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REQUIREMENT SPECIFICATION AND PROTOTYPING FOR USER INTERFACES OF BUILDINGS' ENVIRONMENTAL CONTROLS

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SUMMARY: *Occupant control actions in a building (i.e. user interactions with environmental systems for heating, cooling, ventilation, lighting, etc.) can significantly affect both indoor climate in and the environmental performance of buildings. Nonetheless, relatively few systematic (long-term and high-resolution) efforts have been made to observe and analyze the means and patterns of such user-system interactions with building systems. Specifically, the necessary requirements for the design and testing of hardware and software systems for user-system interfaces have not been formulated in a rigorous and reliable manner. This paper includes an exploration of the requirements of interfaces for user-systems interactions in sentient buildings. The outcome of this effort serves as a starting point for developing a new generation of user interface products to promote higher levels of connectivity between occupants and sentient environments.*

KEYWORDS: *sentient buildings, user interface, environmental controls*

REFERENCE: *Chien S-C, Mahdavi A (2009) Requirement specification and prototyping for user interfaces of buildings' environmental controls, Special Issue Building Information Modeling Applications, Challenges and Future Directions, Journal of Information Technology in Construction (ITcon), Vol. 14, pg. 642-653, http://www.itcon.org/2009/42*

1. INTRODUCTION

Based on advancements in information technology in recent years, new possibilities have emerged to better connect the occupants with environmental systems of buildings. Particularly in large and technologically sophisticated buildings, multi-faceted interactions between building occupants and the multitude of environmental control devices and systems need to be tightly integrated in order to assure effective building operation and performance.

As to the role of user interfaces in the context of intelligent built environments, there are a number of precedents. For example, the ubiquitous communicator – the user interface of PAPI intelligent house in Japan – is developed as a communication device that enables the occupants to communicate with people, physical objects, and places (Sakamura, 2005). The HomeLab project (Philips, 2008) intends to test home technology prototypes in a highly realistic way, thus speeding up technological innovations, particularly in the Ambient Intelligence domain. The MavHome (Managing an Adaptive Versatile Home) project (Cook et al., 2003), at UT Arlington, is a smart environment laboratory with state-of-the-art algorithms and protocols to provide customized, personal, safe and energy-efficient solutions for the users. More recent works on the integration of user interfaces into intelligent environments include Swiss house project in Harvard University (Huang and Waldvogel, 2004), Interactive space project by SONY (Rekimoto, 2009), House_n project at the MIT Media Lab (Intille, 2006), the Adaptive House at University of Colorado (Mann and Milton, 2005), and many others around the world.

This paper explores the requirements and functionalities of user interfaces to enhance the knowledge related to the usability of user interfaces for building control systems. It proposes a new generation of user interface models with novel possibilities for interactions between occupants and sentient environments. "Sentience" denotes here the presence of a kind of computational second-order mapping (or meta-mapping) in building systems operation. This requires that the flow of raw information collected around and in a building is supplied to a building's continuously self-updating model of its own constitution and states (Mahdavi, 2005). Thus, a sentient building may be defined as one that possesses a multi-faceted internal representation of its own context, structure, components, systems, and processes. It can use this representation, amongst other things, toward the full or partial self-regulatory determination of its indoor-environment status (Mahdavi, 2004). Given this view of building sentience, our research provides a number of benefits. Rigorous background information can be provided to user interface designers for further technology development. The resulting new generation of interfaces could provide timely, appropriate, and well-structured context information to the users, together with intuitive representation of the type and range of devices and parameters. This would facilitate a human-centered approach toward effective support for building occupants, who are typically confronted with a multitude of environmental control systems and devices.

In this paper, we first discuss the results of previous research concerning the comparative evaluation of market products (interfaces) for user-based control of building systems. We then introduce a set of user requirements toward design of new user interface products for sentient environments. Such new developments are expected to achieve new levels of connectivity between occupants and the environmental systems for indoor environmental controls in buildings.

