Hybrid Connected Spaces: Mediating User Activities in Physical and Digital Space

Carla Farina, Sotirios D. Kotsopoulos(✉), and Federico Casalegno

Mobile Experience Lab, Massachusetts Institute of Technology,
20 Ames Street, Cambridge, MA 02139, USA
skots@mit.edu

Abstract. The ever connected, almost symbiotic bond between physical and digital domain gives birth to new contexts of use and behavior. Designing a building, conceiving its interior or exterior arrangement, is no longer an issue that can be resolved solely in the physical domain. It calls for the integration of a digital, immaterial dimension introducing new variables and expertise. The fields of Human Computer Interaction, Human Building Interaction and Architecture, designate new environments that appear to be a middle ground between the physical and digital domain. In these new Hybrid Spaces the traditional utilitarian features of space are different, the users act differently, and have reformed expectations. In this paper we question if space can guide, inform, and educate the users to improve usability. To answer this question two projects carried out by the Mobile Experience Lab are presented: the Atlas Service Center at the Massachusetts Institute of Technology, and the Connected Sustainable Home in Trento, north Italy. Motivation for this research was our interest in reconsidering the nature of everyday work and live environments and activities in a way that integrates the latest technological advancements. Hybrid Connected Spaces represent the potential of an original type of symbiotic physical and digital domain that enables new enactments to take place.

Keywords: Interactive architecture · Media architecture
Human-building interaction · User-center design

1 Introduction

The integration of the physical and the digital domain gives birth to a new type of architectural space, the Hybrid Connected Space, which operates in active and reactive modes. This article presents the design and development of two examples of hybrid space that offer different levels of interaction in two different fields. More specifically we present a space for public service, the Atlas Service Center at the Massachusetts Institute of Technology (Fig. 1a), and a domestic living space, the Connected Sustainable Home in Trento, Italy (Fig. 1b).

This presentation provides an overview of the design process of Hybrid Spaces, and discusses the adopted means and ends. More importantly it explains how design, which has always been the dominion of physical and material expertise, is now driven to

N. Streitz and S. Konomi (Eds.): DAPI 2018, LNCS 10921, pp. 35–55, 2018.
https://doi.org/10.1007/978-3-319-91125-0_3

Fig. 1. (a) The vision of the MIT Atlas Service Center. (b) The connected sustainable home, in Trento, north Italy. Exterior and interior views

integrate digital features that demand different skills. The characterization “hybrid” is given because the presented projects involve fusion of physical and digital methods. Hybrid Spaces are distinguished by their enhanced potential to be interactive, connected, and able to meet the user expectations in the digital age.

Motivation for the two projects was our interest in reconsidering the nature of everyday spatial contexts, such like the services and domestic environment, in a way that seamlessly integrates the technological advancements of today. The presented examples are part of a discourse that signifies cross-disciplinary collaboration between Human Computer Interaction, Human Building Interaction and Architecture. The adopted approach is to design new spatial experiences in response to the demands of the new emerging contexts of digital media and technological phenomena.

2 Background

In the era of the digital communication, referred also as Collaborative Social Media Age [1], the evolution of live-work environments is rapid. A virtual overlay generates a new dimension that is typically referred as the 4D-space [2]. The introduction of intangible media augments the experience of the users that act in the physical space. Both private and public environments become increasingly sensitive to the undertakings of wider contexts of individuals and communities. This development is triggered by the exponential growth of Information and Communication Technologies (ICT) and the demand for communication and sharing at all layers of private and public life. Everyday actions change as they are carried out via constantly evolving devices, which have become many in number and indispensable in importance, so that they are comparable to "digital prostheses". These prosthesis devices enable individuals to connect to the virtual domain, to enhance their actions, and to accentuate their social presence. Through connectivity individuals accomplish many tasks: from the exchange of information, to the management of household items and bank accounts, to business meetings, and more.

Tasks that can be accomplished through prosthesis devices, such as smartphones, computers, webcams do no longer require predefined physical environments with specific formal or material identity.

Accordingly, there is no longer need of a traditionally designed physical space to perform such tasks. Human activity becomes "de-contextualized" from physical place and the physical space is losing its functional specificity [3]. Hence, buildings no longer determine a place for a designated activity in the traditional sense, i.e. living (in the house), working (in the office), selling (in the store), and so on.

