Bridging Physical and Virtual Worlds with Electronic Tags

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ABSTRACT

The role of computers in the modern office has divided our activities between virtual interactions in the realm of the computer and physical interactions with real objects within the traditional office infrastructure. This paper extends previous work that has attempted to bridge this gap, to connect physical objects with virtual representations or computational functionality, via various types of tags. We discuss a variety of scenarios we have implemented using a novel combination of inexpensive, unobtrusive and easy to use RFID tags, tag readers, portable computers and wireless networking. This novel combination demonstrates the utility of invisibly, seamlessly and portably linking physical objects to networked electronic services and actions that are naturally associated with their form.

KEYWORDS: RFID tag, portable computers, wireless networks, ubiquitous computing, tangible interface, phicon, augmented reality.

INTRODUCTION

Six years ago a compelling and provocative vision of the future was presented in Pierre Wellner's video and article on the Digital Desk [24,25]. Physical office tools such as pens, erasers, books, and paper were seamlessly integrated (or at least almost seamlessly!) with computational augmentation and virtual tools, using projection and image processing. His works, and our recent efforts (reported here and [5,10]), are directed at more seamlessly bridging the gulf between physical and virtual worlds; an area which we believe represents a key path for the design of future user interfaces.

Since the Digital Desk, there has been an ever-increasing interest in augmented reality and physically–based user interfaces [5,6,7,8,9,10,12,13,15,17,18,19,20,26,27]. A goal of these emerging projects is to seamlessly blend the affordances and strengths of physically manipulatable objects with virtual environments or artifacts, thereby leveraging the particular strengths of each. Typically, this integration exists in the form of physical input artifacts [7, 8,10,24,25,26] virtually linked to electronic graphical objects. Manipulation of the physical artifacts signals a related operation on the associated electronic objects. Typically these electronic objects reside within a proximate computer and associated display. With each new prototype comes a wealth of subtle information about how to best design and support these new "invisible interfaces" (see [4] for an analysis).

The goal of this paper is to share our experiences in designing and building a number of new physical prototypes which incorporate key technologies to address issues which limited the use of earlier experimental systems. In particular, we have combined four technologies (RFID identifier tags and readers, RF networking, infrared beacons, and portable computing) in a seamless and tightly integrated way. This combination has not been previously discussed in the literature. We provide several new examples of augmented reality "devices" that we have created using this package and we describe the underlying hardware and software systems used to support this emerging genre for user interaction.

Similar to Wellner [22,23], Fitzmaurice [6], and Ishii [11], a primary goal of our work is to support everyday tools and objects, the affordances of these objects, and to computationally augment them to support casual interaction using natural manipulations and associations. However, unlike this previous work, we have tried to build invisible interfaces that have little reliance on specialized single-user environments and/or display projection, or custom-designed objects. To this end, we start with everyday objects and embed portable, distributed augmentation in them in the ubiquitous computing tradition founded at PARC [20, 21].

SOME ISSUES FROM PREVIOUS WORK

One exciting set of past work has allowed physical manipulation of invisibly augmented objects. However, the manipulation detectors and manipulation environments have been localized prototypes, being expensive, difficult to deploy, non-portable, and restrictive in terms of the range and class of human interactions. For example, the rear-projection [13] or light-emitted projection [24] systems they employ are expensive - typically $35K for the former and $10K for the latter, per prototype.

These systems were built around a model of "time traveling" into the future to better understand these physical/tangible user interfaces by building custom "user workstations". As a result it is usually difficult to establish a wide-scale deployment and to measure their impact in different environments across many users.

Finally, virtually all of these systems assume that the augmented objects must reside upon the display surface area to have interaction meaning. Notable exceptions are work where tethered objects such as Hinckley's doll's head [12] are used The tether and the location sensor limit the range of object movement or distribution of objects throughout an environment.

A second path has been to augment objects via visible graphical tags, such as bar-codes [2] or glyphs [11]. In the limit case of Barret's "virtual floppies" [1], the augmented object serves solely to house the tag. While these scenarios are much lower-cost, allow many more objects to be augmented, and support multi-location use, the visual obtrusiveness of the tags, and the awkwardness of the readers, has limited their use.