2. BACKGROUND

2.1 Previous research

In a previous research effort (Chien and Mahdavi, 2008a), we compared twelve commercial user-interface products for building control systems. These products were classified as follows: A type ("physical" devices), B type (control panels), and C type (web-based interfaces). Thereby, we considered three dimensions, namely control options, information types, and hardware. The results were arranged in terms of: *i)* comparison matrices of the selected products based on three dimensions (information types, control options, and hardware), and *ii)* product comparison/evaluations by the authors' based on seven criteria (functional coverage, environmental information feedback, intuitiveness, mobility, network, input, and output).

Subsequently, we conducted an experiment, in which forty participants examined and evaluated a subset of the above user interfaces for buildings' control systems, mainly in view of three evaluative categories (first impressions, user interface layout design, and ease of learning).

Comparison results of the selected user interface products for intelligent environments warrant certain conclusions regarding their features and limitations. Interfacing with radically new kinds of environments that involve sentient technologies may require rethinking the occupants' requirements and attitudes. In addition, new interfaces encounter problems associated with numerous new technologies simultaneously embedded into a sentient building. Thus, to arrive at effective and comprehensive user interface models for sentient buildings, it is not only necessary to better understand the features and strengths of the available solutions, but also to anticipate and avoid negative consequences of interface technology integration in this critical domain. In the following, we briefly discuss certain areas of deficiency in the status quo and consider possible remedies.

2.2 Control options and functional coverage

In sentient environments, one key point is how the occupants interact with the multitude of environmental control devices and how they deal with the associated information loads (technical instructions, interdependence of environmental systems and their aggregate effects on indoor conditions) in an effective and convenient manner. The result of the above mentioned study implies that limited functional coverage and intuitiveness of use often correlate. This suggests that an overall high functional coverage may impose a large cognitive load on (new) users.

2.3 Provision of information

If it is true, that more informed occupants would make better control decisions, then user interfaces for sentient buildings should provide appropriate and well-structured information to the users regarding outdoor and indoor environmental conditions as well as regarding the state of relevant control devices. Most B and C type products in our study provide the users with some information such as the state of the devices. However, they do not sufficiently inform the occupants regarding indoor and outdoor environmental conditions. This implies that the occupants are expected to modulate the environment with the condition of insufficient information

2.4 Mobility and re-configurability

The hardware dimension addresses two issues, namely, *i)* mobility: user interfaces with spatially fixed locations versus mobile interfaces; and *ii)* re-configurability: the possibility to technologically upgrade a user interface without replacing the hardware may decrease the cost of rapid obsolescence of technology protocols. C-type terminals such as PDA and laptops that are connected to controllers via internet, facilitate mobility. In contrast, Type A and B products are typically wall-mounted and thus less mobile. As far as re-configurability is concerned, the user interface software may be easily upgraded in Type B and C products, whereas the conventional A-type products are software-wise rather difficult to upgrade.

2.5 Input and Output

Certain type-B and type-C products provide the users with richer manipulation possibilities that – if transparent to the user – could support them in performing a control task. There are other products (particularly type-A), however, that are rather restricted in presenting to the users clearly and comprehensively the potentially available manipulation and control space. Nonetheless, as our results suggest, type-A products are more positively evaluated than the more modern/high-tech (type-B and C) products, especially in view of first impressions and ease of learning. Here, we see a challenge: modern (high-tech) interface products that offer high functional coverage, must also pay attention to the cognitive user requirements so that formulation and execution of control commands are not overtly complicated.

