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Modeling Human-Computer Interaction in Smart Spaces: Existing and Emerging Techniques

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1. Introduction

The main focus of human-computer interaction (HCI) research during the 1980s and much of the 1990s was on desktop computers applied in office settings. Developments within mobile and wireless communication technology, however, have contributed to make computer interaction beyond fixed and predictive desktop settings a reality. This has opened up for new interactive possibilities in and across various use situations. These trends can be seen as a partial implementation of Mark Weiser's ubiquitous computing (UbiComp) paradigm as envisioned almost two decades ago in his seminal article "The Computer for the 21st Century" (Weiser, 1991).

The ubiquitous computing paradigm implies that our interaction with computers becomes more physical in nature. Weiser predicted that we would have continuous interaction with multiple interconnected computers and sensors embedded in rooms, furniture, clothes, utilities, and other items we use on a daily basis. This way, people, places, and physical objects in the world would become potential elements of computer interaction, analogue to virtual widgets (e.g., buttons, hyperlinks, mouse cursors) of graphical user interfaces. Environments, in which digital and physical artifacts are used with sensor technology to implement seamless interaction with technology and surroundings, are often referred to as *smart spaces* (or sometimes context-aware, intelligent, or ambient spaces).

Although we see the rise of smart spaces, the tools designers have at their disposal for modeling computer systems that are part of such environments have not developed accordingly. Conventional modeling formalisms such as UML are essentially intended for communicating software designs, describing the structure of systems and the interactions between software objects. Using UML use case and sequence diagrams, it is difficult to represent physical aspects that are central for human-computer interaction in smart spaces. The same problem also applies to formal HCI methods like task analysis. These shortcomings have motivated designers to employ more informal modeling techniques, such as storyboards and sketches. Arguably, these techniques are more suited for describing how smart spaces present themselves to users. The informality of these modeling techniques, however, can make it more difficult to recognize similarities between different designs, and to re-use former solutions on new problems. One also risks introducing unambiguousness in the generated models.

Drawing on the above, ubiquitous computing and emergence of smart spaces arguably raise the need for methods that extends conventional modeling techniques with capabilities for describing *formal physical models* of computer systems. Motivated by this, we have investigated a technique for describing human-computer interaction in smart spaces through a set of formal notational building blocks and related semantics. The building blocks represent physical and virtual interactive elements that, taken together, form smart spaces. Currently, the formalism supports modeling of location-aware and token-based interactive systems. Both types of systems have received considerable attention in ubiquitous computing research, e.g., (Cheverst et al., 2000; Holmquist et al., 1999). This makes the proposed formalism highly applicable for modeling large number of systems that can implement smart spaces.

In the current work we aim to investigate features that characterize some of the existing techniques available for modeling computer systems and interaction in smart spaces, and discuss the added value the proposed formalism can bring to this collection.

To demonstrate the applicability of the proposed formalism we will address various services proposed and explored in relevant research literature, and show how these services can be represented by means of formalized physical models.

2. Background and motivation

To understand the modeling issues that the emergence of smart spaces raise, there is a need to give a more elaborate account of how interaction in such environments distinguishes itself from conventional desktop interaction.

2.1 Ubiquitous Computing vs. Desktop Computing

Weiser's 1991 vision of ubiquitous computing predicted how our interaction with computer technology would change in years to come. Weiser saw it as a fundamental use criterion that technology allows itself to fade into the background of the users' attention. He suggested that by integrating computers and sensors into our everyday physical environments, and by imbuing computer systems and applications with context-aware capabilities (i.e., enabling them to automatically sense and respond to their physical and social use context) computers would effectively become "invisible" in use. This stands in contrast to interaction with conventional desktop-based systems, which to a much larger extent is a foreground activity.

Dourish (2001) uses the concept of *embodiment* to distinguish how interaction with UbiComp systems is separate from interaction with traditional desktop systems. *Embodied interaction*, as argued by Dourish, unfolds real-time and real-space "as part of the world in which we are situated". This draws attention to both the physical and the social aspects of the use situations.

The ubiquitous computing paradigm, also known as *third paradigm computing*, is distinguished from previous interaction paradigms in terms of the underlying interaction model, points of interaction, the number of devices we use, and types and appearances of computer devices we interact with. Table 1 gives a conceptual overview of how these aspects have changed over various HCI paradigms.

Interaction paradigm	Period	Interactive devices	User-device relation	Interaction Model	Point of interaction
Mainframe computing	mid 1960s – ca. 1980	Mainframes	N users – 1 computer	Centralized	Corporations and larger institutions (universities, hospitals, etc.)
Personal computing	ca. 1980 – mid 1990s	PCs	1 user – 1 computer	Distributed	The desktop in the home or in the office.
Ubiquitous computing ("third wave")	mid 1990s – present	Interconnected laptops, tablet PCs, PDAs, mobile phones and "gadgets".	N users – N computers	Distributed and interconnected	"Anywhere, Anytime"

Table 1. Conceptual view of the three paradigms that have shaped human-computer interaction.

In contrast to what the situation was almost two decades ago, when Weiser expressed his vision, many of the technical components required for building smart spaces are now available. Developments in hardware and in wireless and mobile ICT have motivated research on the smart spaces in various use settings. In particular, this includes settings in which many activities are mobile by nature, e.g., hospitals (Bardram, 2004), construction (Sherry et al., 2004), and the domestic arena (Kosekela et al., 2004; Howard et al., 2006).

2.2 The Physical Reality of Human-Computer Interaction

Over the years, desktop-based interaction has become highly standardized in terms of input and output devices. The typical I/O devices for a PC include a computer mouse, a keyboard, and a screen. This standardization can be seen as a result of the relatively stable and predictable physical and social use conditions for which desktop-based systems are made – a single user sitting in front of a computer screen with required interaction devices ready at hand.

Because of the assumptions designers of software intended for desktop computers can take about the physical and social use conditions, removing these aspects from computer system models are in many ways rational simplifications – they have no significant impact on the system being described. In models constructed by means of de facto languages such as UML we find a high degree of device abstraction hiding details about how user input and output is provided. In the ontology of object-oriented modeling, the user and other system components are in many ways considered conceptually equivalent. For example, in UML use case and sequence diagrams all interactions between the actors of a system (e.g., users, hardware, and software components) are represented notational symbols.

With the emergence of smart spaces, however, the traditional distinction between software systems and the physical world they are situated in is blurred. Conceptually, smart spaces provide computer systems with a physical interface mediating between users and computer technology. This interface is analogous to (and often supplementary to) screen-based interfaces. This highlights the need for modeling principles allowing designers to represent

the physical reality of human-computer ienteraction. Within ubiquitous computing and mobile human-computer interaction this has motivated the use of alternative modeling techniques such as storyboards and sketching, which are more suited for representing physical aspects of interaction (Van der Lelie, 2006; Davidoff et al., 2007).

