

Toward a Ubiquitous Smart Space Design Framework*

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In this paper, a design framework is presented for integrating the various perspectives and major investigation aspects of ubiquitous smart spaces. A key problem in developing ubiquitous smart spaces is how to design a physical space that maps to the underlying computing infrastructure and the corresponding patterns of situated interactions in every life. This paper explores design methods and technological issues encountered in the development of ubiquitous smart spaces. Methods for mapping different aspects of ubiquitous smart spaces are illustrated by a set of system prototypes. The prototypes are finally integrated in an open living laboratory as a tested for smart living.

Keywords: smart space, ubiquitous computing, design framework, interaction design, smart living

1. INTRODUCTION

There is growing interest in developing ubiquitous computing technologies to build a smart space of the future. A smart space provides natural interaction interfaces and an experimental platform for integration of intelligent computational devices that can be ubiquitously interwoven into our daily life. Examples of ubiquitous smart spaces are iRoom [1], AwareHome [2], House_n [3], and GatorHouse [4]. The common goal is to augment physical spaces with ubiquitous computing technologies for supporting our daily life more effectively.

As hardware components become smaller, faster, and cheaper, computational devices are becoming embedded in building elements such as doors, walls, floor, and furniture. These devices are largely invisible and linked together through wireless network. Buildings would largely contain smart appliances that provide access to computational resources at any place and time. A key problem in developing for ubiquitous smart spaces is the integration of physical spaces and the underlying computing infrastructures, mapping to the pattern of situated interaction in everyday life. Many ubiquitous smart spaces projects have emphasized the computational capabilities, with less concern for the design of smart spaces and its adaptability for meeting users' changing needs, resulting in a fixed and unrealistic setting of living environments.

The design of ubiquitous smart spaces requires collaborative efforts in integration of physical environments, digital infrastructures, and creating user experiences in a broader context of human-centered design. In this paper, we do not attempt to identify the technological issues or detail the functionality of ubiquitous smart spaces, but instead focus on design principles in developing a ubiquitous smart space. The paper is inter-

Received February 1, 2008; accepted November 28, 2008.

Communicated by Yau-Hwang Kuo, Pau-Choo Chung and Jar-Ferr Yang.

* This paper was partially supported by the National Science Council of Taiwan, R.O.C. under grant No. NSC 97-2218-E-006-012.

ested in developing a design framework in support of a flexible and adaptable ubiquitous smart space of the future. The development of ubiquitous smart spaces involves possibly unique sets of design criteria. Many types of ubiquitous computing applications are of this sort; our particular interest is the dynamics of architectural space, involving modular physical computing and interactive design processes from conceptualization, design development, prototyping, to usability tests.

This paper is organized as follows. First, a design framework is developed to offer an integrative view of the key issues encountered in the design of ubiquitous smart spaces. Based on the framework, we set forth a set of design criteria for creating ubiquitous smart spaces. In section 3, the concept of buildings is decomposed into modular elements such as walls, floor, openings, and furniture for physical computing. Architecture can be considered as interaction interfaces between humans and computation. Using a modular design approach, building elements together with embedded smart devices can be dynamically composed into a new space for a particular lifestyle of smart living. Finally, physical prototyping of such flexible ubiquitous smart spaces is implemented in a living laboratory. Some of design principles, benefits, challenges, current status, and lessons learned from the development of ubiquitous smart spaces are discussed.

2. A DESIGN FRAMEWORK

Smart space is a collaborative endeavor, involving interdisciplinary fields such as computing, architecture, industrial design, engineering and cognitive psychology. Due to the lack of a design framework, most researchers create a smart space in a laboratory setting simply for demonstrating technologies without considering the inter-relationship among humans, lives, and technologies. More effort is needed in developing an interdisciplinary design framework that articulates various viewpoints on ubiquitous computing technologies, while emphasizing the potential applications of smart spaces to transform our built environments [5].