2.6 Additional observations

In addition to the quantitative processing of the feedback provided by the forty participants in the above mentioned experiment, we also considered a number of their individual statements (open-end comments) regarding the interface products tested. Thereby, we specifically focus on cognitive problems in navigation.

i) Organizational layout: In our experiment with the participants, we were interested to know if the existence of a clear organizational layout of the interface was important to them. Their comments suggest that a well-organized layout may effectively guide the users in task manipulation and facilitate, thus, interactions between users and control devices.

ii) Shortcuts and repetition: A scene function provides the possibility to define multiple set points for multiple environmental parameters simultaneously. Thus, proper combination of such set points can be pre-programmed in conjunction with typical use scenarios. Scene functions thus offer participants shortcuts to simplify the execution of repetitive (and often time consuming, dull and error prone) tasks.

iii) Clarity of terms and icons: The labels (i.e. iconic buttons, tags, and text items) play an important role in how navigation proceeds. Thus, such labels should be plainly worded and clearly visualized. They must be simple and easy to understand. Otherwise, as certain comments imply, frustration may result particularly in the earlier phases of interface usage, as the users are not fully familiar with the product.

iv) Navigation memory: By their nature, conventional physical devices for communication appear to provide more simple options for the users to operate systems due to their limited (one-level) depth. The other products require, in contrast, moving from one "page" (level) to the other. Many participants felt that some products require too many jumps in navigation, whereby each screen substantially differed from the other. This may make learning and retaining of the required manipulation sequence difficult. A smaller number of transitions amongst screens seem to be preferred by most participants. The participants' comments imply that limited functional coverage and navigational ease often correlate. This suggests that an overall high functional coverage can impose a larger cognitive burden especially on new users. Interface design must thus pay particular attention to supporting cognitively friendly use patterns while offering richness in manipulation options.

3. ONGOING DEVELOPMENT

Previous research in the analysis of product comparison and interviews highlighted a number of basic principles and expectations regarding the design of desirable user interface products for sentient environments. Starting from these results, we will make an attempt in this section to further articulate user requirements toward actual design of such interface products.

3.1 Test bed Infrastructure

A test bed infrastructure is set up to simulate office-based sentient environments where a set of services are deployed and seamlessly integrated. The test bed is installed for "self-actualizing sentient buildings" research project (Chien and Mahdavi, 2008b) as a 1:1 mockup of two office rooms located in our Building Automation Laboratory in Vienna Technical University, Department of Building Physics and Building Ecology. This test bed infrastructure involves a system controller associated with a variety of network protocols (based on the Internet, LAN, and LON Network), devices, and services (see FIG. 1). In order to create a realistic office environment, this existing light-weight test bed is equipped with systems for heating, lighting, ventilation, shading, and de-/humidification. These devices include: *i)* HVAC system; *ii)* Radiator; *iii)* Electrical windows; *iv)* Electrical shading; *v)* Ambient lighting system (2 luminaires and 1 task spot for each room); *vi)* De-/Humidification system (see FIG. 2).

Given the background of this test bed infrastructure, a user interface model for future developments in sentient building technologies is currently under development as described in the following sections.