Our approach is to merge these two paths. Like the first path, we try to make the user experience of interacting with the augmented objects as seamless as possible, with unobtrusive tagging. Like the second path, large numbers of existing everyday objects can be easily tagged and used in multiple locales, using a simple and inexpensive infrastructure.

Specifically, our approach is to take everyday objects that already have some useful purpose independent of any electronic system, and to augment those objects via embedded RF ID tags . They are sufficiently inexpensive (as low as $0.20) that they can be considered disposable (or easily recyclable). They are sufficiently small that they do not destroy (or, often, even alter) the aesthetics of the original object. Although custom objects can be augmented, we mainly use everyday items, which have proved to be the most powerful examples. Embedding tags and associating virtual functionality is straightforward (described later). This provides us with a broad range of artifacts to experiment with and an easy deployment scheme.

A tagging system must consider not only the affordances of the tag, but also of the tag detector. RFID tags have three important advantages in this regard. Firstly, RFID tag readers are small enough that they can be unobtrusively "piggy-backed" onto the back of pen computers, plugging into the serial port – the user need not carry a second specialized device. Secondly, they detect RFID tags whenever "waved" in the proximate vicinity of a tag (roughly 10 cm) – precise alignment and registration is not necessary. Thirdly, they are relatively inexpensive (roughly $80 as a one-of off-the-shelf purchase).

This means that we can instrument a number of tablet computers (e.g., Fujitsu® 1200 & 510), laptops, or even Palm Pilots® thereby deploying the system for many users in many contexts. The technology and interactions are not tied to a particular location or workstation.

The system can operate locally with no network dependencies. However, in practice we found that more interesting scenarios are possible when wireless network connections are incorporated [9]. This enables users to access remote web-based material, digital video sequences (potentially too large to be device-resident), and applications like email. Wireless networking provides more flexibility and seamless integration than previous systems allowed. This too is a relatively low cost item and easy to deploy across many devices (at present, we are using an existing PARC wireless network (Proxim RangeLAN2®), with device PC cards costing $475 each).

Lastly, in some scenarios we have used the IrDA ports on the mobile computers to receive a room ID from strategically placed IR beacons. This allows us to further interpret the context of tagged objects, as the system is now aware of the room in which they reside. To achieve this, we have re-used, and re-coded, the IR transceivers (a.k.a. "deathstars"), built in the early 90's for PARC's ubiquitous computing project [21,22]

In the remainder of the paper, we describe implementation details, scenarios, and applications that we hope will inspire and teach others about this provocative UI domain.

SYSTEM OVERVIEW

The essence of the system is the attachment of one or more electronic identification tags each physical item that we wish to augment. These RFID tags are small transponders comprised of an integrated circuit, storing a unique 39-bit ID, and a small coil. There is no on-board power, thereby reducing the size and weight of the individual tags and eliminating maintenance requirements (see Figure 1).

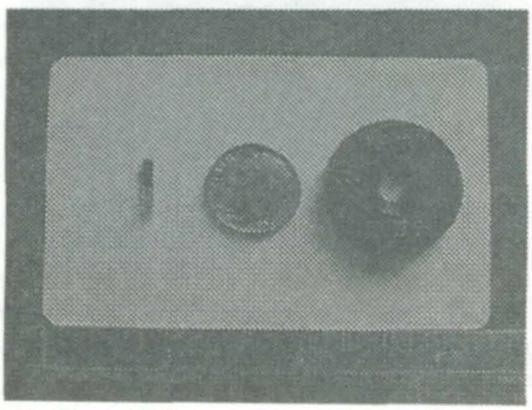

Figure 1. Three RFID tags compared to an American dime and a ruler for scale.

A tag reader is affixed to a computational device. The tag reader draws power either from the associated computational device or from an externally connected power supply. The reader energizes the tag by inductive coupling between its coil and a tiny coil in the tag. The received energy is stored in a capacitor until there is sufficient energy to transmit its ID modulated on a signal at half the induction frequency. (Figure 2).