To integrate ubiquitous computing into smart spaces, this work has developed a conceptual framework that addresses general criteria regarding the multiple disciplines of ubiquitous computing. These general criteria include *integration of physical-digital interaction interfaces*, *sensing and perceptual technologies*, *social and environmental awareness*, and *intelligent devices and service control*. Each criterion denotes a distinct functional requirement for developing advanced ubiquitous computing technologies for smart spaces. After articulating these requirements, the overall system architecture and design principles can be easily realized for different smart space application domains.

This work takes a human-centric approach to structuring the research scope of ubiquitous smart spaces over several dimensions. One dimension depicts *environments* according to the scale of *the physical space*, ranging from furniture, appliances, walls, floor, openings, rooms, buildings, to cities. Another dimension depicts a wide spectrum of *technologies* for ubiquitous computing, including human-computer interaction, sensing, media, display, mobile, embedded, and networking. These ubiquitous computing technologies can be implemented in the varied scale of spaces where information and services are provided when and where desired. The third dimension denotes the *living* requirements concerning safety, health, efficiency, aesthetics, and sustainability. This

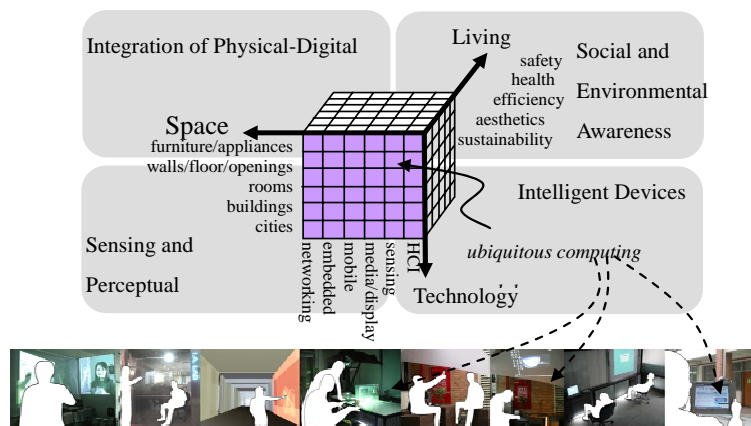


Fig. 1. A design framework of ubiquitous smart spaces.

design space matrix makes the application domain of ubiquitous computing and the different roles of smart living technologies in our everyday life. The design space matrix is depicted in Fig. 1.

This work presents a human-centric design framework that articulates the various perspectives and major investigation aspects of ubiquitous computing for smart spaces. The next section elaborates the core of the proposed conceptual framework. Four key design spaces are presented with respect to the design framework. They are: (1) integration of physical-digital interaction interfaces; (2) sensing and perceptual technologies; (3) social and environmental awareness, and (4) intelligent devices and service control. These design spaces are described in detail in the following sections.

2.1 Integration of Physical-Digital Interaction Interfaces

Different research and development have progressed rapidly by augmenting spaces and objects with sensing, computation, and communication capabilities. These capabilities in different spaces and objects converge on the boundary between physical and digital worlds.

When bringing ubiquitous computing to smart spaces, architectural design can be considered as interaction interfaces between humans and computation. Viewing architecture as human-computer interfaces introduces a new set of problems, since interaction interfaces must be constantly present in the real world and support continuous interactions in everyday life. Several research issues for integrating physical-digital interaction interfaces in smart spaces have emerged.

From explicit interaction to implicit interaction Human-computer interaction is moving from command-based devices (*e.g.* keyboards and pointing devices) to support natural interaction using gestures, handwriting and speech. The move toward natural interaction poses multiple novel technical, design, and social challenges. For example, stepping on the floor of a room is sufficient to detect a person's presence there. Therefore, a new interaction model with user input/output is needed to support several distinct features of implicit human interaction, as follows: (1) Implicit user input cannot be easily

defined in terms of a finite set of modes. (2) The user input has no clear boundary (*e.g.* starting and end points). (3) Implicit human input may be nested and long-lasting. (4) Multi-modal user interactions may operate concurrently. (5) Output can be multi-scaled in different geographical locations. (6) Output may be kinetic operations distributed in different locations. Examples of interaction modalities that integrate physical and digital interfaces for design presentation are shown in Fig. 2.

