Buildings are also transformed by the integration of new technologies into their physical components. Vertical and horizontal surfaces, fixtures and building equipment, acquire interactive capabilities through the integration of electronics, such as wireless sensors, actuators, dynamic automation with embedded microprocessors, smart materials etc. [4]. Buildings obtain new aesthetic appearance and performance through man-to-machine, or machine-to-machine communication. They have the capacity to communicate what they are, where they are, what happens in them, and how to achieve the optimal usability, or energy consumption overtime.

3 The Design Challenge - Hybrid Interactive Space

Physical architecture has evolved in three stages: First, a built structure was characterized by the static presence and passive performance of its physical mass, and its sole objective was to cover and protect; Second, a built structure acquired the capacity to react to user's actions: the user could trigger changes by mechanical or electronic means, such as lighting, sound, or temperature change; Third, ICT technologies, enabled the creation of a reactive performance that is able to track human behavior, predict it, and even suggest it. The increased potential for interaction instigated changes in the form of buildings, by introducing new elements, processes, and experiences [3].

The process to create physical places where the physical and digital domains meet is a mediation procedure that establishes the presence of the user within the virtual dimension. Designers redefine their role as mediators of the virtual dimension, and express it in a language of physical form [5]. However, built space does not simply serve as a container of new technologies. It becomes an expressive and functional tool enhancing the user activities, and a human-scale interface with multiple purposes. All its parts contribute to the interactions of the user. The materials, the lighting systems, the built components, the windows, the walls and floors, the interior fixtures, the furniture etc., implanted with smart technologies, give birth to hybrid architecture. The challenge to obtain built environments in which the reactive performance is coupled with predictive capability leads to establishing a new symbiotic relationship between man and architectural space.

4 The Mobile Experience Lab Research and Vision

The aim of Mobile Experience Lab is to join space, users and technology to generate experiences that belong in this new dimension. Another important aim of the lab is to reinvent and create new relationships between people, information and places. Along these lines, studying how human organize and build their live-work and leisure environments can contribute in improving user experience and interaction.

The projects serve various human activities and have common principles.

1. User Centric Environments: A human centric approach to design. The approach of the laboratory places the users and their needs at the center of the three key elements: space/user/technology. Technology and space are tailored to the needs, desires, and aptitudes of the end users, and are at the heart of the ideation process.
2. Interactive Connected Environment. The spaces that we studied are characterized by the extensive presence of information-communication and mobile technologies. The existence of such technologies into the built environment affects usability and the user's lifestyle, modifies the traditional utilitarian character of physical space, and improves peoples lives through the careful design of new meaningful experiences. Along these lines the built environments are not only structured, but also equipped to enable the user to carry out various activities. The user receives advice and is enabled to achieve better integration within a global system of sustainable choices.
3. Multidisciplinary approach (and collaborative culture). The lab adopts a holistic approach to innovation to synthesize the different design variables: spatial, cultural, social and technological, as these emerge during the design process.
4. Multisensory and multidimensional design tools. Interactive and interconnected spaces are designed, emphasizing their capability to link individuals, space and communities and to respond to user behavior. This approach aims to an alternative mode of physical environments.

This paper presents two projects, offering different levels of interaction in two different functional fields. More specifically it presents the public service environment of the Atlas Service Center at MIT and the domestic environment of the Connected Sustainable Home.

5 Atlas Service Center – MIT. An Interactive Gateway to MIT

5.1 Project Genesis and Objectives

The Atlas Service Center was designed in 2015, with the aim to implement a completely renewed vision of the MIT Student Center. The relocation of the Center into a larger space within the campus, and its unification with other offices, offered the opportunity to overcome the functional and spatial restrictions of the pre-existing Center. It offered a chance to design something completely new, reinventing both the experience of the space and the user activities. The challenge has been to rethink the services through an innovative architecture (Fig. 2).