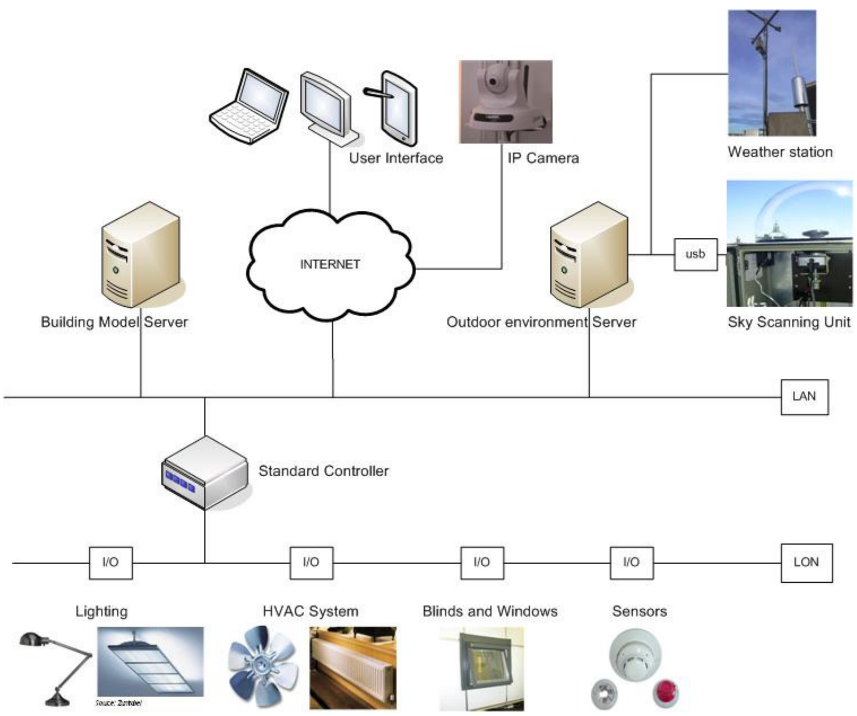

FIG. 1: Test bed infrastructure

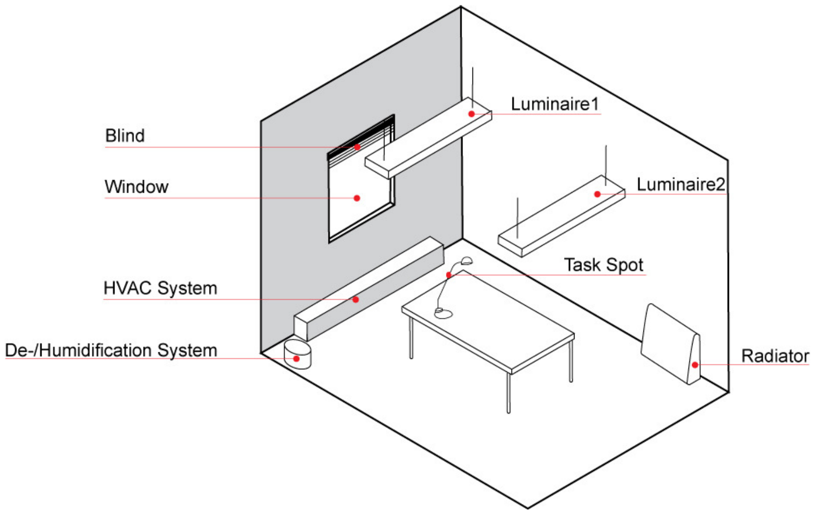

FIG. 2: Schematic representation of the equipped devices in a test room (Lab 1)

3.2 Defining Posture

Posture is a way of talking about how much attention a user will devote to interacting with a product, and how the product's behaviors respond to the kind of attention a user will be devoting to it (Cooper et al., 2007). According to our previous research (Mahdavi, 2007, Chien and Mahdavi, 2008a), we concluded that the essential feature of the indoor climate control user interface is its short-term usage patterns. This kind of user interfaces with a transient posture must offer very short-term manipulation possibilities. They must efficiently offer important and frequently needed functionalities and the appropriate accompanying requisite information, and then quickly step to background, letting the occupants continue their normal activities (such as working on paper-based and screen-based tasks in offices).

3.3 User models and expectations

User models are synthesized from our previous data obtained from 40 interviewees in order to better clarify the design implications of different user requirements. These models are composite prototypes, by assembling related user patterns across individuals with similar characters. Thereby, we specifically considered two user models (primary model with its extension and secondary model) as our human target.

3.3.1 Primary model and extensions

In this type of model, the users always have a great amount of workloads (e.g. paper/screen tasks) that monopolize their attention for long periods of time while working. They tend to have certain organizational and time-saving techniques to structure the course of their working day. Despite the factual importance of the interface for the users' daily activities and conditions, users of a primary interface model are willing only to dedicate a very limited time-budget to learn it. Rather than attempting to load extensive functionalities into a primary user interface product, it must be designed such that it is perceived as being simple and easy to use. The users in a primary user interface model scenario, expects the least possible time (minimum navigation) to complete a certain control action and to immediately return to their office activities. Thus, the most frequently needed control options and corresponding required information must be identified and offered in a primary user interface model. In this case, additional options/information may be expected to disturb the users. Primary model may be further augmented in terms of an extended version with additional (yet non-extensive) options and information features (e.g. indoor/outdoor environment conditions).