3. Dimensions in Applicable Modeling Techniques

Modeling is a fundamental part of all scientific activity. It refers to the process of creating conceptual representations of more complex phenomena. A central aim of scientific modeling is to reduce the complexity of phenomena by focusing only on a limited set of relevant aspects, and to represent these at a specific level of abstraction.

The complexity of computer-based systems has long since made modeling techniques essential tools in the design process. Different computer-related research disciplines have developed various kinds of modeling techniques tailored to fulfill particular needs, and to improve the expressiveness required to describe relevant concepts. Hence, modeling techniques from two distinct disciplines (e.g., interaction design and software engineering) can produce very different representations of the same phenomenon.

The current section aims to give a more precise idea of where the modeling technique proposed in the current work positions itself in the landscape of existing modeling techniques from computer-related research disciplines.—For the purpose of comparing different approaches we will distinguish three dimensions in representations generated with computer-related modeling techniques—*perspective*, *formality*, and *granularity*.

3.1 Perspective
The perspective of a model corresponds to the viewpoint from which a given representation is represented. For the current purpose we will make a conceptual distinction between models that exclusively represent the software system as such, and models that draws attention to the external real-world context in which computer systems are used. We will refer to the first category of models as *system models*, while the second category of models is referred to as *physical models*. Computer modeling formalisms (e.g., UML) have mainly focused on generating system models. In interaction and scenario-based design, sketches and storyboards (picture scenarios) have frequently been employed to represent how computer systems work for people in a context. As apposed to UML representations, the resulting representations are often physical models.

Fig. 1 illustrates a system model (UML use-case diagram) and physical model (storyboard) of a hypothetical location-aware system in a clinical setting. The system automatically presents a patient's electronic record on a mobile device carried by a clinician, as he enters the virtual "presence" zone surrounding the respective patient's bed.
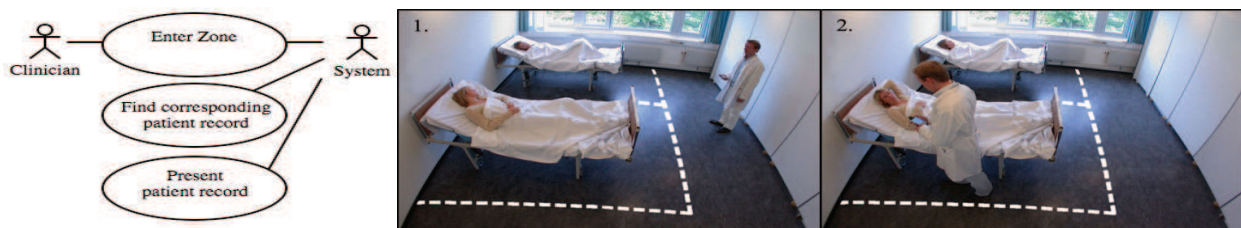

Fig. 1. (*Left*) System model. (*Right*) Physical model.

3.2 Formality of representations

Most conventional computer modeling techniques involve the use of a standardized modeling language. These approaches have been developed to describe computer systems in a consistent way, thereby creating a basis for common understanding among computer professionals. Formal representations can also help professionals recognize similarities between different designs, and thereby support reuse of former solution on new design problems. Automatic code generation and validation of models are some of the additional benefits associated with formal approaches.

Other modeling techniques generate representations that are informal and often more specific with regard to use situations and devices involved. Freehand sketching and storyboarding, informal system charts, and use cases are examples of informal modeling techniques. While formal models are domain specific and require professional experience to comprehend, informal representations, such as those noted above, can potentially act as a common language for a broader group of stakeholders involved in a design process.

Fig. 2 illustrates a formal UML sequence diagram and an informal system chart diagram of the location-aware medical information system represented in Fig 1. The use-case diagram and the storyboard shown in Fig. 1 is another example of a formal model and an informal model, respectively.
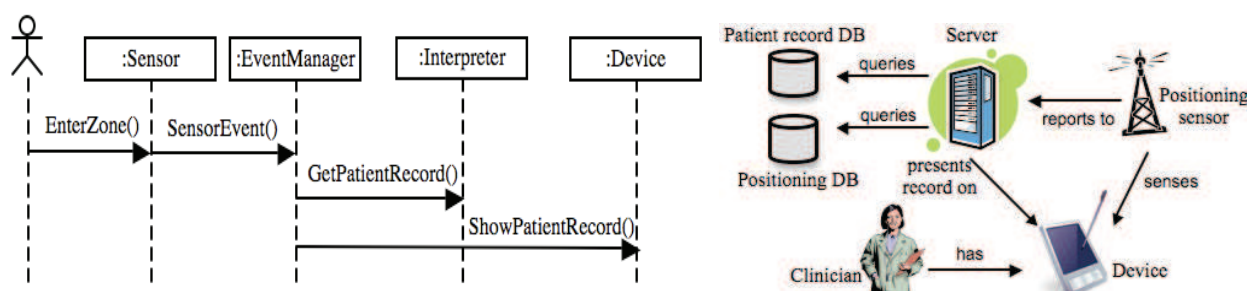
Fig. 2. (*Left*) Formal model (UML sequence diagram). (*Right*) Informal model (informal system diagram)

3.3 Granularity

Granularity refers to the level of detail that a model provides on a phenomenon being described. Both system models and physical models can be described at various levels of granularity. This, however, manifests itself differently. System models aiming to give a generic overview of a software system (e.g. Fig. 2) typically present only key system operations of a system, while sub-operations are hidden from view.

Sketches and storyboards showing physical models can be rendered rough or incomplete to hide details about certain aspects of the phenomenon or behavior being described. As we will show later, increasing or decreasing the number of picture frames included in a storyboard sequence can also adjust the granularity of the representation.

3.4 Defining the problem area

The conceptual differences between common modeling techniques applied in software engineering and interaction design are given in Table 2. Each technique can be classified in a 2 × 2 matrix along the dimensions: *informal representations* versus *formal representations* and *system models* versus *physical models*. The resulting matrix also helps to illustrate the gap in

available modeling techniques the current work is attempting to bridge—a technique that supports the construction of formal physical models.

	Informal representation	Formal representation
System models	- Use cases - Informal system diagrams	- UML use case and sequence diagrams - HCI task analysis
Physical models	- Storyboards (picture scenarios) - Sketches - Videos	**- Formalized physical models**

Table 2. Categorization of modeling techniques.