Interface task	gesture	pens	laser pointer	baton
pointing				
annotations				
directing				
navigation				

Fig. 2. A matrix of interaction modalities that integrate physical and digital interfaces for design presentation.

From foreground computation to background computation As computers vanish into the background, human-computer interaction becomes similar to the way humans interact with the physical environment. Researchers increasingly believe that building space should be transformed into a set of interaction interfaces between humans and computers. Buildings become a ubiquitous tool taking on a role similar to computers-enabling media facilitating rich everyday experience in a coherent way.

From single-user systems to multi-user interactions with mixed reality People live in a world of mixed reality with two distinct environments: the physical environment where people reside with face-to-face interaction and the digital environment where virtual agents interact. Much work is needed to support multi-user interaction in a smart space, and to articulate and connect events in the physical and digital worlds.

2.2 Sensing and Perceptual Technologies

Sensing technologies are increasingly being used to provide implicit input for natural interaction interfaces. The trend toward sensing-based interactions has imposed a basic requirement on any ubiquitous media to support implicit multimodal inputs in smart spaces. Sensing technologies can be briefly classified into three categories: (1) location sensors, (2) mobile sensors, and (3) environmental sensors.

Location sensors Location sensors are embedded in a room or place to detect human presence. Examples of location sensors are web cameras that use computer vision and recognition technologies that identify behavior patterns and interpret the signals of human activities. Other commonly used sensing technologies are optical, magnetic and capacitance sensors coupled with radio frequency devices to receive sensed signals. In these experiments, capacitance sensors are used to create smart floors. The aim of a smart floor is to identify a user's presence and provide location-aware information when a person walks into a space. A matrix of capacitance sensors underlying the smart floor triggers the wall-sized display of audio-video projectors in smart spaces.

Mobile sensors Mobile sensors are worn in human bodies to detect human motion, gesture and social settings. Examples include sensors that equip handheld devices with perceptual capabilities. Mobile sensors can detect how a device is held and determine how to respond. Radio frequency identity (RFID) is another example of electronic tagging associated with the wide variety of objects tracked by barcodes. Coupling with wireless network connections together, RFID technologies enable digital annotations of physical objects and locations, which potentially change how people interact with the physical environment.

Environmental sensors Environmental sensors are conventionally installed in our built environments to measure temperature, humidity, pollution or nerve gas levels to ensure safety and quality. Examples of environmental sensors include the thermostat of a heating system, which switch the heating on when the temperature drops below a certain level, and automatic light switches, which use sensors to detect the presence of humans in public places (*e.g.* stairways and restrooms) to save energy.

This work identifies two significant facets of sensor-based interactions that are relevant to smart space design. The first aspect is a sensor network combined with an adaptive software platform to develop ubiquitous media applications. The other aspect refers to creating user experiences in the cognitive process of sensor-based interactions. Creating user experiences stipulates natural cognitive mapping between human actions and sensing effects. Together, sensor-based interactions require a ubiquitous computing infrastructure that maps to the physical space and its corresponding interaction model.

Sensing and perceptual technologies have been increasingly recognized as useful in developing context-aware smart environments. Often, a mixture of location, mobile and environmental sensors can be applied to command control, replacing existing user interfaces and physical switches in the real world. The nature of sensor-based interactions is implicit, continuous and human-centered. Using sensors for implicit input-output interactions has potential to alter the nature of our built environments. Examples of embedding sensors to building elements that augment spaces with intelligence are shown in Fig. 3.



Fig. 3. Embedding sensors to building elements that augment spaces with intelligence.

2.3 Social and Environmental Awareness

Smart space is uniquely human-centered design. In smart space, ubiquitous media are designed to reduce the cognitive load of human users. Paradoxically, ubiquitous media might turn around and place a considerable demand on humans because they have become part of the physical environment to which people strive to adapt. Even with the most human-centered methodology, ubiquitous media might not be a natural part of the human system. Therefore, researchers need to study how ubiquitous media affect human cognition, and how humans adapt to technological and environmental changes.

