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Abstract: This proposal aims at challenging the existing design paradigm of residential building architecture with insights from pervasive computing, robotics, human-computer interaction and cognitive ergonomics. ICT and architecture will be holistically integrated in order to realize a radical advancement leading to metamorphic houses.

Supported by ICT, domestic environments will self-adapt to the ongoing activities of inhabitants, to increase the comfort of living and optimize the use of space and energy. The same physical space will be transformed for different uses, giving inhabitants the illusion of living in a bigger, more adapted and more comfortable place. The traditional tradeoff between comfort and energy conservation will also be revisited, thanks to an optimal exploitation of natural light, heat and ventilation.

The realization of the targeted breakthrough will be achieved through cross-fertilization between involved disciplines and by the support of a panel of final users, architects and building engineers in the design, development and evaluation phases. COMETAE will introduce a novel approach to smart spaces research, where the space is itself an actuator of the system. Indoor environment, space and energy use will be optimized with respect to environmental factors, occupants' activities and life cycle, by orchestrating adaptive robotic building components, while ensuring occupants' safety. New coupling between inhabitants and their environment will be enabled by combining human-computer interaction and space reconfiguration, considering beauty of interaction and multi-user scenarios.

This proposal opens the way towards a radically new use of ICT, needed to address future limitations of space and energy in the domestic environment, imposed by the ongoing and future evolutions of technology, environmental questions and socio-demographic factors.

Key-words: Metamorphic House; Domestic Space Reconfiguration; Comfort; Space Efficiency; Energy Efficiency; Pervasive Computing; Human-Computer Interaction; Cognitive Ergonomics; Architectural Ergonomics

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1 Targeted breakthrough and its relevance towards a long-term vision

1.1 Breakthrough

This proposal aims at challenging the existing design paradigm of residential building architecture with insights from pervasive computing, robotics, human-computer interaction and cognitive ergonomics. ICT and architecture will be holistically integrated in order to realize the concept of *metamorphic house*.

Supported by ICT and adaptive intelligent building components, domestic environments will self-adapt to the ongoing activities of inhabitants, to increase the comfort of living and optimize the use of space and energy. The same physical space will be transformed for different uses, giving inhabitants the illusion of living in a bigger, more adapted and more comfortable place. The traditional tradeoff between comfort and energy conservation will also be revisited, thanks to an optimal exploitation of natural light, heat and ventilation.

1.2 Long-term vision that motivates this breakthrough

We envision a future characterized by socio-demographic evolutions (*e.g.*, overpopulation, growth of life expectancy, development of house-sharing, longer stay of children in parents' homes, development of teleworking) and environmental questions (namely, resource scarcity). This will result, among others, in reduced space and energy availability in future homes.

The use of space and energy will have to be optimized: the same living space will have to accommodate a large number of activities with the challenge of preserving the comfort of its occupants and minimizing energy consumption. In this vision, the environment changes in accordance to domestic activity, just like does the setting of a theater, following the plot of a play.

1.3 Relevance of the breakthrough towards the long-term vision

A paradigm shift in current design and realization of domestic environments is needed. This requires integrating pervasive computing, robotics, human-computer interaction, cognitive ergonomics, building engineering and indoor environment optimization in a holistic approach. Every discipline will have to learn from the others in order to reach the common goal of designing and realizing space- and energy-efficient metamorphic houses.

The proposed breakthrough will lead to the design of domestic environments that self-adapt their shape, purpose and properties so as to optimize the use of space and energy, while maximizing the comfort of inhabitants and adapting to their context and activities.

1.4 Concrete objectives that constitute the proof-of-concept of such a breakthrough

The realization of the breakthrough can be proved by obtaining three main concrete objectives:

1.4.1 Objective 1

Introducing a novel approach to *smart spaces* research, where the space is itself variable and becomes an actuator of the system. Space boundaries become volatile, as they can be added, modified or removed at wish. The challenges associated to this objective are illustrated below.

Challenge 1.1. Rethinking existing pervasive computing models, in which the domestic environment is seen as a static set of architectural structures like rooms, walls and doors, with predefined locations, purposes and characteristics, which contribute to the determination of the context of devices and users. The use of a spatial map as "background" of context-aware applications is not possible anymore, as the spatial map itself changes, depending on the actions of the system. This asks for designing a novel context model that abstracts from the physical world.

Challenge 1.2. The context and location of devices and users change when the space is modified and reused, and so does the information and the interpretation of the information that they might provide or be interested in. For instance, imagine a sensor located in a corridor between two rooms, used to detect people passing. If the door between the rooms is replaced by a wall, obstructing the way, the sensor will be irrelevant in such conditions. Integrating the new dimensions of architectural reconfiguration asks for rethinking the concepts, properties and models behind the fundamental notion of location and questioning the relation between those abstract models and the cognitive models of the inhabitants.