4. Design Elements and Semantics

Having established that designers of smart spaces could benefit from formal models that put focus on the physical reality of human-computer interaction, we now turn the attention toward how this can be realized with respect to location-aware and token-based interactive systems.

4.1 Design Elements
To formalize the interaction with location-aware and token-based systems, we have developed a set of building blocks representing the following key components: *users*, *virtual zones*, *tokens* and *computer devices*. In smart spaces these are core design elements that can act as links to digital information objects such as web pages, messages, GUI states, communication sessions, etc.

Tokens, as conceptualized in ubiquitous computing, are tangible objects that can contain references to digital information (Holmquist et al., 1999). To access this information a user must take a deliberate action (i.e., scan the token). A post-it note with a barcode identifying a particular web page (also known as *WebStickers* (Ljungstrand et al., 2000)) is an example of a token.

Virtual zones refer to the detection area of a sensor capable of responding to the presence of a user or his physical position. Bluetooth, WLAN positioning, and face recognition, are examples of technologies that have been used to implement location-awareness in indoor environments. Location-based interaction, as apposed to token-based interaction, is typically consequential rather than intentional.

Computer devices can mediate system responses triggered by physical interactions, e.g., present an associated web page when a user enters a virtual zone or scans a token.

Users interact with other design elements contained within the smart space through physical presence, proximity, or touch.

Virtual zones, *tokens,* and *computer devices* can be either portable or fixed to a physical position (Fig. 3).

In addition to the core design elements described above, we have defined two supplementary elements. The *remote communication* component is used to denote network communication over physical distances (i.e., from remote locations). *Token containers* are

physical objects that can hold one or more mobile tokens. A refrigerator with barcode stickers acting as bookmarks to electronic recipes is an example of a fixed token container.
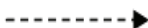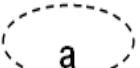

Fig. 3. Formal notation for modeling location-aware and token-based interactive systems. "a" represents an information object.

4.2 Semantics

The semantic relationship between the design elements can be summarized:

- Computer devices, tokens, virtual zones, and users can contain information objects.
- Information objects can be transferred between interaction elements based on proximity or presence (virtual zones), touch (tokens an users), or via remote communication channels.
- Users can carry mobile tokens, mobile token containers, and mobile computer devices, and have mobile virtual zones (that follow a user as he moves around).
- Tokens can be placed in token containers.
- Users can enter and leave virtual zones.
- Virtual zones can sense users and mobile computer devices that users carry with them.
- Mobile computer devices can sense tokens and other computer devices.
- Fixed computer devices can sense mobile tokens, and mobile computer devices.

The general semantic relationship between the core design elements and information objects is illustrated in Fig. 4. Fig. 5 shows the semantic relationship between the various design elements.
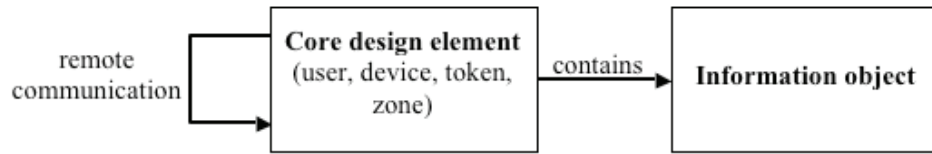

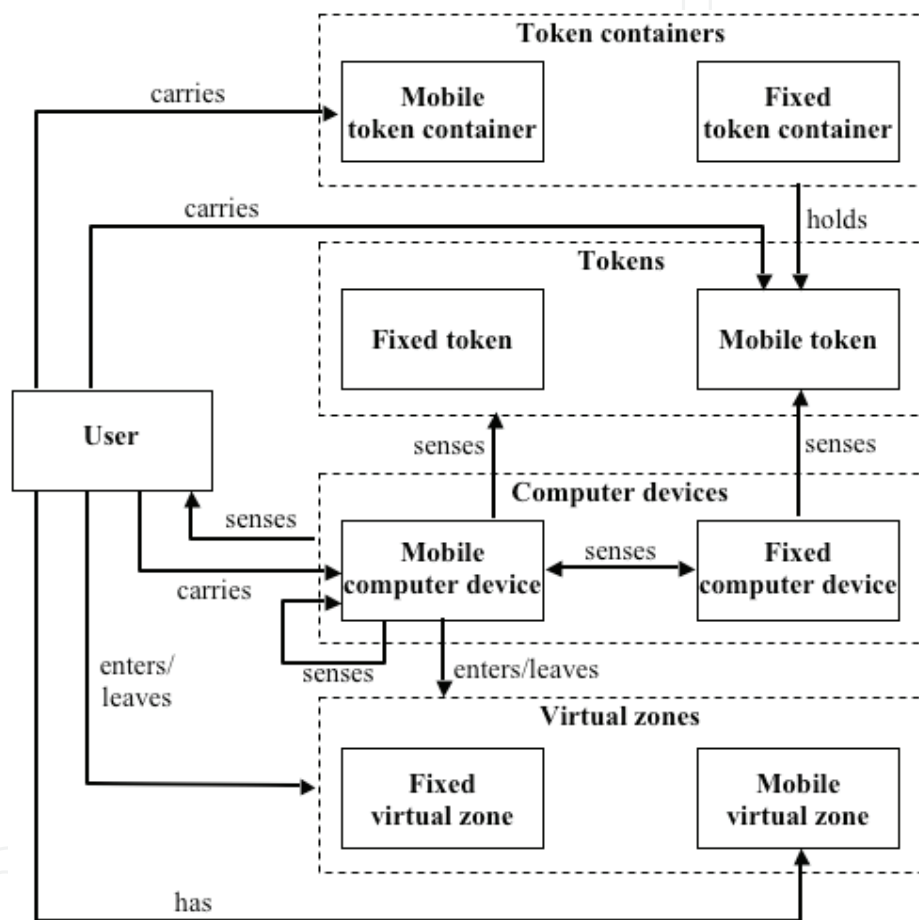Fig. 4. Semantic relationship between design elements and information objects.

Fig. 5. Semantic relationship between design elements.

5. Applying the Formalism

To demonstrate the added value of formal and structured physical models of smart spaces, we will address some functionalities proposed and explored in earlier research on ubiquitous computing. First we will focus on basic interactions with location-aware and token-based systems. Next, we will demonstrate how *session mobility*, i.e., seamless transfer of media content from one interaction device to another, can be represented using the proposed formalism. Lastly, we will present some examples of how the technique can help

represent interpersonal information exchange mediated through digitally augmented places or physical objects.

5.1 Basic Interactions

Given the building blocks described above, the basic interaction with location-aware and token-based systems can be described through simple transitions in the state-space of the system and the physical environment. Figs. 6-11 show the underlying interaction design patterns for presence, proximity, and touch-based interaction in smart spaces.

