PHYSICAL PROTOTYPING OF INTERACTIVE SPACE

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Abstract. This paper outlines new techniques and methods for physical prototyping of interactive space. The proposed methods address three important issues: *seamless integration, explicit representation,* and *physical prototyping*. We report the experience and lessons learned from a research project called Smart Living Space. Our goal is not to propose a smart space in any detail, but rather to describe how the interactive techniques can be integrated into design practice. Finally, we illustrate how the methods can be deployed in a real-world example of interactive space.

1. Introduction

As digital technology becomes invisibly embedded in our physical environment, buildings become a complex *interactive* system. The complexity may be *external*, imposed by performance of physical computing devices such as sensors and actuators embedded in building elements. The complexity of interaction may be imposed *internally*, as interaction design behavior conceptualized and perceived in the heads of designers and users. By interaction design, we mean the discipline of creating the interactive behavior and the art of mediating and facilitating interactions between humans, spaces, and artifacts. Today, interaction designers can only consider complexity *intuitively*, in the experience of tacit knowledge in a particular design domain. There has been no way to represent or measure it.

Obviously, as the invisible and ubiquitous computing era has arrived, the distinction between architecture, industrial design, and computing is blurring. It is time to consider how we can seamlessly integrate computer-augmented artifacts, physical computing devices, and spatial elements together in order to make sense of our surroundings. One solution to the integration problem is to add more layers of interactive technology into building design. An often used strategy is to “hide” computers behind building interfaces such as walls, doors, and ceilings. We argue that this approach has misunderstood the vision of invisible and ubiquitous computing. It solves one set of invisible computing problems while introducing other problems of "islands of interactions" in building design.

In this paper, we describe a method for interaction design. The proposed method addresses three important issues:

- seamless integration of physical computing modules,
- explicit representation of interactive behavior, and
- physical prototyping of interaction design.

The work presented is part of the Smart Living Space project at National Cheng Kung University in Taiwan. Our goal is not to propose a smart space in any detail, but rather to describe the essential technique used in the interaction design process. During the project, CAD/CAM techniques were deployed to study the form of interactive space. A set of sensing-based physical model were used for preliminary study of the interactive behavior in real time. Finally, we developed a full-scale physical prototype of the interactive space where designed interactions were examined.

In this paper, we report the experience and lessons learned from the development of this Smart Living Space project. Some assessments of the modular approach to interaction design are reviewed.

1.1. INTERACTION DESIGN

The term *interaction design* was first proposed by Bill Moggridge with IDEO in the late 1980s (Moggridge, 2006). It is often associated with the design of user interfaces in a variety of media responding to user experience. Other terms sometimes used for aspects of interaction design include '*human-computer interaction*' and '*user-experience design*'. Until recently, when computing devices are being deployed everywhere, interaction design becomes the art of making connections and communications between people *through* designed space, products, and services.

Below, we quickly review some salient characteristics of interaction design, in a manner supporting physical prototyping.

- Traditionally, designers interact with design media by 'conversations with materials' (Schon, 1983). The materials refer to sketches, papers, clay, and physical models. In growing numbers, interaction design involves human-computer interaction with building interfaces. Interaction behaviors are partially controlled by interactive devices and computer code. Interaction design turns out to be a process of 'conversations with code', rather than 'conversations with materials'.
- Prototyping is an essential technique for communicating interaction design. Three types of prototype can be classified: paper prototype, digital prototype, and physical prototype (Snyder, 2003). Most people have difficulty to understand designed interactions until they see and use a full-scale physical prototype.
- Interaction design is essentially an iterative process. The process includes requirements analysis, task analysis, prototyping, inspection and evaluation- then the process iterates.
- Interaction design is not deterministic, but can only be realized when people use it. Usability tests are usually performed during the design process to assess the qualities of interaction design.

- Interaction design is a multi-disciplinary activity, ranging from architecture, industrial design, computer science, mechanical engineering, to cognitive science. Coordination among aspects of interactions is clearly necessary and seems to require an integrated design environment for coordinating varied aspects of design.