1.4.2 Objective 2

Designing a system that realizes a metamorphosis of a living place by orchestrating adaptive intelligent building components, so as to optimize visual and thermal comfort, air quality, space and energy use with respect to environmental factors, occupants' activities and life cycle. Activity is assisted by proposing reconfigurations that facilitate it. For instance, a wall moves to merge two previously separate rooms, so as to simplify domestic collaboration and coordination. The associated challenges are illustrated below.

Challenge 2.1. Designing *information fusion*, *context reasoning* and *decision making* techniques that use relevant information sensed from the environment to select an optimal reconfiguration of the living place. Inputs from building engineering and indoor-environment optimization disciplines will help identifying the relevant criteria for this challenge related to artificial intelligence.

Challenge 2.2. Designing reconfiguration strategies, realized by distributed robots that share the same place with humans, ensuring the safety of occupants during and after the reconfiguration. Highly reliable robotic technologies are needed.

1.4.3 Objective 3

Rethinking the modalities and requirements of human-computer interaction (HCI) design when applied to metamorphic domestic environments. The challenges associated to this objective are illustrated below.

Challenge 3.1. Designing a new user experience combining space reconfiguration and HCI, *i.e.*, designing a new coupling between the inhabitants and their environment, integrating common HCI criteria (utility, usability, acceptability and appropriation) to enable intelligible, controllable and safe metamorphoses.

Challenge 3.2. Handling multi-user scenarios, where different actions of the system may be required.

Challenge 3.3. Widen the user experience criteria by integrating aesthetics in human-computer interaction. Functionality and ease of use are a must in domestic environments. However, beauty is also particularly important in a house. Reconciling beauty and usability is a challenge in this context.

A small-scale experimentation platform (*e.g.*, a 30-square-meter apartment) will be designed and implemented following the proposed holistic approach. The resulting platform will allow to apply the novel trans-disciplinary approach to a concrete and simple case-study and thus prove its effectiveness. The platform will also allow to realize an early and continuous evaluation of the appropriability of the resulting system for final users.

The platform will capture the context of inhabitants and of the house and choose the metamorphosis that optimizes visual and thermal comfort, air quality and energy use with respect to users' ongoing activities and environmental factors. The metamorphosis of the house will be realized by orchestrating intelligent adaptive building materials.

2 Novelty and foundational character

2.1 Novelty of the proposal - Challenging current thinking

This proposal challenges the common assumptions of building design with insights from pervasive computing, robotics, human-computer interaction and cognitive ergonomics, using a holistic approach.

Nowadays, the problem of space efficiency is commonly addressed by architecture using special furniture (e.g., wall beds), either manually or mechanically operated. The reconfiguration is sometimes done at the level of walls and spaces, with reconfigurable and modular houses appearing in the commercial landscape. These solutions share the assumption that people will actively participate in the process of reconfiguring the house, with physical actions or at least explicit commands. The lack of self-adaptation of the environment negatively impacts the living comfort, as the manual intervention interrupts and interferes with domestic activity.

On the research side, recent initiatives known as *interactive architecture* and *architectural robotics* have seen joint efforts of architects and computer scientists to investigate the augmentation of architectural structures with simple sensing and reacting capabilities. These works did not shift the existing architectural approach by realizing domestic environments that self-adapt to inhabitant activities and life cycle, but they rather realized materials and structures that react to simple external stimuli or explicit interaction by modifying their color, shape or other properties of their aspect.

2.2 What is the scientific foundation that you aim to develop?

The proposed breakthrough will lead to a radical advancement in the context of building design by holistically combining pervasive computing, robotics, human-computer interaction, cognitive ergonomics, building engineering and indoor environment optimization.

The involved disciplines and final users will benefit from this combination of disciplines, as it happened in the past for, *e.g.*, the medical imaging domain. In that case, both computer science and medicine have evolved thanks to the combination of the two disciplines and the result is an improvement in human health. In the case of COMETAE, all the disciplines will benefit from the trans-disciplinary approach and the result will tackle the societal challenges previously described, namely, the space and energy scarcity in future domestic environments.