In Fig. 6, an information object associated with a virtual zone is automatically presented on the user' mobile device as he or she enters that zone. Fig. 7 shows a similar variant, where a fixed device replaces the mobile device used in the previous solution. In the location-based solution shown in Fig. 8, the virtual zone is anchored to the user. It remains fixed to the user as he or she moves about, and it can respond to physically proximate computer devices.
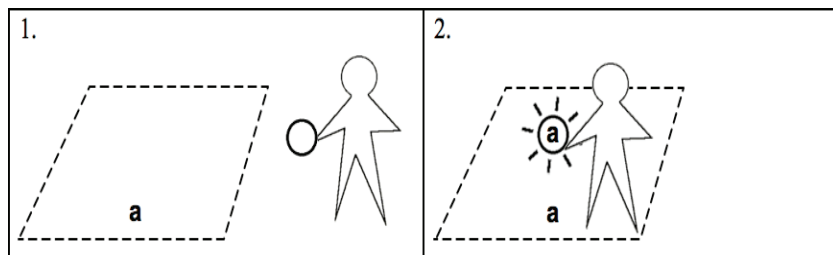

Fig. 6. Location-based interaction with mobile device.
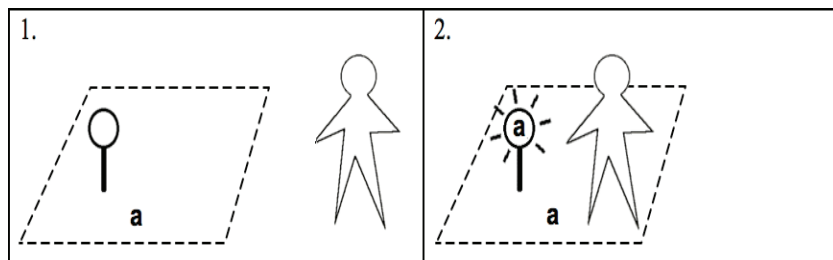

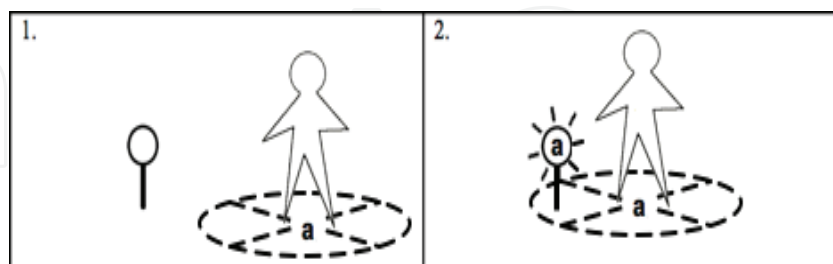Fig. 7. Location-based interaction with fixed device.

Fig. 8. Location-based interaction with mobile virtual zone and fixed device.

Figs. 9-11 show some basic token and touch-based interactions. In Fig. 9, a user carrying a mobile device accesses the information object associated with a fixed token as he scans the token. In Fig. 10 the roles of token and the device are switched vis-à-vis Fig. 9. Alternatively, in smart spaces the user can also act as a token or physical link to an information object. This is illustrated in Fig. 11.
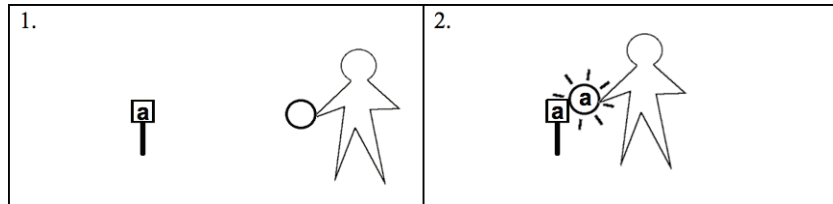
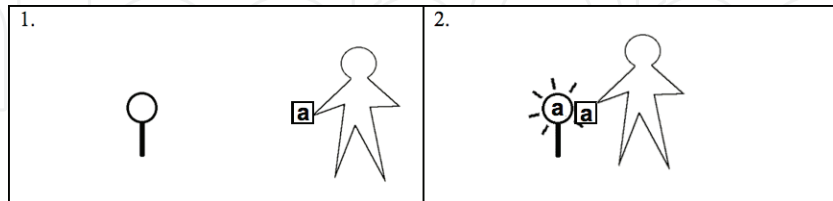Fig. 9. Token-based interaction with mobile device and fixed token

Fig. 10. Token-based interaction with fixed device and mobile token.
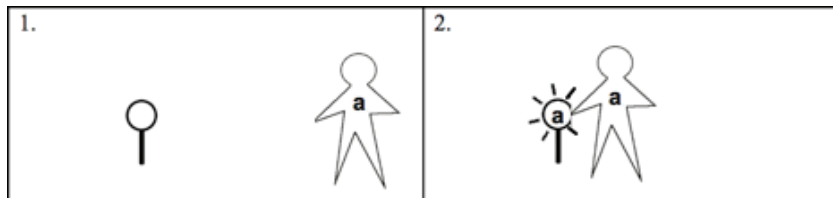

Fig. 11. Touch-based interaction. The user acts as a token or physical link to a specific information object.

The design patterns shown in the current subsection form the basis of many of the services that implement smart spaces. In the following two sections we will explore two such services in greater detail.

5.2 Session Mobility

Session mobility is commonly understood as seamless transfer of media of an ongoing communication session from one device to another (Østhus et al., 2005). A simple example of how session mobility can be modeled as a location-based service using the described notation is shown in Fig. 12. Here, the user enters a virtual zone with an associated information object. This causes the information object to be presented on the device contained within that zone. As the user moves from one zone to an adjacent zone the presented information object (session) is relocated to a compatible device.
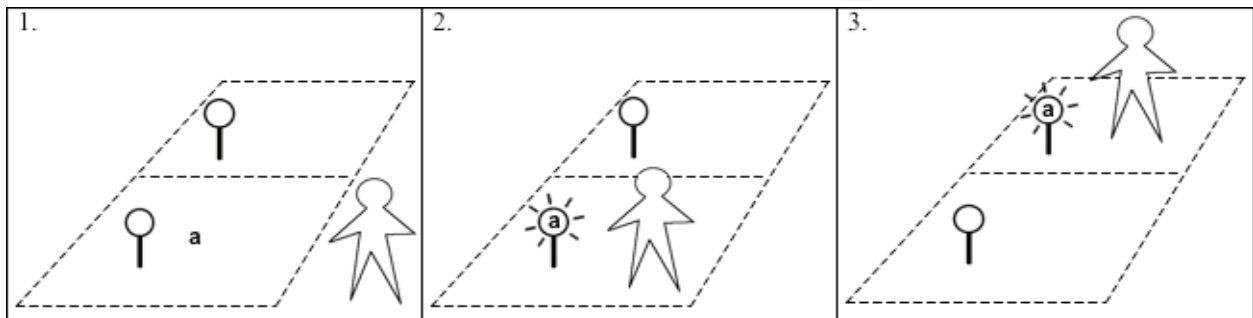

Fig. 12. Presentation and relocation of an information object based on a user's location.