3.3.2 Secondary model

The human targets of the secondary interface models might have as much as a working load as those of the primary interface models, but they value more a sense of control over their environment and the associated devices and tools. Thus, they are more willing to allocate time and patience to manipulate their control user interfaces and to deal with rather complicated settings and details. Likewise, they would be open to and interested in acquiring more information about their environmental conditions and means and ways of controlling their workplaces. As a result, a secondary user interface model needs to be more detailed and versatile. It must provide the users with much more options and information than primary models, as the secondary model users can be expected to master all kinds of control options, assign/modify their customized scenes, and acquire multiple categories of indoor/outdoor information.

3.4 Requirement profiles

We generated a set of requirement profiles arranged in accordance with the previously described dimensions, namely information types (see Table 1), control options (see Table 2) and hardware (see Table 3). In this context, a desirable user interface product may serve both user models mentioned above. Moreover, it can embody the integration of the functionalities associated with these two user groups.

TABLE 1: The requirements for the information types dimension.

CODE of classification			User Types		
			Primary		Secondary
			B*	E**	
Info Types	General Info	Date/ Time	•	•	•
	Indoor Info	Temperature	•	•	•
		Humidity	—	•	•
		Air Velocity	—	—	•
		Carbon Dioxide	—	—	•
		Illumination	—	•	•
	Outdoor Info	General Weather conditions	•	•	•
		Temperature	•	•	•
		Humidity	—	•	•
		Wind Speed	—	—	•
		Wind Direction	—	—	•
		Global Irradiance	—	—	•
	Device Status	HVAC System	•	•	•
		De-/Humidification System	—	•	•
		Windows	—	—	•
		Blinds	—	—	•
		Ambient Lighting System	—	•	•
		Task Lighting	—	—	•

(* Basic; ** Extended)

TABLE 2: The requirements for the Control Options dimension.

CODE of classification			User Types		
			Primary		Secondary
			B*	E**	
Control Options/ Extensions	Control via device	HVAC System	•	•	•
		De-/Humidification System	—	•	•
		Windows	•	•	•
		Blinds	•	•	•
		Ambient Lighting System	•	•	•
		Task Lighting	•	•	•
	Control via Parameters	Air Movement (path)	—	—	•
		Air Change Rate (h^{-1})	—	—	•
		Temperature (℃ or ℉)	•	•	•
		Ambient Illuminance (lx or %)	•	•	•
		Task Illuminance (lx or %)	•	•	•
		Humidity (%)	—	•	•
	Control via perceptual values	Warm/Cool	•	•	•
		Brighten/Dim	•	•	•
		Humidify/Dry	—	•	•
		Ventilate (Air Flow)	—	•	•
	Control via scenes	Entering	•	•	•
		Leaving	•	•	•
		Screen Task	•	•	•
		Paper Task	—	—	•
		Meeting	—	•	•
		Presentation	—	—	•
		Break	—	—	•
		Energy Saving	—	•	•
		Cleaning	—	—	•
		All lights on	—	—	•
		All lights off	—	—	•
		Lights default	—	—	•
		User-based Scenes	—	•	•
	Control via Schedule		—	•	•
	Control via micro-zoning		—	—	•

(* Basic; ** Extended)

TABLE 3: The requirements for the hardware dimension.

Aspect	Requirement
Input	Users may input their data and commands via mouse, keyboard and touch panel (12 inches plus recommended for secondary level)
Output	Users are provided with data via LCD screen and Touch panel (12 inches plus recommended for secondary level)
Mobility	Primary level could be realized both spatially fixed and mobile interfaces. Secondary level should be rather realized in desktop terminals for long-term detailed manipulation
Network function	Users may access all resolution levels (basic, extended, secondary) via internet
Re-configurability	All interface types must be technologically upgradable without replacing the hardware

3.5 Illustrative scenarios

To better portray the interface, certain illustrative scenarios with manipulation steps are described and demonstrate how the occupant adjust the indoor climate conditions as follows.