The development of involved disciplines will be boosted by the cross-fertilization:

- The new generations of architects will benefit from the possibilities opened by the holistic approach, being enabled to design metamorphic living places.
- Pervasive computing will develop new expertise in models and tools for smart spaces, by considering the requirements and constraints of metamorphic architecture and indoor environment optimization. For instance, the topology and configurations of the living place will have to be modeled starting from building blueprints provided by architects.
- The scope of indoor environment optimization will reach beyond physical comfort, integrating parameters provided by activity recognition and cognitive ergonomics. For instance, current activity of occupants will be mapped to indoor conditions to realize.
- Artificial intelligence will develop new algorithms that allow to optimize places' configuration and indoor environment by taking into account constraints and requirements in terms of safety, occupants' comfort and natural light and heat exploitation. For instance, the robotics specialists will define together with human-computer interaction experts the most suitable modalities for ensuring safe and intelligible reconfigurations of the living place.
- Cognitive ergonomics will develop activity models relative to the appropriation of the (reconfiguring) space, in relation with the in-home systems and help other disciplines to take into account the users' needs.
- Human-computer interaction will have to develop interaction modalities that support space reconfigurations and indoor environment optimizations that are suitable, safe and aesthetically pleasant from the occupants' point of view, as well as develop models for the design of HCI in metamorphic houses. Namely, HCI specialists will design interaction modalities that allow users to select a suitable and safe adaptation between those that cognitive ergonomists suggest as the most suitable ones in a given situation, from the user point of view.

Anthropological aspects will be considered by analyzing user requirements with a theoretical framework provided by cognitive ergonomics, relying on a background of cognitive anthropology with phenomenological and enactive approaches. Existing literature in philosophy and psychology investigated the ethical and psychological aspects of the scenarios opened by interactive architecture. Those considerations will be taken into account as acceptability and usability constraints. Heterogeneous needs and preferences of users, depending on socio-cultural aspects and age, will be taken into account by iteratively evaluating the system on users of different ages and cultures.

3 S/T methodology

3.1 Outline of the scientific and technological approach and methodology

The realization of the targeted breakthrough will be achieved through a mutual understanding of challenges, possibilities, limitations and expectations of each discipline. Panels of final users, architects and building engineers will support the design, development and evaluation phases following a spiral life cycle. Such an approach is iterative and each iteration consists of three phases: *(i)* collecting initial requirements based on analysis of user characteristics, needs and domestic activity in a framework provided by cognitive ergonomics; *(ii)* rapidly designing and developing an experimentation platform based on new research ideas; *(iii)* evaluating the results on users in realistic situations. New requirements are provided by the evaluation results and are used in the next iteration to design, develop and evaluate a new platform.

A user-centered approach, placing the inhabitants at the center of the design process, will be adopted. In such an approach, the design is driven by analysis of user requirements, goals and needs, focusing on cognitive factors that come into play during users' interactions with their house. Analysis of existing domestic activity and simulations of plausible scenarios will be used to identify user needs and expectations. System requirements will be obtained with the described iterative approach from user requirements and from knowledge of technological constraints. Describing future situation scenarios will help both users and technical experts building a mental model of how the system will work, thus allowing validation and further requirement collection. Usability and appropriability will be iteratively tested, placing users into situation by implementing realistic scenarios.

In the design process, special attention will be given to abstracting from the limitations brought by today's technologies and materials. The goal of the project being that of establishing a new trans-disciplinary collaboration towards a long-term vision, the focus will be on identifying and tackling the barriers between disciplines, so as to enable the cross-fertilization. However, experimentations on a real small-scale platform, including field-tests on final users, will prove the effectiveness of the novel approach when applied on existing technologies and materials.

The objectives enumerated in Section 1.1 will be tackled as explained below.

3.1.1 S/T methodology to reach objective 1 and the associated challenges (cf. §1.4.1)

Challenge 1.1. In order to enable the metamorphosis of the home, we will establish methods for maintenance and adaptation of a novel context model, which can capture all interesting aspects of the metamorphic home and is used as a basis for all reconfigurations and adaptations. The model will change dynamically as the smart home applications evolve. This requires the model to be linked to the basic design decisions of architects, to allow the integration of models provided by new materials, to allow the definition of new applications as well as to provide an abstraction to the physical IT-infrastructure consisting of physical sensors and actuators.

Challenge 1.2. As space is reconfigured, the same sensors assume different roles and the interpretation of their values by applications changes. In order to abstract away from this aspect and provide applications with a consistent view on phenomena and locations in a smart space, we will design a novel virtual-sensor abstraction. The virtual sensor abstraction will hide away details such as physical sensor location and provide instead semantically tagged information that can be queried by applications.