Fig. 13 shows session mobility modeled as a token-based service. Here the user relocates an ongoing session by first associating it with a mobile token, and then carrying the token along and transferring the contained information object (session) to a compatible device at a different location.
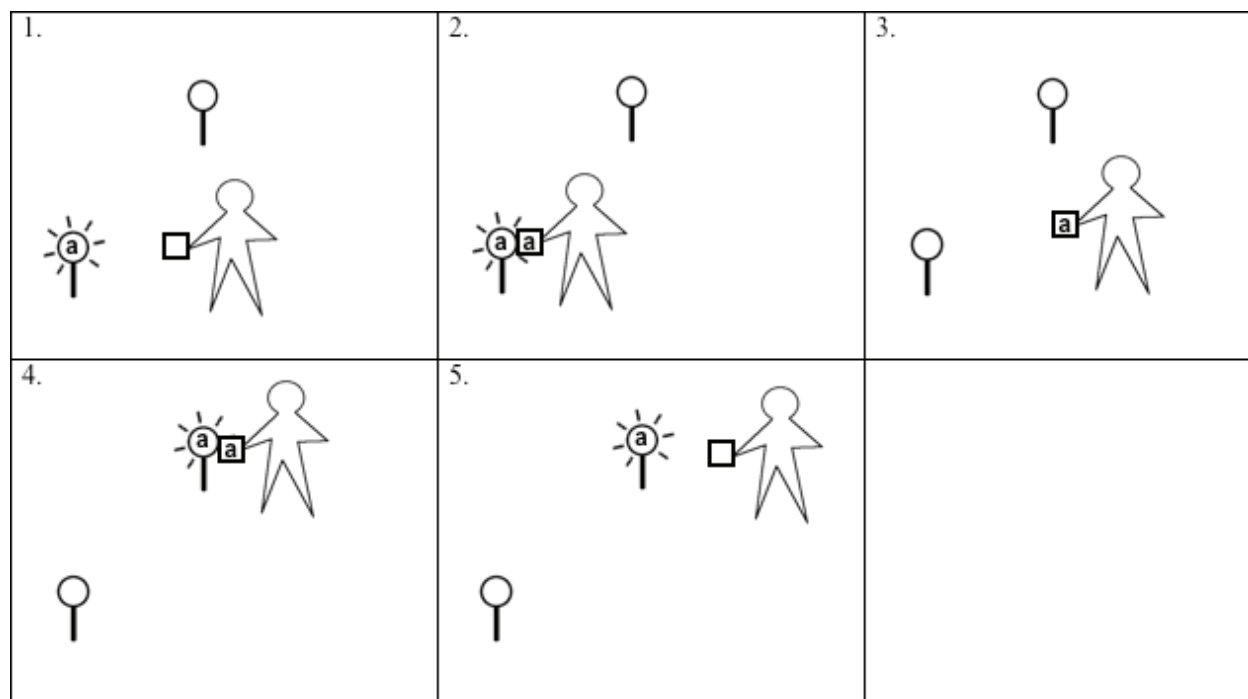

Fig. 13. Token-based relocation of an information object.

A slightly different variant is shown in Fig 14. Here, removing a token from a container associated with one device, and replacing it in a container linked to another device, relocates an ongoing session.
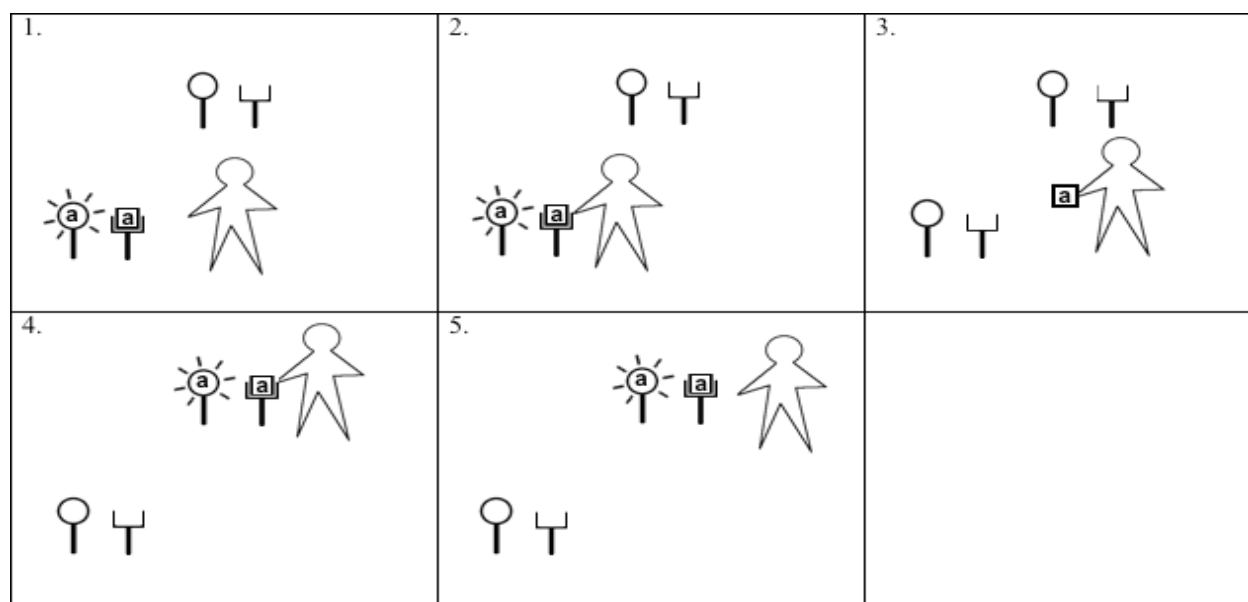

Fig. 14. Relocation of an information object using tokens and token containers.