Location: *One office of an electrical company*

Persona: *Alice (32), who is a mother of three-kids, works in this company as a manager. She likes everything to be straightforward and easy to handle.*

Background: *It used to be necessary to switch and adjust various environmental control devices separately in this modern office. These routine manipulations had to be made repeatedly every day. These tasks were too time-consuming and annoying for Alice. She needed to stop her work and adjust the devices. Sometimes she was too busy to do so and worked in an uncomfortable environment unconsciously. Now this user interface model may help Alice to conveniently bring about desirable indoor conditions in her office.*

8:30 am.

Start of a working day

It is Friday morning, 8:30 am. Alice enters her office and announces her arrival by logging in this interface via the browser. She feels the indoor air is already "fresh" when she comes in. As a matter of fact, at 8:00 am the system has activated the "standby" mode, which she set up the previous day. She then presses the "screen task" button, which enables the screen scene. This scene illuminates the office at the specified level, to enhance her screen task.

2:00pm.

Midstream of the day

Alice is working on a paper task and trying to finish it before leaving. However, her room is facing the afternoon sun resulting in excessive illumination and glare. Thus, she calls up "control via perceptual values" in "Home" control groups and chooses "brightness" option. A control box is triggered on the main control zone of the interface screen. She presses "dim" button twice. In response, the room's model-based device control system (Mahdavi 2008) *searches for the optimum combination of the positions of the related devices to bring about Alice's desired conditions. Subsequently, the positions of the blinds as well as the light output of the two luminaires and the task in the office are changed. Meanwhile, the animated icon in the control box becomes dim by 2 levels, providing confirmative feedback regarding brightness change. This control feature is very useful because the system relieves the user from parts of the control reasoning burden and does what it is good at.*

Once the control task is accomplished, she clicks somewhere else to terminate the control box and the screen reverts to a default view of "Home" control group. Now she could work on her paper work comfortably again.

4:30pm

Early evening

As the day progresses, Alice calls up the "information booth" on the right-hand of the screen to check the outdoor weather information. It shows that it is going to rain. She then activates the "window" control box in the "Devices" group. She adjusts the window state from open to close via the slider and clicks somewhere else to end the control box. After a while, she checks her watch. She is aware that it is about time to leave. It occurs to her that she should set up a "weekend" scene so that the applicable settings are stored and used in future as well. She triggers the shortcut button on the screen displaying a scene editing screen, which shows the details concerning device options, date/time, and a supervisory icon that guides her through the configuration process. Once she finishes the setting, she clicks the save button and a screen pops up to let her enter the name for this scene ("weekend") and assign a suitable icon for it. The "weekend" scene is now available on the scene zone. She clicks this new "weekend" button and logs out the interface. After a while, she leaves the office and devices shift to the non-occupancy mode. Alice can further manipulate control settings and/or check the state of her office via internet at any time during her absence.

3.6 Prototyping cycles

In order to transform the above-mentioned requirements to concrete designs, initial prototyping (i.e. generation of user interface mock-ups) is being currently conducted following a scenario-based design and focus group method (Carroll, 1995). These requirements together with illustrative scenarios offer an underlying concept model for the implementation of the detailed design of the interface model, including framework, screens, icons, and navigation plans. The design approach follows a "design-evaluation-redesign" process (Figure 3) involving users (see Boehm, 2007, Sharp et al., 2007). In the early stage of development, three design concepts were proposed and discussed interactively via sketches and paper mockups. As the design progress became more detailed and concrete, by comparing the features and deficiencies, one of these design concepts was selected and further developed for an interactive version prototyping and construction. To provide an illustrative example of the initial results, Figure 3 and 4 show a set of screenshots of a user interface prototype for the test cells of our Building Automation Laboratory. The layout design and navigation structure are being developed based on the above mentioned requirement profiles and design principles. Through the whole process, focus groups and interviews were conducted to polish the details of interface design in the methods of scenarios, picture-driven animation using powerpoint, as well as interactive mockup manipulation.