Fig. 2. The vision of the new Atlas Center. View of the interactive map and the digital Kiosk

The goal was to design a new space that represents the values and the spirit of MIT, characterized by innovation, research, and intellectual dynamism, and to create an iconic gateway to the Institute. Under this perspective the starting point of the project was to rethink the characteristics of the physical architecture and user experience, to provide better service, and to strengthen community ties. Along these lines, we simplified and speed up many services by making them more transparent and by eliminating waiting times; we proposed a new scheme of spatial organization to manage discontinuous streams of users to optimize the use of space, and we crafted a sense of place with iconographic value.

The underlying philosophy guiding this project was to optimize the use information communication technologies in enhancing utility and improving service performance. The interaction between user, devices, and space provided the basis for turning the Atlas Center into a social meeting hub. The new Atlas Center was envisioned as a hub for experiencing new media that connect the visitors to the campus, a point for sharing information, and providing service to the community. The digital interaction was designed in parallel to the physical space and the social interaction. The role of information communication technologies was pivotal in promoting social interaction and communication between individuals. Ultimate challenge was to design a service space that would support the user, enable him to understand and carry out multiple tasks in shorter time, and provide an immersive experience by endorsing social connectivity. We called this space a “hybrid space”, a space that exists in symbiosis with the user.

5.2 Working Methodology: From Brainstorming to Body-Storming

Controlling the numerous variables, affecting the physical, functional and virtual levels of the design, demanded a multidisciplinary approach and the adoption of multi-communicational tools and methods.

The design process was organized in several stages that determined the nature and the features of the *Hybrid Space*. Each stage enabled dialogue and collaboration among different specialists.

In the initial phase of the Ethnographic Research, interviews and meetings identified the needs and desires of the Atlas staff and its users, and the deficiencies of the existing Atlas Center. The information gathered at this stage, enabled the formation of use scenarios describing the ideal workplace, in which the quality of service and the communication between staff and visitors would be improved.

The use scenarios and their needs were synthesized in a brainstorming session to map the user needs (Fig. 3). The Brainstorming Experience Map was the starting point of the preliminary design phase that aimed to develop multiple design layouts.

Fig. 3. The brainstorming process. Mapping out the user experience and all the necessary programmatic requirements. With many moving parts and various needs this required multiple meetings with specialists of various backgrounds.

In the preliminary design phase the preferred scenarios were visualized and set in the physical space. Building elements and physical components were designed and prototyped in physical scale, paths and actions were outlined, and various technologies responding to the needs of the plans were sought. The functional needs shaped the spatial arrangement and determined its requirements.

Four key characteristics of the design solution are explained next in further detail.

(a) Open Plan and Open View. The administrative activities grouped in the same space – specifically more than 18 of services and activities – demanded a space characterized by functional transparency and flux that makes the services visible and accessible. This led to the proposal of an open and dynamic plan with transparent dividers and direct visual contact between public and operators.

(b) Multifunctional Space. The need to manage a large number of users, students, staff and visitors, with discontinuous flows during the different seasons of the year, was met by a multifunctional spatial system. The use of mobile walls and multifunctional elements for discontinuous use of particular services allows for flexible change of use and transformation based on demand.

(c) Network of Digital Systems. Systems connected to the physical space speed up and simplify the services by eliminating the waiting time. It has been envisaged implementation of Mobile Integration and Hands-Free Authentication Systems, like the Hermes System, in combination with a system of Digital Kiosks. The Kiosks are physical entity that characterizes the design and the dynamic circulation of individuals in space.

(d) Interactive Tools. A touch-sensitive tangible map and an interactive media-wall were proposed as interactive media interfaces. They are incorporated into the space to enforce the socialization and connection between users.

After identifying the key design elements, functionality and interaction were sketched and modeled with the aid of analogue and digital tools. The sketching and design phase allowed various ideas to take visual manifestation. Digital and physical models were developed to enable the accomplishment of the various functional tasks. From sketches and ideas (Fig. 4) five alternative design layouts were developed. The design ideas were initially developed and tested with graphic methods and tools: from two-dimensional plans, and 3-dimensional drawings, to physical models and 3D printing (Fig. 5).

Fig. 4. Sketching. After receiving the design brief, visiting the service center, and going through the interviews the team started sketching the first design schemes. A dynamic space that promoted movement in zones was key priority.