Another solution would be to let the user take the role as token as shown in Fig. 15.
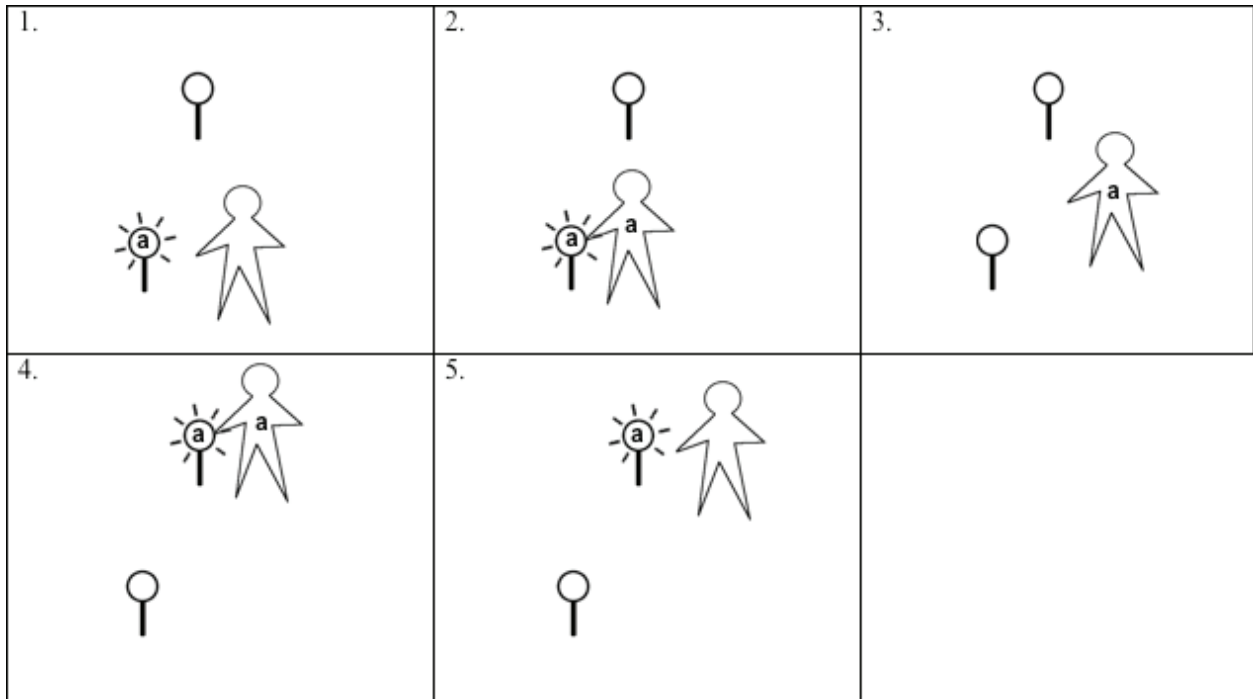
Fig. 15. The user acts as a physical reference to an information object.

5.3 Interpersonal Communication

While much of the research on smart spaces has focused on single-user scenarios, smart spaces and contained physical and digital resources can also be shared among people inhabiting these spaces. Figs. 16-20 show how different variants of information exchange between people can be modeled using the proposed design elements.

Fig. 16 and Fig. 17 show two examples of how synchronous information exchange can be modeled. In the first example, the mobile virtual zones associated with each user act as extensions of the users' bodily spaces. The mobile devices that a user is carrying can respond to the presence of another user (i.e., his extended bodily space).

In the latter example, the mobile devices must touch or be in immediate proximity of another device in order to hand over an information object.
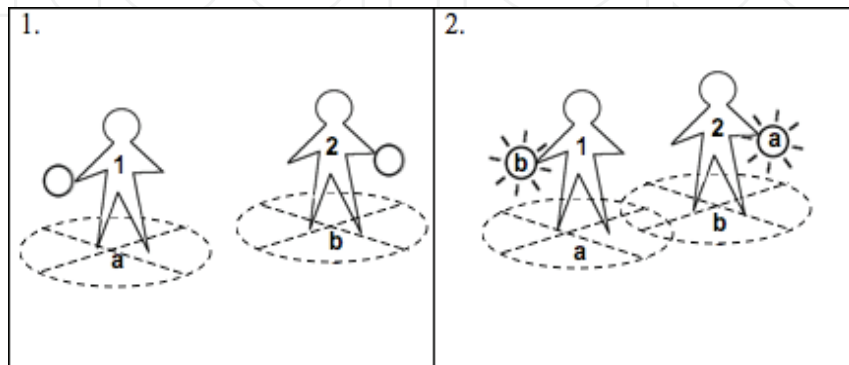
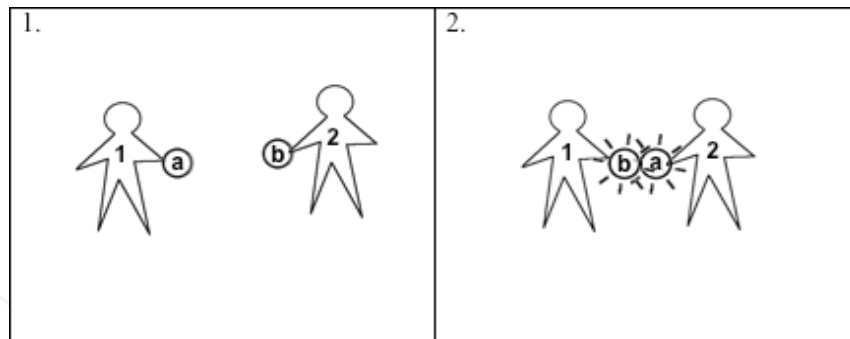Fig. 16. Synchronous information exchange with mobile virtual zones.

Fig. 17. Synchronous information exchange using mobile devices that "handshake".