Communication between tag and reader only occurs when both are proximate. The actual distance varies based on the size of the antenna attached to the tag and to the transmitter. In our present system, distances range from 5 to 10 cm. Once the ID sequence (transmitted serially) is received, the tag reader passes this on to the computer system as an ASCII string via an RS-232 connection. The system cannot correctly detect multiple tags simultaneously present within its proximity. For this reason, our use scenarios all involve the reader being "waved" near or on a tag of interest.

When the reader detects a tag, our application program interprets the ID input string, determines the current application context, and provides appropriate feedback. In particular, we maintain an ASCII file that maps ID numbers to one or more actions. For example, one common action is to invoke a specified program with some associated parameter(s); others tell programs such as Internet Explorer or Word to display certain documents. The system currently supports 21 such actions. We provide auditory and visual feedback to confirm that an RFID tag was within range and was read by the hardware. If the ID number has not been previously registered, i.e., associated with an action in our tag file, we prompt the user to enter an action(s) and any associated parameters via a dialog box. Network and server connectivity is provided by a separate wireless RF networking system. If the program or the file to be retrieved reside on the network, we can have filenames that are independent of the particular sensing computer.

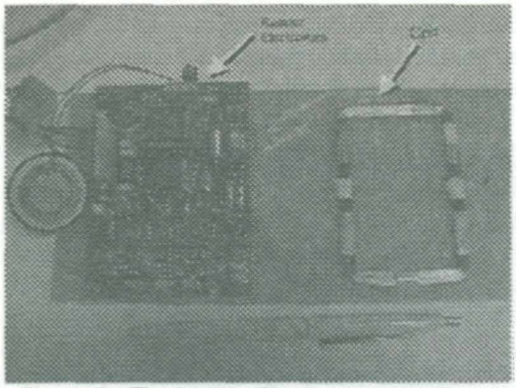

Figure 2. The tag reader system components

We believe this tag system has some interesting advantages over other methods of tagging documents, such as bar codes [2] or glyphs [11]. Specifically:

- **Unobtrusiveness.** These tags are sufficiently small that, with some care, they can be unobtrusively (or even invisibly) added to most physical objects. This extends beyond tagging paper or printed material. Although we are currently using 3 specific commercially available tags, we are investigating tags with other form factors to further support subtle integration. This flexibility lets us choose many different locations for tag positioning and supports tagging of highly curved 3D shapes, as opposed to the more limited, surface-only space used by glyphs and barcodes.
- **Robustness.** RFID tags don't degrade over the course of normal usage. They are impervious to dust, dirt, and smearing, and are quite physically robust. They are routinely used over long periods of time in very harsh environments, such as in tracking livestock [16].
- **Post-Hoc Augmentation.** RFID tags are easily added as a post-process to many physical objects, a task that can be more difficult with bar codes or especially glyphs.
- **Easily sensed.** Because the tag and the reader have been designed to be loosely coupled during interrogation, the tags do not have to physically contact the sensing device, let alone "dock" in a specific location with a specific orientation. This flexibility makes the tags easier to use, and adds to the unobtrusiveness mentioned above. They are read in tens of milliseconds; we are not restricted by image processing software quality and related processing time, camera hardware or image resolution, camera placement, angular skew, or visual obstruction of objects.
- **Aesthetics.** Bar codes, and in some cases glyphs, are used to label many commercial products. However, we are often less inclined to have a bar code stamped upon certain items because appearance is important. While barcodes appear on any number of products, it is frequently on the packaging that is subsequently discarded. The look of a product in these cases limits the widespread use of visual labels. Furthermore, the size of these labels is often constrained by the scanning technology, print quality and cost, i.e., small labels are, at present, infeasible.