Recognizing human activities Many domains of cognition are relevant to the above aims. One domain focuses on human factors test and evaluation of ubiquitous computing applications to be designed and created for smart spaces, including identifying the human cognitive processes and capturing the reactive and adaptive behaviors of the human users when they try to interact with ubiquitous media. Activities take two forms. Efficiency-driven activities must tightly couple cause and effect, and avoid making mistakes in the interaction. Exploration-based activities have more room for ambiguity, enabling users to learn through engaged interactions.

Exploiting natural mapping between actions and perception The need for adaptation occurs when actions and perception do not match. Observations from this work show that creating new forms of sensor-based interactions often leads to confusion and annoying user experience, but this problem is not due to technology. Rather, the effects of the responsive actions do not match with the desired outcome. People feel comfortable if they can expect what is happening in their environment. Therefore, natural mapping between actions and perception needs to be incorporated into a design, resulting in immediate understanding and compelling user experience.

Creating spatial clues to direct user behaviors What metaphors can be used for ubiquitous computing in smart space? In other words, what is the next “desktop” metaphor? Current experiments are aimed at creating spatial metaphors to guide user behaviors in a smart space. People like to understand every aspect of their surrounding environments. Users may wander around if they do not know where and how to activate a device, and hesitate to proceed with an action if they cannot predict its effects. In designing smart spaces, the set of possible actions and movements needs to be visible to users, and the peripheral information should be moved into the foreground of the user’s attention.

2.4 Intelligent Devices and Service Control

This attempt to support smart spaces requires not only linking many sensors and media to locations. Some fundamental conceptual shifts occur in the backend system architecture for application and service control.

Transforming low-level sensor data to high-level application context The first problematic question is, “How is sensor data transformed to application context? How is it interpreted?” In all cases, sensor data derives from low-level device output represented

by bits. The low-level sensor data (e.g. “0” or “1” denoting the state of the sensor) has to be translated to high-level application information (e.g. “walking into a space.”). When the sensor detects a person in a given context, a particular interpretation of the context can be formalized in a triple $\langle user_ID, location, event \rangle$: a user identifier, the user’s location and the user event. A triple of the context can be extended to environmental features (e.g. temperature and humidity) and the human state (e.g. emotion and psychological reactions).

Triggering context-aware responsive actions The next question following sensor data context is, “What action is suitable for ubiquitous media in reply to a specified context?” In the example of smart space, the spatial components such as walls and floor may respond such that an action is triggered in terms of a specific spatial and social context identified by the sensor networks. The responsive action can be multimedia access control (e.g. automatically display of a pre-programmed video), environmental control (e.g. switch lighting on or off), or surveillance monitoring (e.g. start recording, send alert emails).

Application execution and service control Responsive actions are generally executed in two main stages, service execution and application control. Applications specify and execute services, which include from multimedia access control, environmental control, and surveillance monitoring. In a complicated example such as smart space, however, services may involve complicated process coordination, stipulating effective management of applications and their corresponding internal events dispatched from sensor networks.

Infrastructure for coordination of intelligent devices User activity tracking may involve integrating inputs from many heterogeneous devices and sensors. For example, capacitance sensors are embedded in the floor to provide location information. Other sensors such as cameras are used by programs that identify a user’s gesture. Each sensor has its own driver, requiring integration of heterogeneous sensor data. Data integration necessitates a separate layer of system components in the backend to generate an integrated high-level application context related to the interaction.

To handle these problems, a system architecture was developed for building ubiquitous media applications in a smart space, as shown in Fig. 4. The system architecture decouples sensor networks from spatial system components, services, and application programs. Second, a separate coordination manager layer consisting of context agents is required to coordinate activities across system components in the backend. The context agents schedule events and monitor the validity state of the spatial system components, so that the applications and services can be executed in the correct order.