3.1.2 S/T methodology to reach objective 2 and the associated challenges (cf. §1.4.2)

Challenge 2.1. Indoor environment and energy use optimization will be realized by optimally adapting natural and artificial light, heat and ventilation to occupants' activities. Comfort parameters (*e.g.*, indoor temperature, air velocity and chemical composition, relative humidity, daylighting levels, sun penetration) will be obtained through environmental and wearable sensors (*e.g.*, augmented eyeglasses sensing light level). Occupants' activities and localization will be inferred using environmental sensors (*e.g.*, sound, motion and CO_2 sensors), video and infrared cameras, as well as wearable sensors (*e.g.*, accelerometers and gyroscopes) and augmented household appliances. Sensed data will be processed using information fusion techniques (*e.g.*, *Bayesian networks*, *belief functions theory*) and optimal indoor environment will be determined. Interaction with users will allow overruling the system (cf. Challenge 3.1). Actuators will include adaptive windows, with fine control of natural ventilation, daylight and solar gains as well as artificial lighting, heating and mechanical ventilation systems. Actuators will be distributed in the space to provide comfort conditions at the occupant(s) location.

Challenge 2.2. When the living place is empty, optimal reconfigurations will be realized automatically using adaptive walls and furniture, able to change position, shape, *etc.* In presence of occupants, their safety will be guaranteed by predicting the effects of reconfigurations on both physical safety and indoor air quality. Physical safety will be ensured by only realizing reconfigurations that respect some constraints (*e.g.*, on the minimum required space per occupant). If the execution of a reconfiguration fails (*e.g.*, due to physical obstacles), the living place will be brought back to a safe state. Interaction with users will also be used to realize safe reconfigurations (cf. Challenge 3.1).

3.1.3 S/T methodology to reach objective 3 and the associated challenges (cf. §1.4.3)

Challenge 3.1. In order to design new intelligible situations relying on space reconfiguration and interaction, novel interaction modalities will be developed. These will use multimodal interfaces to understand the situation, share and negotiate the desired changes, so as to make the metamorphoses understandable, appropriable and controllable by users. An active safety system will be developed in collaboration with artificial intelligence specialists. To this end, the interaction will be used to inform users about ongoing metamorphoses, to adaptively control them, to guarantee occupants' safety and to handle situations where both the occupants and the system concurrently modify the house.

Challenge 3.2. Where the activities and needs of multiple occupants may ask for different actions, multimodal interaction will leverage distributed interfaces (*e.g.*, speech and gesture recognition combined with distributed displays) to allow negotiation between users in order to find a consensus on the metamorphosis to realize and to share a common awareness of the changing situation.

Challenge 3.3. In order to reconcile usability and aesthetics of the targeted domestic system, beauty will be integrated as a requirement for human-computer interaction. Joint work with architects will identify the best strategies for designing interaction and interfaces that go well in a house.

3.2 Risks of failure and how to address these risks

Risk 1. Guaranteeing the acceptability and appropriation of the final system is a critical task, because the goal of our groundbreaking approach is to design future households. In particular, when dynamic architectural structures like moving walls and adaptive windows are involved, the intimacy and safety of inhabitants can be dramatically affected. Furthermore, sensing technologies and advanced interfaces can collect and store sensitive information concerning the users.

Associated actions This risk will be addressed by: *(i)* realizing field-tests and user studies throughout the design process; *(ii)* designing and enforcing minimum quality constraints and *(iii)* adopting a modular architecture as a design philosophy. The latter choice will guarantee the possibility of designing and customizing the system to user preferences and constraints. We will design and develop a framework that allows inhabitants to choose and control the tradeoff between level of privacy and functionalities offered by the system.

Risk 2. Experimentations and user tests may be affected by the maturity of involved technologies.

Associated actions This risk will be minimized by selecting materials and technologies that have already shown to be effective in previous research and tests. The new technologies developed during the project will be extensively tested or otherwise used to implement non-critical features of the experimentation platform.

3.3 What would constitute success?

Success would be the design and implementation of a small-scale experimentation platform that is reconfigured by the pervasive system following and fitting in with inhabitant activity, optimizing the use of space, natural light and heat. Field-tests, reproducing real-world situations where users live in the metamorphic house, will measure:

- Energy saving, comparing the energy consumption of the house when the actuators are managed by the system and when they are explicitly operated by users. This will quantitatively evaluate the energy saved by the *smart* behavior obtained through ICT.
- Acceptability and appropriation, collecting quantitative data related to measurable usability and user satisfaction, through interviews and questionnaires.

The safety of the platform will also be evaluated by architects and building engineers.

3.4 Lessons learned from a possible failure

A failure would set the agenda for future work towards the realization of the long term vision, especially in terms of advances in architecture, augmented building materials, human-computer interaction, models of human activity, pervasive computing and their integration.

3.5 Suitability of the approach to the multi-disciplinary nature of the breakthrough

The proposed methodology allows the involved heterogeneous disciplines to mutually understand each other's challenges, possibilities and limitations. The iterative refinement and reorientation of the design and development, based on mutual feedback between the different disciplines and stakeholders, allows this mutual understanding. The approach also guarantees that the constraints and possibilities of every discipline, as well as the barriers obstructing their collaboration, are taken into account since the beginning of the design process.