There are two principle disadvantages of the tagging technology we have described:

- **Associating Functionality.** At present our system supports a general binding of tag to semantics. However, this comes at a price. The administrator of the tag system or the user must register actions and maintain this file. Barcode labels and glyph labels, which are produced and subsequently affixed to objects, rely on the same post-hoc process. While printed material can be readily associated with particular barcodes or glyphs at the system level automatically, to execute a particular action, additional instructions must be explicitly provided. In both scenarios, the challenge is to provide easy mechanisms for performing the association of a physically tagged object to a particular set of actions.
- **Knowing what is tagged.** The advantage of

"unobtrusiveness" carries a corresponding disadvantage. Since barcodes and glyphs both rely on being visible, it is clear which objects have these tagging mechanisms. In our scenario, tags can be so unobtrusive that they are invisible. While this can have aesthetic advantages, it has obvious drawbacks – the user cannot, without instruction, guess which objects are tagged, where, and with what semantics. How to best combine unobtrusiveness with obviousness of use is a major focus of our current work.

However, overall the technologies and research area seem both promising and useful. We have explored a variety of applications and prototypes. We briefly outline some of these in the next section.

SOME SAMPLE APPLICATIONS AND PROTOTYPES

Using our prototype system, we have implemented a variety of virtual associations for a variety of physical objects.

Augmenting Books and Documents

By augmenting a physical document or book with an RFID tag, we introduce a virtual linkage between that physical document and an equivalent or related electronic document(s). For example, consider a book consisting of a collection of printed pages, such as a technical manual, a patent application, or a conference submission such as this paper. (It is most natural to associate tags with the document as a whole rather than the individual pages of these documents. This more accurately reflects our cognitive model of that object.)

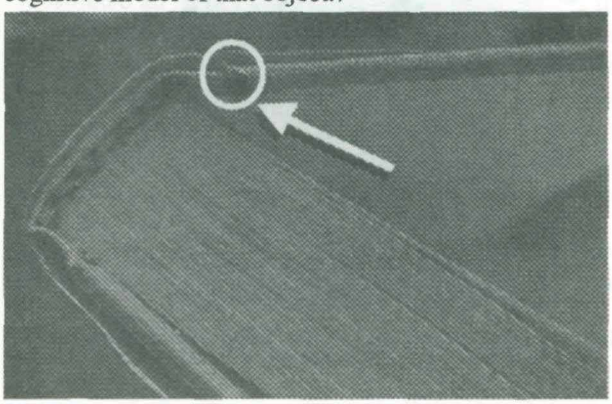

Figure 3. An augmented book -- tag location is highlighted

Although current RFID tags are too large and thick to invisibly embed within a page, they can be easily accommodated in most forms of document bindings. For example, tags can be located upon or within a document binder as shown in Figure 3, can be embedded within other marks such as an embossing seal (Figure 4) or can even be located in or on the document staple.

When a computational device such as a tablet computer detects the tag, an associated virtual document is displayed. This is particularly useful in the case of collaborative and/or iterated documents, which go through versioning – no matter which version the user is physically holding, when they bring the document near to their computer, they can see the latest electronic version.

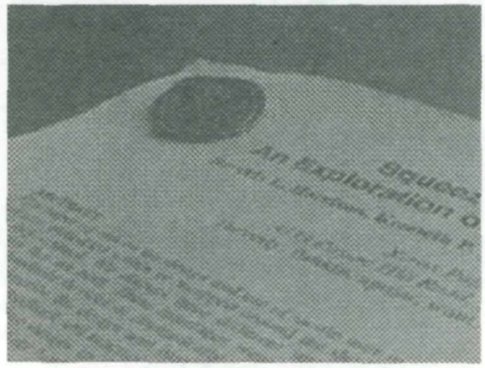

Figure 4. An augmented document -- tag is in the seal.

Augmenting Small Documents: Business Cards

Tags can be associated with any physical document, even those smaller than a book. For example, Figure 5 shows a tag placed on the back of a regular business card. The virtual association for this physical document is the home page of the person so represented – when the business card is brought close to the computer, their home page is displayed. We have also implemented business card tags that automatically generate email messages with the addressing information already filled in.