Figs. 18-20 illustrate methods for asynchronous information exchanges. The representation shown in Fig. 18 is a conceptual model of the token-based CybStickers system (Rahlff, 2005). It allows users to communicate via tokens that can be physically distributed, and then be linked with digital information from a remote location. Other users can access the information object by scanning the respective token.
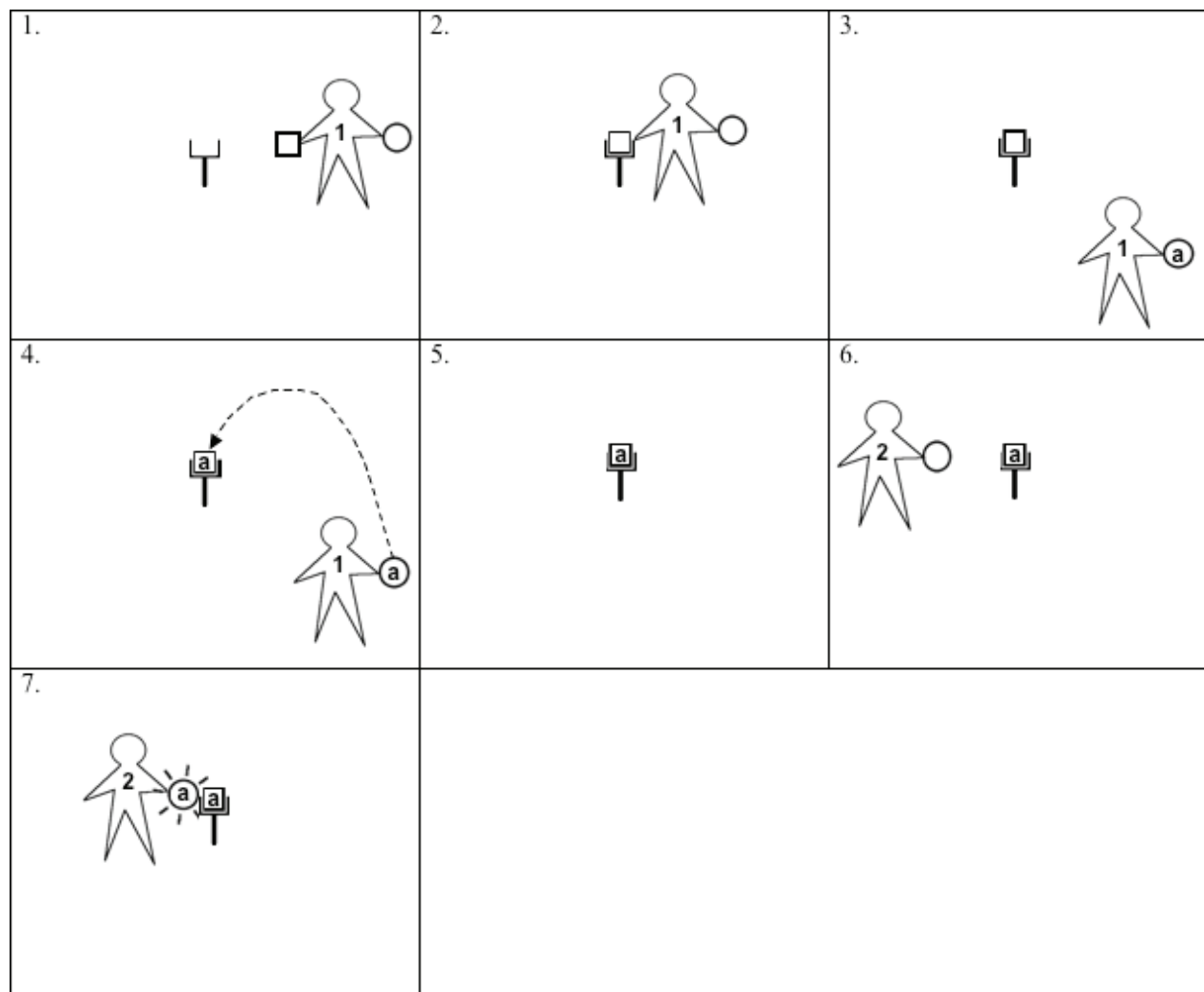

Fig. 18. Token-based information exchange via mobile token that can be linked to an information object from a remote location.

A location-based alternative implementing the same principle is shown in Fig. 19. In this setup a user can link an information object to a remotely located virtual zone. Potential recipient can then access the information object as they enter that zone. The location-based reminder service described by Sohn et al. (2005) is an implementation of this model.

Fig. 20 shows another instance of token-based information exchange. Here, a user distributes a set of tokens (e.g., RFID tags) with reference to two distinct information objects (*a* and *b*). The tokens are initially held in a mobile container (e.g., a book or folder). After the tokens have been distributed the can be accessed by other users at the respective locations.
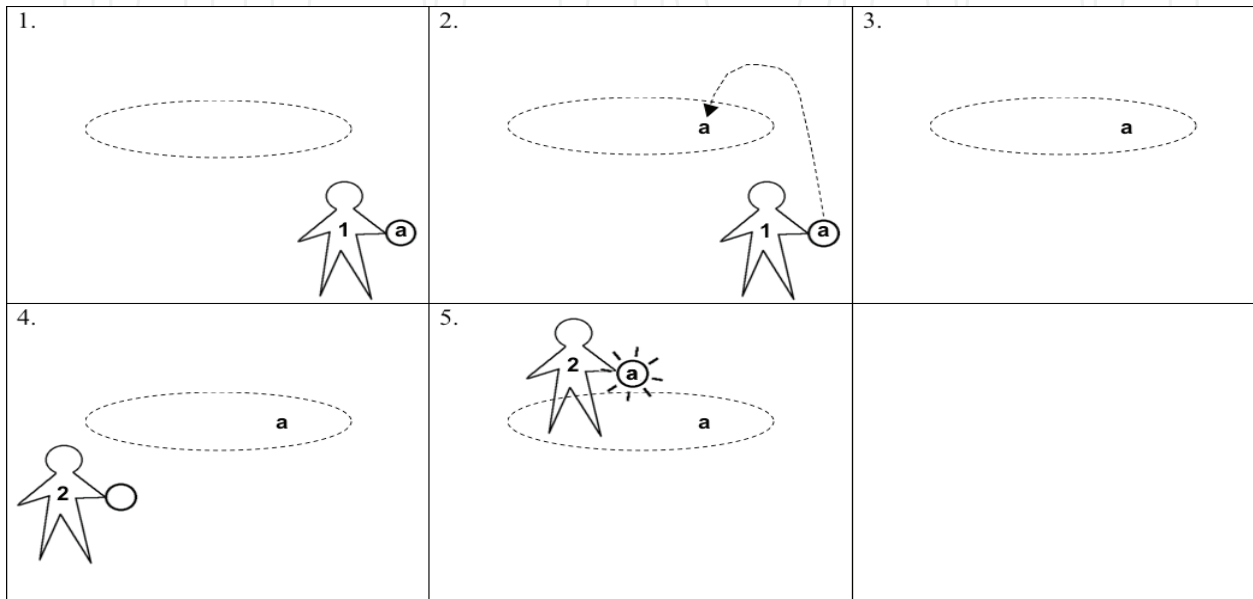