Interaction design has been applied in many application domains. We are interested in methods and technologies that aid designing for interactions, in particular in the area of human-computer interaction. This paper describes work in progress for developing new techniques and methods supporting interaction design. There are many types of interaction design. Our interest is in interactive space, making buildings as an interaction interface between humans and computation. Examples of interactive space are interactive workspace, digital museums and smart home. Many types of interactive space are of this sort; our particular interest is smart home of the future.

1.2. AN EMPIRICAL STUDY

In order to give substance and later demonstrate the interactive technique and method, we apply them to a real-world example. The example is drawn from the design of *Smart Living Space*, which is a long-term research project involving numerous faculties and professionals across multiple disciplines in our university and industry. The goal is to build a live-in laboratory for smart living space. The live-in laboratory can be dynamically configured to different settings of smart living of the future. An initial setting is to configure the live-in laboratory to be a smart home for experimental test bed. The experimental smart living space includes a set of interactive systems:

- a moving wall system allowing dynamically configuration of the space,
- smart living objects such as walls, doors, and furniture augmented with sensing technology, and
- home automation control system with advanced sensor networks.

To learn how interaction design is developed in this project, we recorded and collected some of the drawings, physical models, and verbal/written communications between the project participants. Over the course of three months, we involved in the design team and observed problems with the development process of the smart living space.

Based on our observations, we present the problems and obstacles that we analyzed:

1. The first problem is lack of *an adequate communication tool* for shared understanding of designed interactions. Traditionally, we use sketches, drawings, and architectural models physically or virtually for design communication. But interaction design is about *interactive behavior* which is implicit and hard to represent.
2. The majority of the problem occurs in the different realizations of varied aspects of designed interactions conceptualized by multiple professionals. Most interactive behavior is embedded in computer code. The design team members had problems to realize the designed interactions *behind the scene*. Simulation of such dynamic interactive behavior is beyond the capability of existing CAD systems. There is no adequate design media to simulate interactive behavior and provides real-time feedback to designers.

3. Lack of *a development framework* results in “islands of interactions”. In the technical level, a common communication protocol is required for developing varied digitally augmented artifacts in smart living space. In the conceptual level, a framework is required for simulating different aspects of smart living scenarios, in a manner supporting “fluid” interactions. By “fluid” interactions, we mean to articulate interleaving human activities and make sense of continuous interactions when people move from one place to another. For example, a moving partition wall system may be re-configured dynamically to a variety of spatial settings. Each wall can be adapted to a translucent screen when and where it is desired. The users autonomously adapt and make sense of their surroundings to shape everyday life. Existing digital media have difficulty to predict such fluid interactions with user autonomy.
4. The cost of *interactive design iteration* is much higher than traditional design in terms of time and effort. During the project, we split the design team into ten groups and spent two days for exchange of design ideas. In each design meeting, some flash videos were developed, changed, adapted and revised to describe various smart living scenarios. A variety of architectural physical models were developed to show how computing devices were integrated in the interior space in detail. After the design change, the sensors, actuators, video displays need to be calibrated according to the change.

Seamless integration, explicit representation, and *physical prototyping* are the three major requirements and challenges in developing an interactive space. The three different dimensions of design requirements together provide a basic framework upon which new techniques and methods can be developed. With such a framework, new opportunities become available for developing easy-to-use plug-and-play modules for interactive space, some of which will be explored.

2. Seamless Integration of Physical Computing Modules

To illustrate the method of seamless integration, we now start with a set of design operations for seamless integration of physical computing modules. We start with a scenario of smart home where space is intelligently responsive to the needs and desires of their inhabitants. Then we come up a conceptual design where part of the building skeleton can be automatically changed in real time. The building itself changes the shape to adapt to sunlight using sensing technologies. We consider this adaptive building skeleton is part of the user interface module to be developed in interactive space, in a manner supporting responsive architecture. Figure 1 shows a sequence of CAD/CAM processes for manufacturing a building skeleton model.

To test the idea, we use a laser cutter to accurately produce a prototype of the skeleton model (Figure 1 *Left*). A servo motor and sensors is installed in the skeleton (Figure 1 *Middle*). A set of skeletons are assembled in a sequential order, allowing the model changes its shape (Figure 1 *Right*).