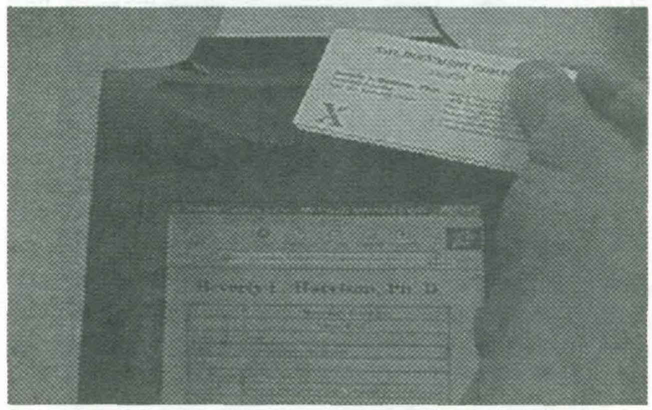

Figure 5. A business card associated with the web page of the person on the card.

Extending Document Functionality: Services

A book or document can be linked to an associated service. For example, in Figure 6 below, we show an augmented book that is linked to the corresponding Amazon.com® web page to order a copy of the book. We could additionally link in the author's home page, the New York Times® reviews of the book, or other correspondence related to the book. We could link all of these sources to a single book by displaying a page of hyperlinks, one for each option.

A tagged item can also be linked to a context-aware service that is to be performed on a document already being displayed. For example, a French dictionary was augmented with a tag (Figure 7).

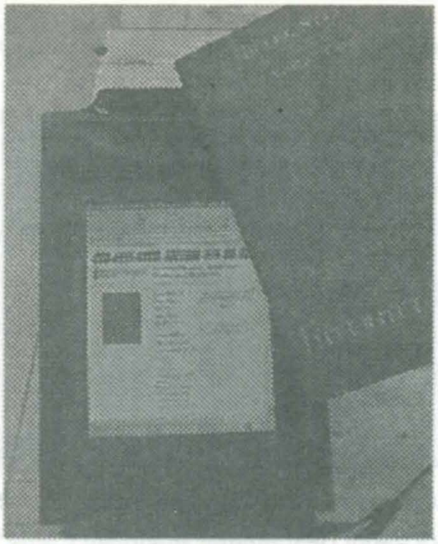

Figure 6. Augmented book linked to Amazon.com web site for book ordering.

When sensed, the dictionary can invoke a language translation program that translates the currently displayed document. The language of translation can be based upon the physical affordances of the dictionary, in particular the title and content, e.g., a French dictionary will perform French translation. In this way, we can use everyday objects and tools in the office place to invoke electronic *services* upon documents analogous to and synergistic with the real-world services they already perform.

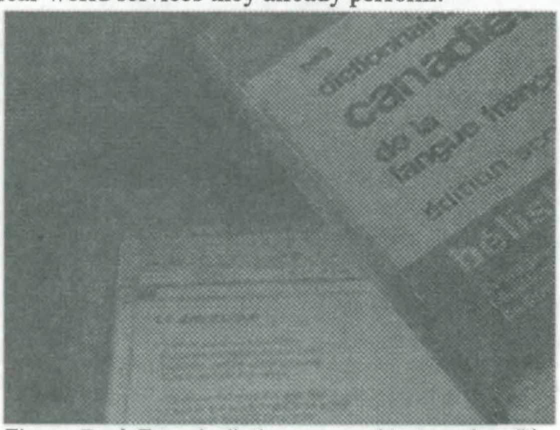

Figure 7. A French dictionary used to translate "the Jabberwocky"

Tags which set context

As shown by the French dictionary example, tag semantics can be a function of the existing context on the sensing computer. Tags can, therefore, have an associated action that sets that context, either instead of, or in addition to, launching applications and services. Two particularly useful examples of this are using tags to establish user ID, and to establish location

User ID

Tags can be imperceptibly added to existing physical artifacts used for user identification, such as ID cards, signet rings, watches, jewelry, or even keys. When such an artifact moves close to the computer, the user specified by the tag has their profile and preferences applied to the current context.