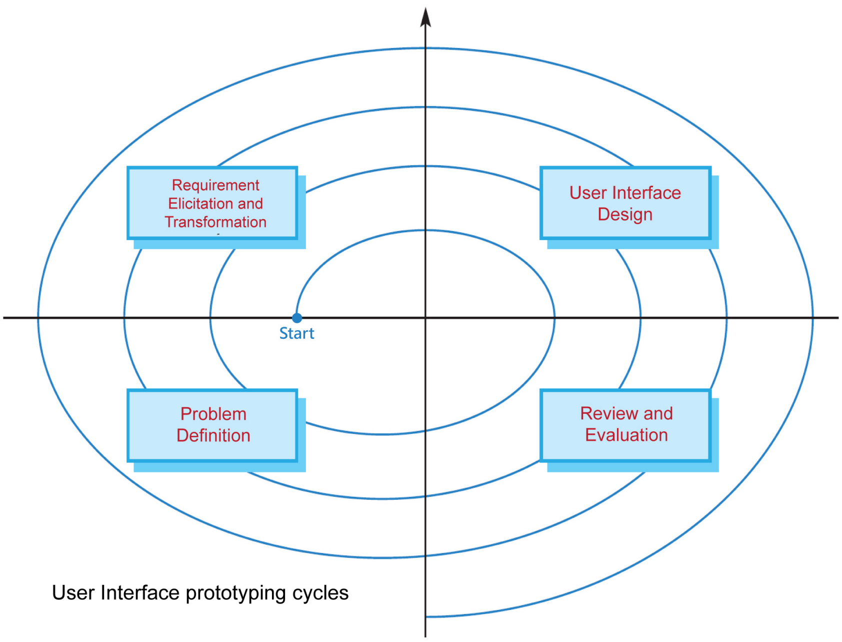

FIG. 3: User interface prototyping cycles (based on Boehm 2007).

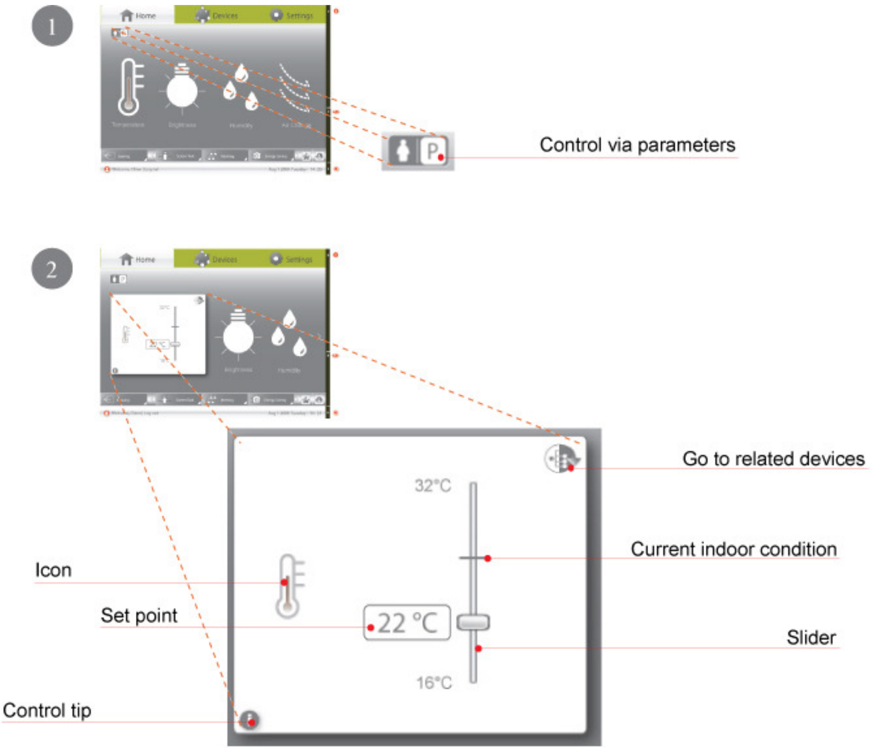

FIG. 4: Sample screenshot of "control via parameters".