Fig. 5. Rapid prototyping. Testing ideas trough rendering, modeling, and 3D printing

The layouts (Fig. 6) were also represented by the means of graphs capturing spatial and functional solutions according to alternative design strategies from the most conservative to the most innovative one.

Fig. 6. Presentation and discussion of the design layouts.

After generating alternative design layouts (Fig. 7) where the functional requirements were fulfilled, and the form of the physical elements was taken into account, the next step was to test the user's experience and ability to navigate. It was clear that perception, understanding, and quality of experience within space, as well as its usability, are non-measurable qualities with traditional tools. To evaluate the spatial experience not only through vision but also through a multi-sensory process, various tests were invented involving multiple users in a process of co-design.

An important stage of the project was the *body-storming* process, where users had the chance to dive into a simulated real-world environment comprised of physical scale models of the design. Through the real-size prototype (Fig. 8) the users had the chance to experience what he had imagined. The body-storming phase provided a way to test and evaluate user experience and to receive feedback in order to improve it. The design was built in all its key features, without aesthetic and formal details, to test the distribution of the activities and services and to verify the degree of transparency, accessibility and satisfaction of the user. Feedback was obtained through questionnaires on space usage and general impressions. After this series of tests the design of the Atlas Center was re-described, and the vision was refined.

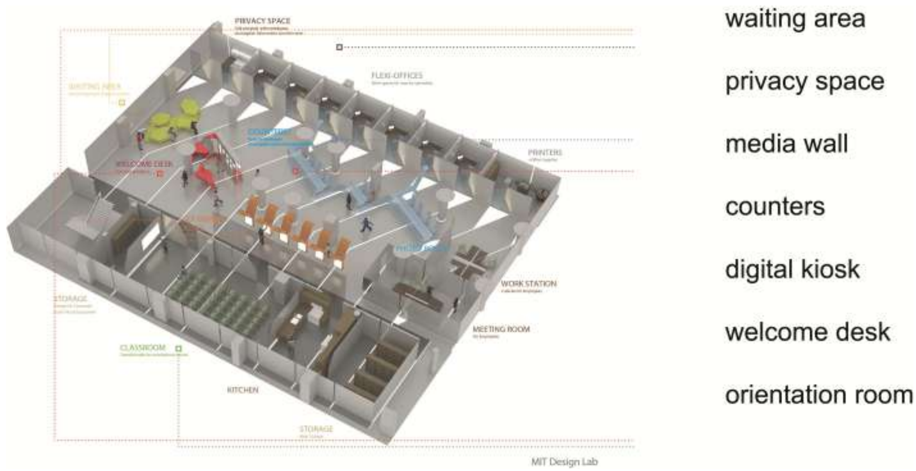

Fig. 7. The final design layout. Functional and design elements were defined. User experience, digital interaction and concept of the physical space were formulated to be tested in the body-storming phase.

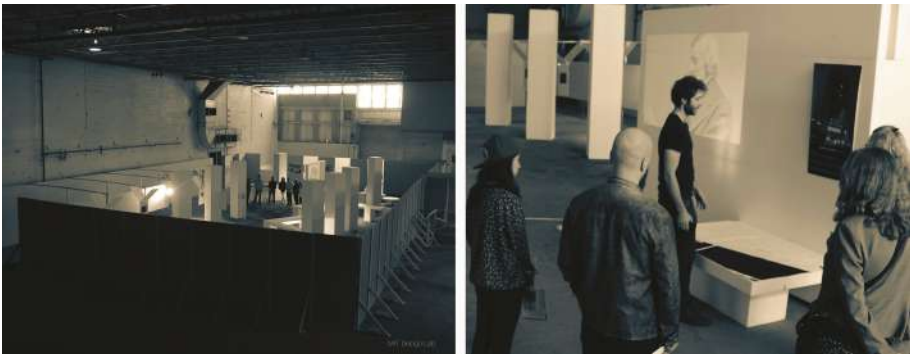

Fig. 8. Full-scale light-weight foam prototype of the service center. Participants joined from IS&T, architecture & planning, DSL, HR, parking & transportation, administration, SHASS, medical, DUE, RLE, IMES, and mobile experience lab.