Location

Locations such as tables, chairs, and doorways can be augmented, either by the addition of tags, or additional coil sensors. In the first configuration, the computer senses the location – in the second, the location senses the computer. In either case, the semantics are similar. By automatically detecting context in this way, the device can perform various actions, such as only displaying documents in certain locations, displaying the last document used in this location, etc. We have also augmented the rooms with IR beacons to provide room ID information within this system. The beacons transmit room information either automatically (e.g. every 10 seconds) or upon activation via laser beam (e.g. a hand laser pointer). The IR port on the pen computer detects the room information so transmitted and sets context accordingly.

Augmenting "Bookmarks"

Tags can be used to create ephemeral or transitory associations. For example, we took physical bookmarks and augmented them with two tags, one at each end (Figure 8). Waving the bottom end of the bookmark by the reader binds the bookmark to the current page of the current document. Waving the top end loads the last bound association onto the display.

Figure 8. Augmented bookmark referencing a particular document page.

Any number of user interface mechanisms could be used to signal the "put association" action as opposed to the "go to association" action – tapping on different parts of the computer, reserving one side of the bookmark for each action, having a "write-only" enabler on the bookmark, and so forth.

This example shows that while the tag ID is read-only, the tag can be "conceptually writeable", by using the ID as a pointer to a remote writeable document. This is similar to the work of Barrett and Maglio [1], whose "tags" took the form of floppy disks, with only one action (displaying a document) supported.

Augmenting "Non-Document" Objects: The Photo Cube
Virtual links may be ssociated with any physical container or object and may reference various media, not just textual information. For example, consider a "photo cube" (Figure 9). In this document container, a set of 6 related documents (photographs) are bound together within the same physical object. Each face or side of the cube has its own associated information set, augmented by a unique ID tag. This is one example of a 3D-augmented object.

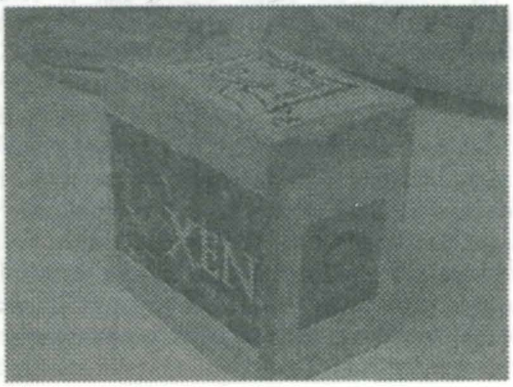

Figure 9. The augmented photo-cube.

To implement this prototype, we took a small balsa wood cubeoid (5cm by 7.5cm by 7.5cm), and drilled holes in each face such that each face could accommodate a disk-sized tag (see Figure 1). Each face was then covered with a photograph – one photo of each author of this paper. (One co-author did not have an immediately available photograph, therefore the other team members jokingly substituted an image of "Xena, Warrior princess"™, from a popular television program). Each of these graphics had a corresponding Web site link. The virtual association for each face, then, was to the Web home page for the person or organization shown on that face. For example, in Figure 10, a photo of a team member is being touched to the computer. In Figure 11, as a result of this action, the computer is displaying that person's home page. The photo-cube illustrates one mechanism associating particular affordances of a specific physical object with a *set* of virtual documents.

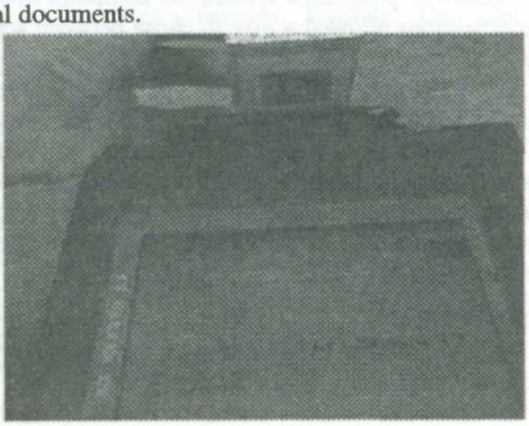

Figure 10. Cube face moved next to computer (just prior to screen change) -- BEFORE.