Figure 2. Developing physical computing modules with CAD/CAM processes.

Rather than developing physical computing modules from scratch, we choose the Phidgets system with a variety of USB-attached sensing devices (Greenberg and Fitchett, 2001). After installing the Phidgets system, we go back to the stage of designing interactions. Here we are more interested in how the building skeleton system can be controlled remotely. For example, one can change the building shape corresponding to the occurrence of human activity in a remote site. In order to achieve this, we install a wireless computing module to the Phidgets system, which allows remote control over the servo motor. In the remote site, we install a camera with a vision detection program. The camera would detect the presence of people and send a message back to the server. The server in turn dispatches the message to the Phidgets system to trigger the servo motor, which in turn remotely controls the skeleton model.

Indeed, we are interested in the *interactions* that designers attempt to support through design, rather than the *artifacts* ultimately produced. In order to simplify the demonstration, we apply the integration method to a moving partition wall system, which is only a portion of the Smart Living Space project. But the application of the moving partition wall system is sufficient to demonstrate the technique and method developed in this paper.

3. Explicit Representation of Interactive Behavior

To test our interactive system in a real-world example, we apply the physical prototyping technique to a moving partition wall system. The moving partition wall system allows dynamic configuration of space for different design scenarios. Each partition wall is embedded with LED lights and sensors. A lighting sensor is associated with the Phidgets system and deployed to detect the luminosity of the built environment. The embedded LED lights are controlled by capacitance sensors, lighting sensors, and RFIDs. The idea is that embedding sensors to each wall enables various LED lighting patterns in the presence of people. Once people move, the LED lights change the color and display messages. In addition, the wall is intelligent enough to 'know' the adjacency relationship with other walls, as shown in Figure 2.

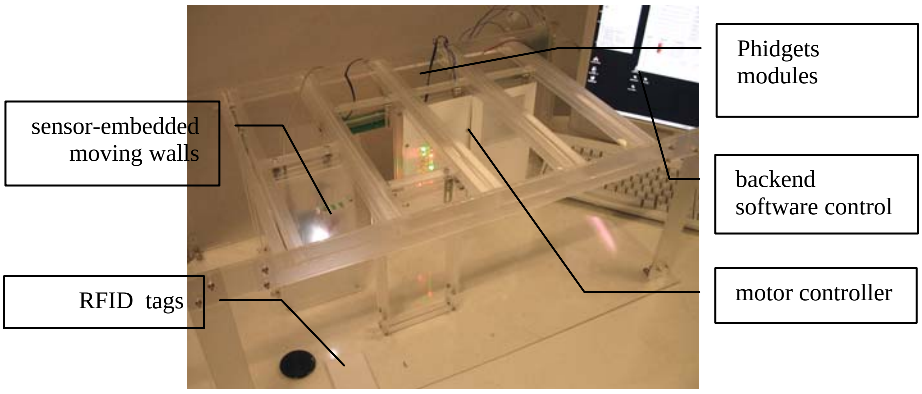

Figure 2. The sensor-based physical model serves as a medium for explicit representation of interactive moving partition wall system.

During the project, we implemented this idea by embedding the *Phidgets* sensor system to the CAD/CAM-based architectural models. The user directly manipulated interactions by moving the wall model to different settings. Once the wall is moved, it triggered the corresponding reactions e.g. different LED light patterns. When we presented this physical prototype to the professionals and faculties, they discussed designed interactions through direct manipulation of the model. Indeed, the sensing-based physical model serves as a media for explicit representation of interactive behavior. It also helps us make better predictions about how users will perceive and interpret the designed interactions we design.

This sensing-based prototype provides a new thinking-by-interaction approach toward interaction design. To assess the interactive behavior, a video program has been developed to record users' direct manipulation of the interactive moving wall system. Recording the user's direct manipulation is stored in a sequence of movie clips. The sequence of movie clips allows users to test sensors and actuators, get user feedback early, and understand dynamic behavior of the system in real time. A sequence of movie clips serves as a basis for usability tests, as shown in Figure 3.