5.3 Design Vision - Physical and Digital Space

The new Atlas Center aims to operate as a visually open, dynamic environment. It is characterized by the combination of traditional private office spaces and transformable multifunctional areas that can be used for meetings and other activities. Transition spaces that are designed to encourage physical and virtual interaction connect all these spaces into a whole. The transition spaces play the role of a unifying link between the meeting and virtual interaction areas. All spaces are equipped with glass partitions, dynamic lighting, and digital devices. The result is a Hybrid Space where physical and digital means complement each other. Meeting, interaction and connectivity are some of the main features of the space as a whole. Traditional ways to provide service to the public, where human contact and physical gesture are of primary importance, are integrated with "invisible" digital services. Digital services inform and speed up the process, enabling the visitor to begin some of these operations remotely before even entering the physical environment of the Center.

A hands free authentication system in physical space is applied to the Atlas Center area. Hermes System [6] developed by MEL team, makes use of credentials stored on the users smartphone to authenticate them when they enter the physical space of the Atlas Center, or are in close proximity. By using this system it is possible for visitors to have access to all services and to avoid delays. Several interactions can be completed remotely: for example, order a new ID card or student pass. This possibility affects the use of the space so that more space can be dedicated to other activities.

The designated area of the Digital Kiosks involves a section of physical space that is dedicated to digital operations. Digital Kiosks offer services to speed up activities and reduce waiting times. They enable to access the Center's online platform, compile modules, and use some services without the need of assistance by an operator.

A touch-sensitive Tangible Map [7], three-dimensional interactive university map (Fig. 9) provides an interactive navigation experience by offering information on buildings, schools, and events, and enabling to store information on the user's smartphone. The main space includes an Interactive Media Wall. It is a digital showcase on University and community news and events, connecting the users with the student community. It is a combination of real-time general information, and more detailed task specific information. It can also be interactive, and the large surface subdivided into modular screens can present a single image or multiple images side by side.

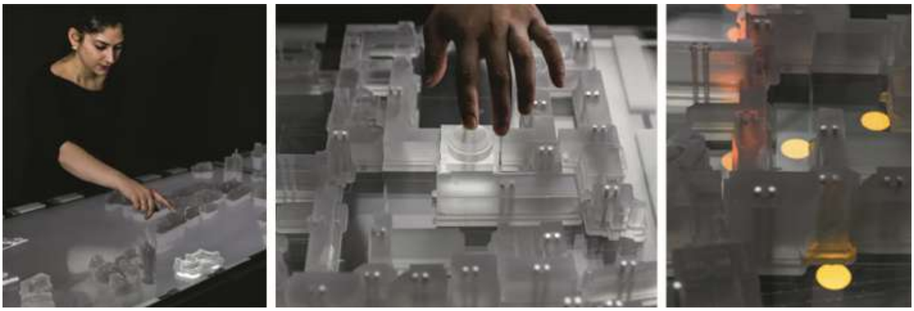

Fig. 9. The mockup of interactive 3D campus map. The tangible map allows access to data related to the MIT buildings by touching a sculptural interface

The design of the digital devices is complemented by the design of the physical space that is equipped with accommodating areas, such as the Welcome Desk, the exhibition area and seats designed to foster human interaction. The Welcome Desk maintains a "human" dimension to guide and assist the visitor in the services.

5.4 Interaction Types

The digital systems and mobile apps combined with the physical components of the space enable different levels, types, and flows of interaction, namely internal interaction, and interaction with the community.

Physical interaction is confined within the Atlas Center and happens between visitors and the Atlas operators. Digital Kiosks exist for this purpose (Fig. 11). The Digital Kiosks allow visitors to book specific services, but also consult and download the available digital modules of the Atlas Center. Placed within the main area, the Digital Kiosks obtain central value as architectural and interface elements. A similar function is carried out by the Welcome Desk, which is designed as a welcoming module involving the presence of tablets and floating operators (Fig. 10).

Fig. 10. Rendering of the Welcome Desk. The Welcome Desk becomes a smart way to optimize the traffic flow inside the space.

Fig. 11. Rendering of the gallery of Digital Kiosk. The installed system permits bluetooth authentication - automatic login if within 1 m.

