Merging the Physical and Digital in Ubiquitous Computing Environments

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ABSTRACT
Designing digital interfaces for physical environments with ubiquitous displays and sensing introduces a new set of human-computer interaction challenges. Physical objects, digital interfaces, and multi-person human activity must be simultaneously considered. We are building and testing physical components for an interactive environment that merges the physical space and the digital interface. We have identified three types of expectations of constraints that users bring to the new environment: architectural-constraints, device-level constraints, and widget-level constraints.

Keywords
Ubiquitous computing, interactive environments

INTRODUCTION
Much has been written about integrating displays, computational sensors, and interfaces ubiquitously into environments [1], but when such environments are constructed in research labs they are typically designed for single users and have a single type of display device. We are creating a research test bed with multiple I/O devices that can be used simultaneously by multiple people. We have built "digitally augmented" versions of devices found in an actual apartment such as a kitchen table and work counter. Computer systems track the positions of people and objects, receive input from occupants of the space, and display information on table, counter, and wall surfaces.

THE INTERACTIVE LAB ENVIRONMENT
Our test bed environment currently consists of two specially designed display surfaces. Fig. 2(a) shows the "digital table," which is a movable table with an embedded projector that creates the display surface on special optically-treated plexiglass, and the "digital counter. The counter consists of vertical and horizontal plexi surfaces that receive rear projection; a hydraulic lift can raise and lower the entire counter mechanism. The digital table has an embedded camera used to track positions of objects on the surface and detect finger touches. Commercial ultrasound positioning pens are used on the table surface and horizontal counter surface to detect stylus touch.

USER EXPECTATION OF CONSTRAINT AND DESIGN
During the design, construction, and testing of the table and counter we have observed that users have expectations of three types of constraints.

Architectural constraint expectation
The position and surface properties of physical materials in the space implicitly convey meaning about their functionality to users. People generally expect surfaces with the same appearance to have the same surface properties. Analogously, we have observed that users who see that one part of a plexiglass surface is touch sensitive will infer that all parts of the surface are touch sensitive. In addition, users who observe data projected onto one part of that surface assume data can be projected onto all parts. The user's interaction model is established by seeing one interaction example on a surface and propagating that model along surfaces with the same "architectural" properties.

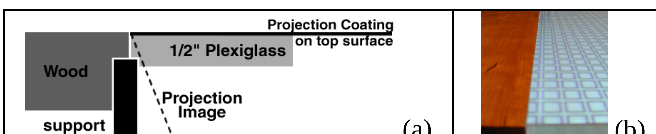
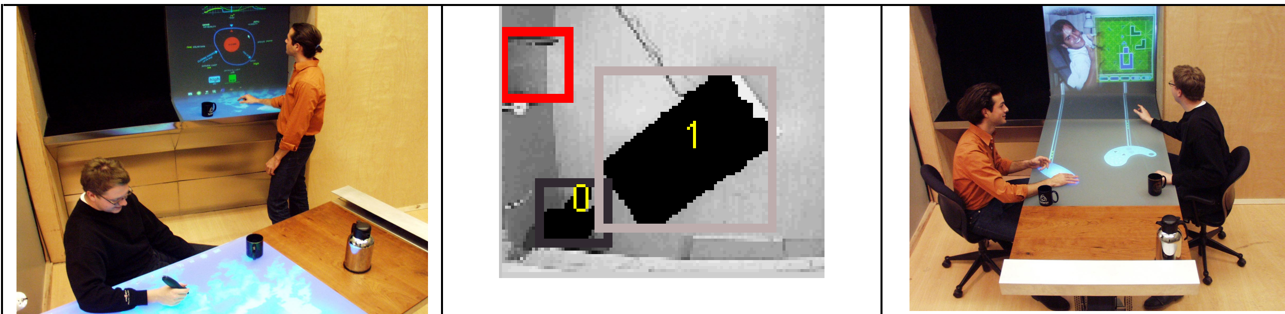


Figure 1: Achieving seamless digital-physical integration.

The table and counter in our space were deliberately designed to meet the user's physical expectation and not establish digital expectations that the environment cannot meet. Doing so required that the devices seamlessly merge the physical and digital to avoid "dead" surfaces with digital surface properties but no interactive ability. The devices accomplish this by using a small notch in the plexiglass that provides for surface support without



(a) (b) (c)

Figure 2: The digital table and digital counter apart, being moved (computer tracking view), and together.

obstructing the light path from the projector, as illustrated in Fig. 1(a). Images projected on the plexi extend "edge-to-edge," and the display surface can be abutted seamlessly with other materials without creating spaces that users expect to be interactive in some way but are not (Fig. 1(b)).

The walls of our ubiquitous environment are identical projection screens. In future work when we implement displays or input devices on one wall surface, we believe users will infer that the same functionality will work on all the walls by inference; we will design accordingly.

Device-level constraint expectation

Users also bring expectations about how devices work. A kitchen table should move around, and it it should be possible to combine two tables. Combining the functionality involves no more than putting the physical objects together. An environment that can automatically track movable objects like people and tables (Fig. 2(b)) and that has "edge-to-edge" digital devices can extend the physical metaphor to the digital domain. Fig. 2(c) shows a mock-up of an interface that exploits the seamless merging of devices. When physical devices merge, digital interfaces should merge as well.

We have observed other device-level expectations. Fig. 3(c) also illustrates how people will typically sit at the table. They expect to be able turn naturally to focus attention and to place objects anywhere on the table they desire. Allowing them to do and still access digital information requires interfaces that automatically react to the position of people and objects on the table.

Finally, nearly all GUI software is designed for a situation where single or multiple users control a single display. Displays embedded in environments create a situation where multiple-users control multiple parts of single and multiple displays. The boundary of a display established by desktop PC use no longer sets the expectation of where the user's control and display begins and ends. The user's present expectation is further confused if interaction devices such as laser pointers are employed for control of data on remote displays [2].

Widget-level constraint expectation

Even at the widget level, users bring expectations to the ubiquitous environment. These expectations interact with the physical space design. Users assume when they are presented with a common desktop widget (e.g. text box) that just happens to have borders perpendicular to borders of physical materials (e.g. the table's edge) that they can't rotate the widget to make interaction more comfortable. Instead of trying to rotate the widget or asking why they can't, users will rotate their bodies.

SUMMARY: EXPECTATION AND CONFUSION

The three types of constraints interact with one another. For example, we have observed that if the table is near the counter, users will assume that pens that work on the table will work on the counter. The architectural properties are the same – why should the interactivity model be different? But users are also using a device-level constraint. A pen is a pen is a pen; in the "real world," pens function on most all surfaces.

As we extend our ubiquitous computing environment, we expect to continue to encounter such expectations of constraint. We are beginning to develop interfaces that respond to these three levels of constraints and exploit them to simplify, not complicate, the user's model of interaction.

ACKNOWLEDGMENTS

Ron MacNeil and the entire House_n team.

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