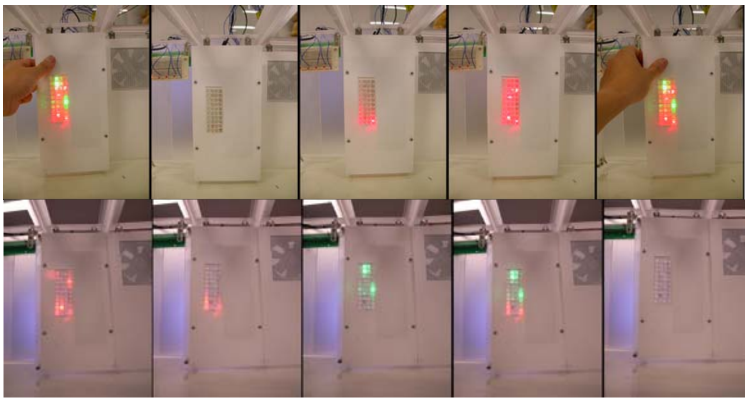

Figure 3. A sequence of movie clips of user interactions with the sensing-based model.

4. Physical Prototyping of Interactive Space

Physical prototyping of interactive space is a challenging problem for any interaction design project, but for smart living space, it is particularly so. Any interactive space is unique, and so it is risky to generalize from one project to all projects with a similar physical prototyping technique and method. However, due to the complexity of interaction design, a *modular* approach to rapid physical prototyping is required for reducing the cost. Unlike product design, physical prototyping of an entire building space is unlikely possible. Each building is unique and seldom to be repeatedly produced. But interactive space may be decomposed into reusable building components and computing modules for physical prototyping.

We classify three kinds of interaction design modules that are strongly interrelated, but can be developed in parallel.

- *Action modules* refer to a structure or representation of human actions to be supported through designed interactions. Examples of atomic actions are "open", "push", "touch", "grab", and "step on". A set of atomic actions can be composed into a composite action module. For example, one may "open" a door by "grabbing-twisting-pushing" a door knob. We focus on designing "verbs" not "nouns".
- *User interface modules* focus on what space can afford, rather than on objects. Examples of spatial user interfaces are doors, walls, floors, ceilings, furniture, and appliances. A building's physical structure can be decomposed, refined, and reconfigured to afford intuitive user interfaces.
- *Physical computing modules* include input devices and output devices. An example is the Phidgets system. Phidgets integrates USB-attached physical devices in a physical computing module, including RFIDs, pressure sensors, and servo motors.

By mapping action modules, user interface modules, and physical computing modules, we can easily develop a physical prototype of interactive space augmented with digital technology. A full-scale physical prototype of the interactive moving wall system has been developed and tested (Figure 4).

Figure 4. *Left:* A full-scale physical prototype of interactive wall modules. *Right*: The interactive moving wall system is under construction in the live-in laboratory.

5. Conclusion

In the Smart Living Space project, we take a modular approach to physical prototyping of interactive space. The interactive space is composed of an interactive moving wall system, smart floor, networked ceiling, and interactive furniture. The interactive moving wall system allows dynamic configuration of spatial layout in response to users' preferences. Each wall panel is decomposed into parts that can be fabricated by laser cutters. Each part has several layers of built-in physical computing modules (e.g. Phidgets and Motes sensors), with wireless connection to a sensor network. The entire interactive space is equipped a sensor network controlling lights, security system, fire system, and the heating and air conditioning.

The interactive system described in this paper is being developed in conjunction with our research project to develop smart living space of the future. The target of the project is to develop a live-in laboratory for a long-term cross-disciplinary research. In this paper, we report the experience and lessons learned from the development of this Smart Living Space project. Some methods of the modular approach to interaction design are reviewed: *seamless integration*, *explicit representation*, and *physical prototyping*. By applying new techniques and methods, it is likely to yield a direct benefit to teaching human-computer interaction design studios. Most importantly, the convergence of physical computing and CAD/CAM-based physical prototyping may provide an opportunity for a profound transformation of future design practice. As the time of writing, the smart living space is under construction and is expected to finish in Fall 2007. The live-in laboratory will serve as an experimental test-bed to demonstrate how the digital revolution shapes our everyday life through new kinds of interaction design.

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