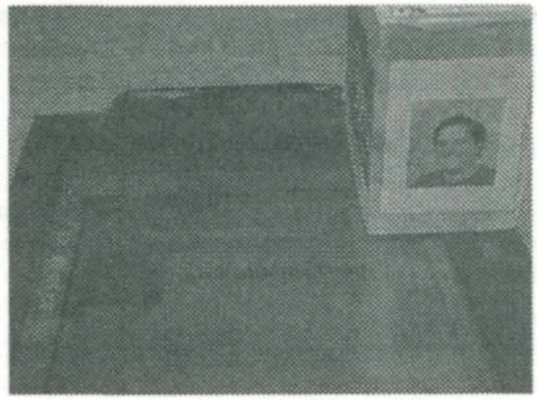

Figure 11. After the photo-cube is proximal, the image is updated with the currently associated web page -- AFTER.

Augmenting "Non-Document" Objects: The wristwatch
To better illustrate potential links between everyday object associations and virtual functionality, we created a wrist watch application (Figure 12).

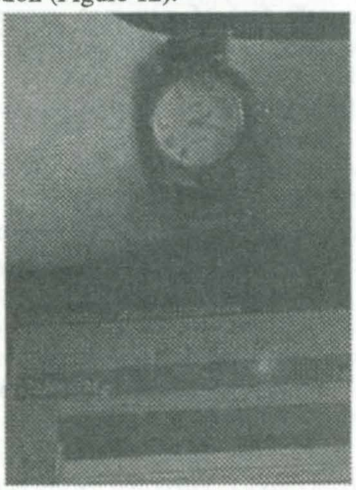

Figure 12. Augmented watch linked to calendar.

In this scenario, a tag is embedded in a wristwatch. When the user brings the wristwatch close to the active zone on the computer a calendar application for that particular user is shown for the current day, at the current time. The wristwatch behaves in all other respects exactly as it normally would. When the computer is held and used normally, the watch is not located near the sensor zone and therefore it has no effect. If the watch is deliberately moved over the top of the tablet computer and hence into range, the calendar program is loaded. In this way, we keep all prior uses of the watch, while leveraging its affordances: they are already worn, are already associated with scheduling, and are already easily (but unambiguously) available for moving into a target area of a computer.

Portable Use
By tightly integrating the tag reader into a portable computer with network support, portable use of becomes possible. For example, our workplace has many printers scattered throughout. To print a particular document at one, you have to know the exact pathname of the document, and the exact name of the printer. To make this easier, we have

affixed RF tags to a number of these printers. By simply "waving" the portable computer proximal to the printer, the current document is sent to that printer.

CURRENT IMPLEMENTATION

We now briefly outline the hardware we used for the scenarios, and the software we wrote to support this system. We then discuss some of the limitations we discovered in implementing and testing this system.

Hardware Integration

Our system was designed around a pen-based computer, the Fujitsu® 1200, – a tablet computer with a 20cm diagonal and VGA resolution. We integrated the RFID reader electronics onto the back of the housing. To provide wireless network connectivity for these mobile devices, we chose a Proxim Rangelan2® frequency-hop spread-spectrum radio in a Type II PC card format. This type of radio system operates at 2.4GHz. The units we acquired provide up to 500 feet of coverage centered on each network access point. The raw bandwidth of the radio is 1.6Mbps with a data rate of 500kbps available to applications, taking into account the protocol overhead. The Trovan® 656 OEM reader turned out to be ideal for our task (shown in Figure 2). It was easily concealed on the back of the tablet and power was delivered to it by tapping into the internal power supply of the machine, with only minor modifications to the computer's housing. All of the interpretation and storage of the tag-IDs is carried out by our software system and we only rely on the Trovan® reader to deliver valid digital representations of the tags across the RS-232 serial interface. The Trovan® RFID tags use 39 bits for each ID Physically larger tags and coils have a greater read range. The tradeoff between tag size, reader coil size, and read range is governed by the application. For the applications described in this paper, we were always able to find some combination of the many readers, coils and tags to achieve the desired property.