3. PHYSICAL PROTOTYPING OF UBIQUITOUS SMART SPACES

To show how the framework can be applied to the design of ubiquitous smart spaces, I describe two physical prototypes recently developed: *the interactive workspace* and *the interactive media exhibition*. The first prototype is *the interactive workspace*

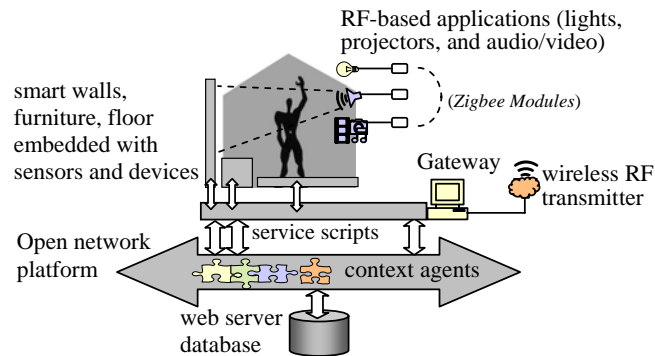


Fig. 4. The system architecture of ubiquitous smart space.

built for design reviews and critiques. A design review process requires multiple views of design and varied representations of buildings for a better understanding of building designs. Examples of building representations include sketches, drawings, 3D models, and animation. In order to explain design ideas clearly, designers occasionally use different interaction modalities for design communication such as hand gesture pointing to the 3D models. These special requirements for design reviews and critiques have motivated us to transform a workspace to be interaction interfaces between humans and computation.

A set of smart space components has been implemented in the interactive workspace, including *RFID entry*, *an interactive door*, *a wall-sized display*, *smart floor*, *tangible models*, and *LED-mounted hand gesture recognition*. The RFID entry is a corner space in the entry that identifies a project and triggers multiple displays of project information in the interactive workspace. In a weekly design meeting, one can pick up a project display tablet and plug it into the smart wall. This automatically brings up a project web page with related links on the wall screen. Designers can use LED-mounted hand gestures or laser pointers to remotely resize, move, or rotate the 3D models on the screen. Smart floor can identify the presenter's location and switch the display from the wall screen to the interactive door screen. The interactive door is equipped with a transparent screen and touch sensors. The interactive door broadcasts digital design information to outsiders. Passersby may leave messages from the outside for commentary. The messages are captured and added to the project home server page. With the transparency and touch-screen capabilities, the interactive door serves as a medium for social and situated interactions. A snapshot of the interactive workspace is shown in Fig. 5.

The second prototype is *the interactive media exhibition* in the museum of science and technology. A research prototype of ubiquitous smart space has been implemented for Taiwan New Landscape Movement Exhibition. In the exhibition, I adapted the original setup for interactive workspace project and transformed it into an interactive media exhibition called IP^{++} . A view of the IP^{++} prototype in Taiwan New Landscape Exhibition is shown in Fig. 6.

The IP^{++} project is composed of four major components: *smart floor*, *interactive walls*, *smart cubes*, and *information canvas* for ambient displays. Smart floor is a combination of a set of elevated floor boards, each of which is embedded with capacitance

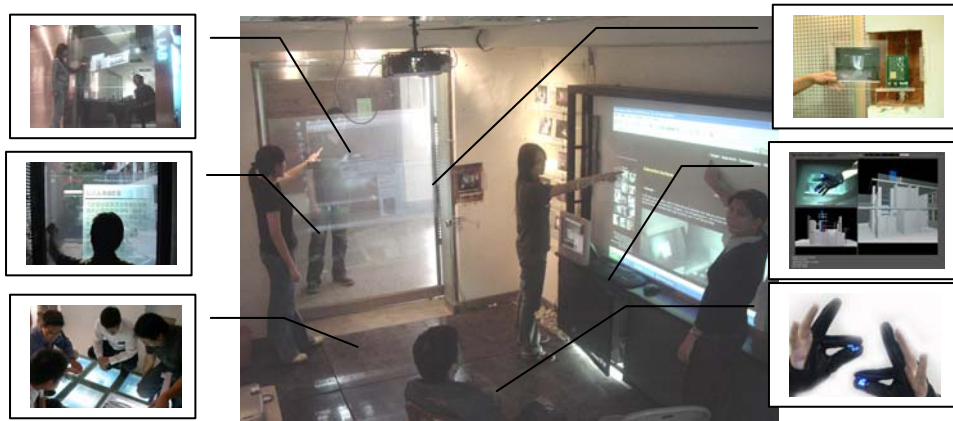


Fig. 5. A set of smart space components is implemented in the interactive workspace: an interactive door, a wall-sized display, and smart floor (left); RFID entry, computer-augmented tangible models, and LED-mounted hand gesture interaction (right).