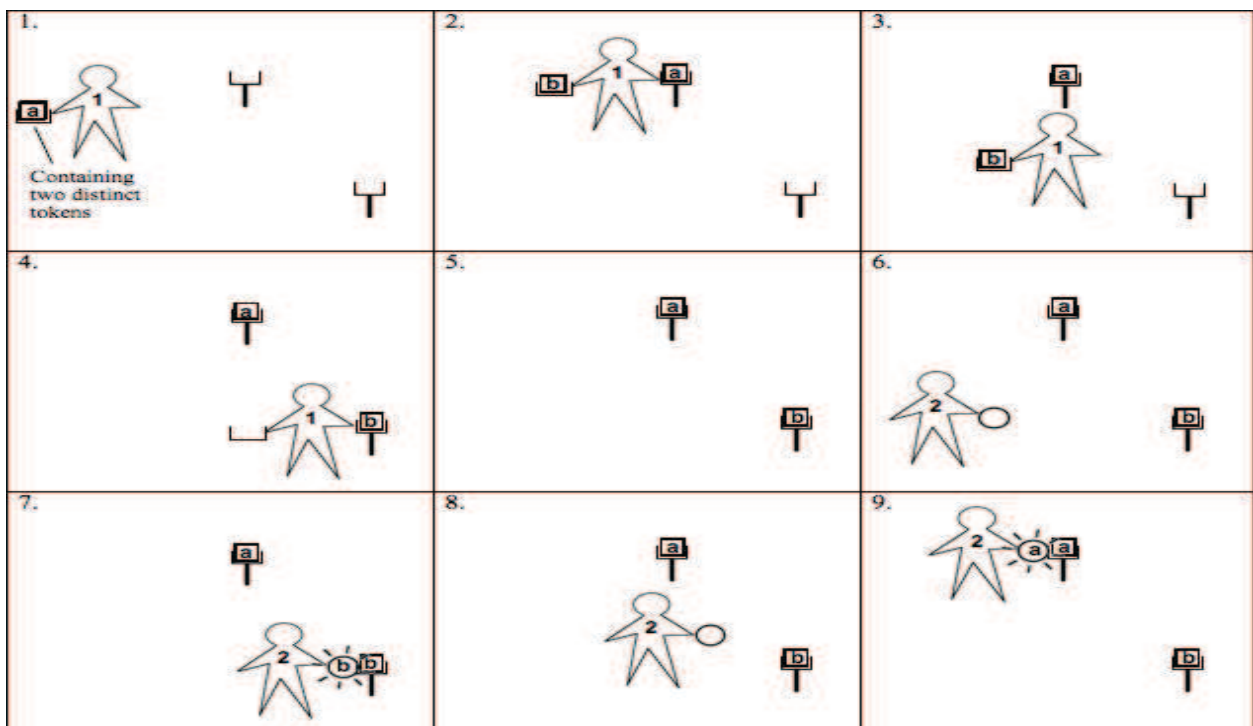Fig. 19. Information exchange mediated via a physical location.

Fig. 20. Instance of token-based information exchange.

6. Discussion

In this section we will briefly discuss how the presented modeling technique can contribute to inform design of ubiquitous computing and smart spaces. We will also point out some limitations.

6.1 Main Contributions

De facto computer system modeling formalisms tend to remove physical features of the system that is modeled. This makes it difficult to use such approaches to guide thinking about design of smart spaces, in which digital services and real-world user actions and events merge.

How users can provide computer input, properties of the devices and tools, and collocation between elements of interaction are not easily communicated through system models. This highlights need for physical models.

In this essay, we have argued that one way to accommodate physical design aspects of smart spaces is to think visually. The proposed method has adopted features from narrative modeling techniques such as storyboarding. By describing interaction in smart spaces sequentially through snapshots or frames it offers a simple way for designers to "zoom" in or out on an interaction sequence by adding or removing frames. As illustrated in previous section this makes it possible to represent both high-level interaction patterns, as well as more specific use scenarios.

By introducing a set of formal design elements the proposed modeling technique allows designers to create structured representations. This can help draw attention to the different roles design elements can play in interaction in smart spaces. Essentially, the design elements reflect the basic physical capabilities (mobility, immobility, portability) of the real-world entities they represent. The semantic relationship between the design elements reflects the most common methods of physical interaction (proximity, presence, and touch) supported by UbiComp technology. The examples provided in the previous section highlights that while the actual system operations (i.e. the functional specification) are likely to be constant, the composition of design elements that form the physical interface of smart spaces is highly flexible.

Being able to describe such compositions in a structured way can make it easier for designers to recognize similarities and distinction between different interaction design solutions, and re-use or adjust previous models to new design problems.

Results from a preliminary focus group evaluation (Dahl, 2007) also suggested that one of the key benefits of the formalism is that the generated models promote reflection and discussion among designers concerning how design solutions present themselves to users.

6.2 Limitations

As with any modeling technique from computer-related disciplines there are also certain limitation associated with the approach we have presented and discussed.

Firstly, it is limited to representing location-aware and token-based systems only. Alternative interaction techniques for smart spaces, however, include pointing and gesturing (Levin-Sagi et al., 2007), speech-based (Potamitis et al., 2003), and gaze-based interaction (Bonino et al., 2006). Formalizing these interaction techniques will require custom designed notations and semantics.

Secondly, the proposed building blocks are rough. Details concerning interaction elements and usage are hidden from the constructed models. For example, computer device may support different interaction styles such as stylus and touch-based interaction. Most token-based systems require that users hold or maneuver tokens in specific way in order to successfully scan them. For example, an ATM requires that credit cards are inserted the correct way into the ATM card slot. For some token-based system the different ways a token is manipulated can have different semantic meaning (Shaer et al., 2004). Modeling such details require richer representations for which informal sketches or icons may be more appropriate.

Thirdly, because the modeling technique focuses on generating physical models the underlying software methods that implement location and token-based abstracted away.

As the limitations above suggest, the proposed modeling technique is a supplement rather that a substitution to other modeling formalisms.

7. Conclusion and Future Work

The merging of the physical and the digital is a hallmark for smart spaces. In the current work we have argued that this raises the need for modeling techniques that can help direct thinking about physical aspect of human-computer interaction. Inspired by visual modeling techniques, such as storyboards and sketching, and the structure characterizing conventional system models, the proposed formalism offers a novel perspective on smart spaces.

Through this essay we have shown that it can be an effective visual "thinking" tool for exploring the interaction design opportunities that smart spaces can offer.

To form a more comprehensive understanding of its practical applicability, the modeling technique needs to be evaluated more extensively with designers and as part of a design process.

8. Acknowledgements

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Human Computer Interaction: New Developments

Edited by Kikuo Asai

The book consists of 20 chapters, each addressing a certain aspect of human-computer interaction. Each chapter gives the reader background information on a subject and proposes an original solution. This should serve as a valuable tool for professionals in this interdisciplinary field. Hopefully, readers will contribute their own discoveries and improvements, innovative ideas and concepts, as well as novel applications and business models related to the field of human-computer interaction. It is our wish that the reader consider not only what our authors have written and the experimentation they have described, but also the examples they have set.

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