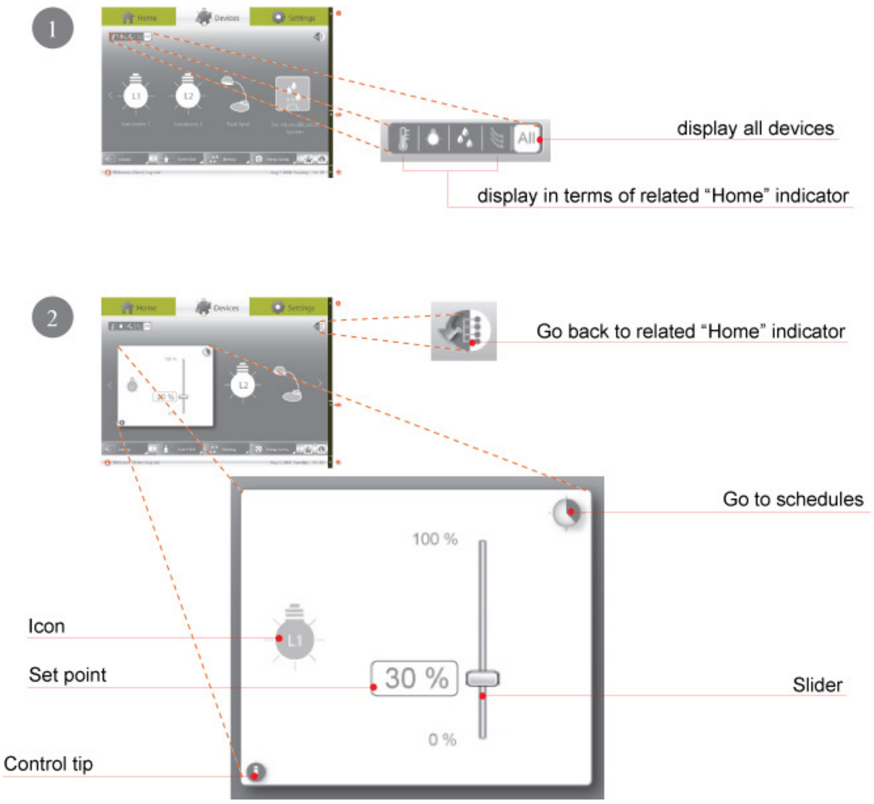

FIG. 5: Sample screenshot of "control via devices".

4. CONCLUSION

While the present paper does not offer a detailed final design for desirable user interfaces for future sentient environments, the user requirements and illustrative scenarios for developing such interfaces have been formulated. The user requirements embody the user models and a set of dimensions for product specification involving information types, control options, and hardware. Moreover, Initial prototyping cycles are being conducted leading to preliminary user interface mock-ups. These early prototypes will be tested and refined toward mature future interface products toward achieving desirable indoor climate conditions while meeting the objectives of a sustainable building operation regime.

The methodologies and design described in this paper offer the occupants and the user interface developers certain structured perspectives to view and manipulate the building control system. However, future research must more explicitly address the circumstance, that users' expectations from building control systems may differ from location to location (climate) and from building type to building type (e.g., office versus residential buildings). User interactions with building control systems must be carefully re-examined in view of ethnography, building typology, and contextual (geographic, climatic) circumstances. Furthermore, studies on self-adaptive user interfaces for the control systems may contribute to enhancing living and working conditions for building occupants.

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