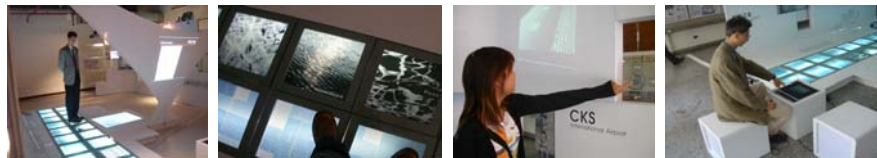


Fig. 6. A sequence of snapshots of the IP^{++} interactive media exhibition.

sensors to detect human presence. When the sensor-embedded floor detects the presence of people in that location, they would trigger an event (*e.g.* ambient displays) over the floor and information canvas. An interactive wall is composed of small-sized wall modules, each of which is embedded with an optical sensor for detecting when someone is passing by. Smart cubes are a set of computer-augmented furniture that has capacitance sensors inside. Parts of the smart cubes are installed with all-in-one computers and monitors. Information canvas is made of stretchable material for situated ambient displays. Together, smart floor, interactive walls, smart cubes, and information canvas construct a smart space out of traditional architectural space for interactive exhibition.

There are three kinds of sensing-based interactions to experiment with the IP^{++} prototype. First, visitors to the exhibition are invited to walk through the IP^{++} exhibit space. There are three sensor-embedded smart floor boards representing the *past*, *present*, and *future* development of Taiwan landscape. As the visitor moves on to one of the smart floor boards, the floor sensor triggers the display of animations corresponding to the *past*, *present*, and *future* Taiwan landscape information. The projected information is determined by the backend IP^{++} database system according to the visitor's location at the smart floor boards.

Secondly, a set of physical icons is designed and attached on the interactive wall, allowing visitors to directly interact with a computer-generated three dimensional model. Visitors use gestures to interact with digital 3D models without wearing any devices. The physical icons are embedded with optical sensors for issuing commands such as “*rotate*”, “*zoom in*”, and “*zoom out*” of the 3D model. As the visitor moves one or both hands over

the optical sensors, the system would issue an implicit command to rotate, zoom in, or zoom out the computer model correspondingly. The significance of this exhibition is device-free and permits complex gesture with a composite command.

Our final experiment in this exhibition is a lounge area installed with three computer-augmented cubes. One cube is served as a computer display while the other two sensor-embedded cubes serve as smart seats to sit down. As the visitor seats herself on the cubic box, the sensor inside the box would detect the presence and trigger the display of information relevant to the exhibition on the surface of the other cubic box.

The IP^{++} project reflects the inherent feature of ubiquitous smart space. First, architectural space turns out to be physical-digital interaction interfaces. We investigate a set of composition rules to design the IP^{++} modules coupling with architectural design. For the purpose of modularization and adaptability, all the parts of smart floor, interactive walls, and smart cubes can be reconfigured into different spatial settings. Secondly, the IP^{++} modules are augmented by sensor networks with sensing, computing, and communication capabilities. Sensor networks are developed in conjunction with the execution of applications and the provision of context-aware services. A usability test is being conducted to study how visitors adapt to ubiquitous smart space in the exhibition site.

4. THE IMPLEMENTATION OF AN OPEN LIVING LABORATORY

In order to test the adaptability of the initial prototypes, we expand the prototype to a real-world large-scale open living laboratory for smart homes. An initial focus of the open laboratory has been the development of smart living technologies to facilitate everyday lives and enhance rich user experiences in a coherent way, and more recently, become a living laboratory for open innovation in the home of the future.