Software Infrastructure

Two threads of a multi-threaded Windows program, written in C++, monitor the serial port and IR port, respectively, for incoming tag IDs. A third thread is notified of each incoming tag. It looks the tag up in the semantics database, and then executes them. . Some application programs are invoked as remote "black box" services via "spawn"-type commands, while others are communicated with at a finer level via OLE.

Sometimes the same tag will be rapidly detected twice: to filter this out, a hysteresis is imposed on each tag. If a tag ID is detected which is not associated with any semantics, the program can either ignore the tag, or launch a dialog box querying the user for the semantics of the tag. The latter mechanism is used to update our system whenever a tag is attached to a new document. We created a shared network database, mapping each tag ID number to its virtual association. By placing this database on the network, and making the association descriptions generic, we were able to support augmented documents in a portable way and ensure consistent object responses across multiple computers/users.

Some Limitations of the Current Implementation

The reader and the RFID tags communicate by inductive coupling between two coils. The reader coil is large relative to the tag and is responsible for providing energy to it and for reading the small signal that is returned. Placement of the reading coil on the housing of a tablet computer has to be done bearing two issues in mind. First, the reading coil must be in a position that is both convenient and natural for a user interacting with tagged objects. Second, the mounting location must be chosen to minimize interference from the host computer. We found that the pen sensing electronics on a Fujitsu® 1200 generates signals that are directly in competition with the reader system and coil placement is critical. If care is not given to this part of the design, the apparent tag reading range of the system can be reduced to a centimeter or less. In our prototype we could generally rely on a reading range of approximately 5-10 cm.

The Trovan® system can only read one tag at a time and some care needs to be taken beyond a tag separation of 1cm because the tags will interference with each other. However for objects that are large enough to support multiple tagged regions, it is usually possible to final suitable locations for their placement.

Because the positioning of the read coil is critical to the ease of use of the system, we have examined this problem in some detail. The exact dimensions of the read coil affects the overall inductance and the Q value. Dimensions that are optimal for one application are not for another. For example, placing a reading coil on the underside of a tablet computer, where there is lots of space to embed it, gives a designer more flexibility with the coil geometry than if it were on the front, where space is limited. To solve this problem we expanded the original system so that a variety of coils could be positioned around the computer housing. The modifications allowed a user to chose between sensing locales with a manual switch. For some applications it might be desirable to use the physical world to automatically choose the active coil. For instance, if the tablet was placed on a table, a micro-switch could detect the contact pressure and thus disable the coil at the back of the unit and switch in a more useful coil at the front. An alternative approach is to automatically multiplex the various coils onto the reader electronics.

CONCLUSIONS

There has long been a discontinuity between the rich interactions with objects in our physical world and impoverished interactions with electronic material. Furthermore, linking these two worlds has been difficult and expensive. Yet "invisible interfaces" still hold promise to leverage the natural, intuitive manipulations based on a wealth of affordances and everyday skills married with powerful computational and network information and functionality. In this paper, we have described our efforts at bridging this physical-virtual gap by subtly augmenting physical objects, making them computationally sense-able through combining several technologies in a widely deployable manner. We have illustrated a number of examples of how this augmented environment might support coupling physical objects to a virtual form or to representative services (actions). These concepts can clearly be extended further. We have described a software and hardware implementation that supports this system and can be extended and enhanced in a variety of ways to encompass more complex scenarios. The research described in this paper reflects our approach and philosophy of creating what we hope will be "invisible interfaces" for the workscape of the future, leveraging the strengths and intuitiveness of the physical world with the advantages and strengths of computation.

ACKNOWLEDGEMENTS

We thank PARC summer intern Dimitriy Portnov, who implemented the IR "deathstar" component of the system. The physical/virtual concept has been a hot topic at Xerox PARC during the last two years and we wish to acknowledge the many people and conversations that have influenced our thinking: Rob Burtzlaff, Helen Davis, Keith Edwards, David Goldberg, Dan Greene, Anthony Lamarca, Tom Moran, Beth Mynatt, Bryan Preas, Mark Weiser, and Polle Zellweger.

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