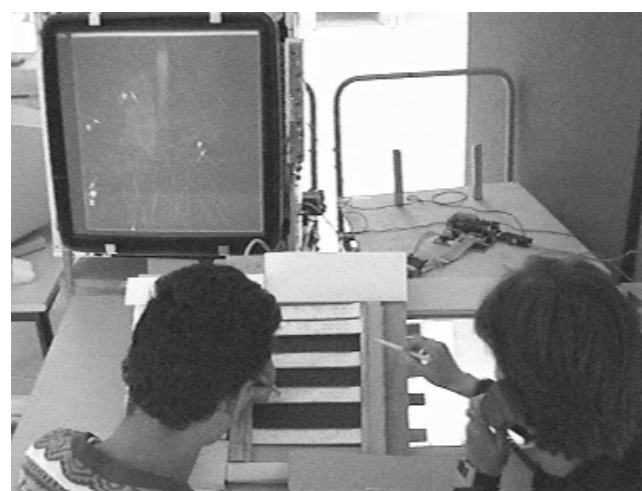

Figure 17: Prototype of Caméléon

DISCUSSION

When is an augmented reality approach appropriate? We begin by looking at what users already do with objects in the real world. We then examine what functionality the computer can add. If the off-line version has important characteristics that cannot easily be duplicated with a standard mouse/keyboard/monitor style of interface, then it makes sense to explore an augmented reality approach.

Note that integration of physical and virtual objects is not always easy. Augmented reality can create as well as solve problems for the user. A very simple is example is the act of erasing information. Erasing pencil marks on paper is simple and straightforward. Similarly, in most on-line text editing applications, erasing is a simple task that is easy for users to learn. Yet what does it mean to erase when the two are linked? What happens if marks are erased on paper and the computer version does not detect the change? Or similarly, what happens if the computer erases information, but it remains physically on the paper? Augmented reality applications merge electronic and physical objects; when the methods of interacting with each are not in sync, the result can be confusing.

When designing augmented reality applications, it is important to consider how to make the integration of real and virtual as seamless as possible. Each application must choose the best combination of techniques for detecting information from the real world and presenting electronic information to the user. For example, a number of options are available to track the position of a user's hands. A data glove or special dots on the hands be detected with a sensing device. A video camera and image analysis algorithms can identify location. In each case, the choice depends upon the nature of the application. If the user is already wearing gloves, a data glove makes sense. If low-resolution pointing is all that is required, the combination of a camera and light pen makes for a lightweight, portable system. If very accurate position information is needed, a graphics tablet may be required.

Similarly, many possibilities are available for displaying information. A doctor can wear a head-mounted helmet and see a video image of the real world mixed with electronic information. Electronic images can be presented over one eye. A video projector can project information directly onto the patient's body. Electronic ink or paper [16] will provide a lightweight, stable mechanism for displaying almost any information. Finally, imagine a kind of transparent, flexible screen that shows critical information when placed over the patient. The choice depends on the specific characteristics of the application: constraints of the user, the object or the environment.

Augmented reality applications also present interesting challenges to the user interface designer. For example, when superimposing virtual information onto real objects, how can the user tell what is real and what is not? How can the correspondence between the two be maintained? Actions that work invisibly in each separate world may conflict when the real and the virtual are combined. For example, if a computer menu is projected onto a piece of paper, and then another piece of paper is placed on top of the first paper, the computer project continues to be on top. In a paper world, each piece of paper obscures the ones beneath, giving a clear view of the one on top. On a computer screen, the same thing happens with overlapping windows. But when the paper and electronic information are combined, odd things occur. For Ariel, we created a blank sheet of paper that the computer could detect via a tiny infrared light on the corner. The computer would track this sheet and project pop-up menus onto it, solving the "overlay" problem.

The most innovative aspect of augmented reality is not the technology: it is the objective. Instead of replacing physical objects with a computer, we create systems that allow people to interact with the real world in natural ways and at the same time, benefit from enhanced capabilities from the computer. The future we envision is not a strange world in which we are immersed in "virtual reality". Instead, we see our familiar world, enhanced in numerous, often invisible ways.

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