To meet the changing needs of open innovation, the living laboratory must be dynamically configured to varied settings for different purposes. There are multiple perspectives of the open living laboratory. Our work chose to focus on the design of the dynamic wall system for dynamics, flexibility, and adaptability. The requirements include:

1. a flexible smart wall system allowing dynamically configuration of the space,
2. a modular design of wall panels, each of which has its computational identity-embedding RFIDs, sensors, and actuators with changeable physical materials, and
3. a kinetic responsive wall system that can dynamically change its appearance corresponding to environmental change.

A full-scale physical prototype of the interactive moving wall system has been developed in the open living laboratory, as shown in Fig. 7. The responsive wall system supports dynamic configuration of spaces for social and environmental contexts. The system allows the wall to dynamically change its physical property (*e.g.* from opaque to transparent) according to varied spatial configuration. Each wall is mounted with smart glass and embedded with RFIDs. The wall is intelligent enough to ‘know’ the adjacency relationship with other walls. When connected, the smart wall detects its state of connectedness and triggers the smart glass to turn from transplant to opaque.

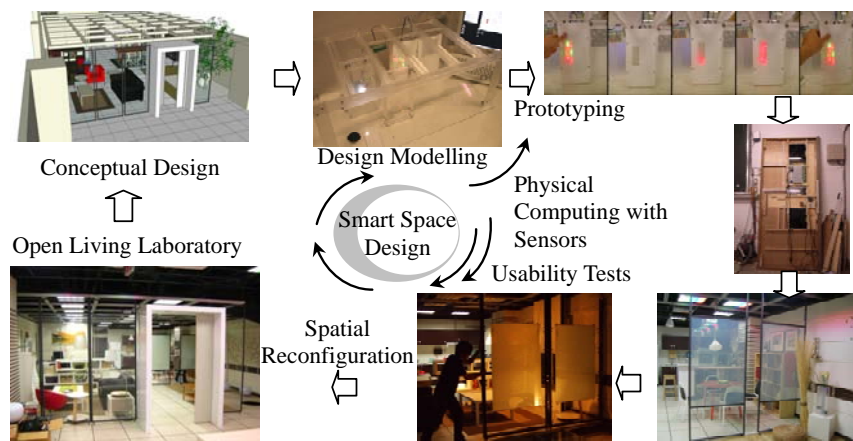


Fig. 7. Smart spaces are conceptualized, explored, modeled, prototyped, tested, reconfigured and the loop repeats.

Over the course of design, we recorded the entire design process. During the project, we presented this physical prototype of the open living laboratory to the professionals and faculties. People discussed design alternatives through direct manipulation of the physical prototype. Indeed, the physical prototype serves as a media for shared understanding. It also helps us make better predictions about how users will perceive and interpret embodied interactions.

Smart space design at its core is an iterative process, as shown in Fig. 7. Spaces are conceptualized, explored, modeled, prototyped, tested, reconfigured and the loop repeats. In the meanwhile, ubiquitous computing applications are identified, explored, measured, revised and enhanced in the open living laboratory according to the result of usability tests. As the open living laboratory provides a means to compress the loop and make it easier to iterate design alternatives and evaluate their usability, they in theory can improve the quality of life.

5. CONCLUSION

As ubiquitous computing technologies become invisibly embedded in our physical environment, buildings become a *complex* smart living system. The complexity may be *intrinsic*, imposed by building performance or the construction technology, as in housing design. Alternatively, the complexity of interaction may be imposed *extrinsically*, as a set of sensing capabilities and computational rules, as in certain system infrastructures in smart homes. Today, most designers and researcher can only consider complexity of smart spaces intuitively, in the experience of tacit knowledge in a particular application domain. There has been no way to generalize design knowledge from one project to all projects with a similar design process, method, and technique.

In this paper, a conceptual framework is presented to identify the design principles of ubiquitous smart spaces. This work sets forth a set of methods that are essential to realize the human-computer interaction design process. The methods support the formu-

lation of design solutions for integrating new technologies in ubiquitous smart spaces. Most importantly, the design prototypes, as the convergence of computers and buildings, have shown the potential for a profound transformation of design practice in smart space design. The design framework and the implementation of the prototypes have served as a logical basis to elaborate broad design concepts and ubiquitous computing technologies that may be carried out toward the smart space of the future.

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