Design provides form and locality to solutions that are given in response to functional needs. Specialists who deal with abstract, intangible problems often provide these solutions. A designer has to bring the components into human scale and arrange them in physical space. The Atlas Service Center shows that multiple activities and services can be arranged into an overall spatial experience that is both functional and delightful, with a technological aspect that strongly favors human communication.

The reference to a Piazza comes naturally into mind, because it the Atlas Center works as a meeting place for individuals, community and services. The possibility of connectivity is emphasized and stimulated by physical and virtual means.

Within this new methodological framework it is possible to identify the new role and duties of the designer. The architect or interior designer has the role of a mediator, collecting and organizing the user needs, and ultimately situating them within physical space.

The interaction with the MIT community becomes possible through two design elements: the Media Wall (Fig. 12) and the Digital Map (Fig. 13). The Media Wall displays information related to MIT services and news, as well as events related to the student community. The Media Wall also visualizes MIT's history and innovation pickups, supports connectivity within the campus, displays announcements and enables the visualization of tutorials. The Digital Map offers an interactive navigation experience related to the buildings of the campus. Both the Media Wall and the Digital Map are installed in physical space and are expressed by iconic architectural elements. Therefore the space of the Atlas Center becomes a meeting area of communication providing services and showcasing various campus activities. It is a digital Piazza, where physical and virtual dimension are integrated, and physical social interaction and virtual connectivity are complemented.

Fig. 12. The mock up of the Media Wall, during the body-storming process.

Fig. 13. Visualization of the interactive map. Mock up of the interactive map, during the body-storming process.

6 The Connected Sustainable Home: A Tutor for the Inhabitants

The Connected Sustainable Home is a prototype home, designed and built in full scale by the Mobile Experience Laboratory in northern Italy. This research project was part of a research-collaboration, the Green Home Alliance, between the MIT Mobile Experience Lab and the Foundation Bruno Kessler, in Trento, Italy. The research was extended from 2009 to 2012 when the prototype was installed and tested in Trento, in the campus of the Foundation Bruno Kessler (Fig. 14).

Fig. 14. The connected sustainable home. Left: exterior view of the prototype installed in the campus of the foundation Bruno Kessler, in Trento northern Italy.

The design concept of the connected sustainable home follows a holistic approach, where passive and dynamic systems are integrated in the same structure to yield a unique living experience. This prototype house unit was designed to integrate three layers of innovative technologies: a building material system using advanced digital fabrication, a computational system employing AI methods of building control, and an energy production system from renewables [8]. A network of sensors and actuators and an intelligent control system were integrated in the modular building structure made out of local wood, while the sustainable energy system was designed to provide the necessary power. The fusion of these three layers of innovation resulted into a new domestic living experience: connecting the occupants to the community, enforcing sustainable use of the available energy resources, and helping the users to achieve better levels of comfort in non-intrusive, non obstructive ways.

The process of designing the connected sustainable home was a test bed for exploring how home living space can interface with its inhabitants and how domestic living experience can be affected by the patterns of user behavior and local culture [9]. Main objectives were to improve the quality of life, reduce energy consumption, and encourage environmentally responsible ways of living without undermining cultural identity. Interfacing with the house systems becomes possible through monitoring of the daily activities. These actions range from lighting up a light fixture, to opening a window, or going to bed. The intelligent control system of the house adapts the house states to serve these behaviors. Based on these behavioral patterns the control also suggests alternative ways to save energy and optimize comfort.

There are several innovative aspects related to the design of the connected home prototype [10, 11]. In this paper we focus on user interaction. A direct way to attest the interactive features of the home is through the operation of its dynamic south façade. The Dynamic Façade is made up of electro-active windows that modify their position (open-closed) and tinting levels (obscure-clear) based on different inputs provided by the activities of the residents, and the climatic conditions [12]. Each windowpane involves an overlay of two electro-active materials. The first, electrochromic layer enables precise adjustment of the incoming sunlight and heat. The second, poly-dispersed liquid crystal (PDLC) film, is used to control privacy and provides an advanced alternative to the traditional systems of blinds, or louvered grilles. The next Fig. 15 presents the basic state combinations of activated windowpanes, namely: a. the PDLC layer is active and the electrochromic layer is inactive; b. both the PDLC and the electrochromic layers are active; c. both the PDLC and the electrochromic layers are inactive; d. the PDLC layer is inactive and the electrochromic layer is active; e. an exterior view of a window with both the PDLC and the electrochromic layers active.

Fig. 15. Basic combinations of window states: frames *a, b, c, d* are window views from the house interior, while frame *e* is a view of a fully tinted window from the house exterior.

Three missions of interface design were identified and challenged in particular: interfacing between interior and exterior; interfacing between private and public, and supporting individual expression.

6.1 Interfacing Between Interior and Exterior

Interfacing between interior and exterior aims at overcoming the extreme conditions and the variability of the local climate. During the process of mediation between interior and exterior, energy is consumed. The Dynamic Façade provides a flexible apparatus that modulates sunlight penetration, incoming heat and natural ventilation at the house interior. These features rely on the integration of electro-active materials, sensing, actuation, and control capabilities. The efficiency of the façade rests on the capacity to monitor and modify the solar transmission of individual windowpanes in real time. Simulation methods were used to project the façade performance in the local climate conditions (Fig. 16). The autonomous control system performs real time simulation, compiles the available data related to the seasonal levels of sunlight, heat, humidity etc. and feedback from sensors, to adjust the states of the electro-active materials as needed to optimize the long-term house performance and thermal [13], and visual comfort [14].

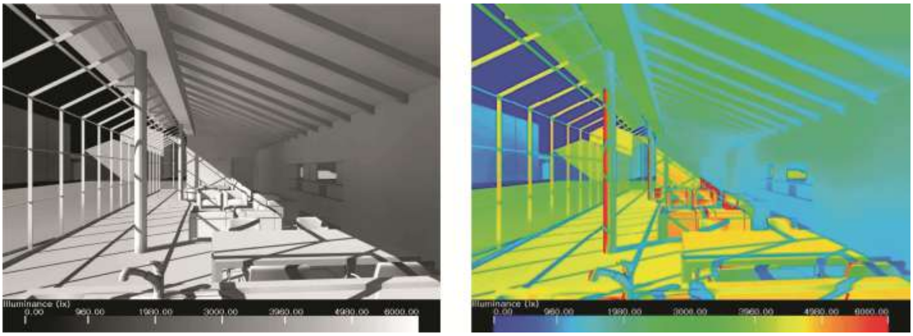

Fig. 16. Solar radiation simulation indicating the angle and intensity of the incoming sunlight in the prototype, on June 21, at 1 PM, in Trento, N. Italy

In the autonomous mode the façade adapts its state based on the desired conditions without requiring supervision or input by the inhabitants. Hence, in the summer the windowpanes are adjusted to reduce the heating effect of incident solar irradiance, and in the winter, to expose the interior to the warm winter sun. Although autonomous functioning is based on an algorithmically calculated action plan, aiming at long-term goals, the façade is also engaged into synchronous interactions with the inhabitants. A parallel, responsive mode permits the adaptation of the façade if an optimization setting is overwritten by a short-term action. For example, if a resident opens many windows in a hot summer day the system would respond to the change of interior temperature by reconfiguring the façade settings (e.g., changing sunlight modulation pattern) to balance the heat loss.

6.2 Interfacing Between Private and Public

While servicing the adjustment of sunlight, heat and view the façade also determines the association between the private interior and the public exterior. As Lyndon and Moore [15] point out, the history of architecture could be approached as a struggle between the membrane and the frame: "Between solidly opaque and flexibly open, based partly on materials available, but more fundamentally on how definitively inside is separated from outside". The modern, inoperable curtain wall is a contemporary expression of definitive separation between inside and outside. Inoperable curtain walls are energy intensive since they require support by artificial lighting and air-conditioning systems, they restrain user behavior and they neglect the urban context. The Dynamic Façade was envisioned as an interactive, automated alternative [16]. Its varying configurations affect privacy and transform how the prototype is perceived from the public street. Without prescribed states the façade functions as a programmable matrix of apertures, allowing the users to determine dynamically how to engage with the street and the neighbors (Fig. 17).

Fig. 17. Left: artist's rendition of the Dynamic Façade's response to human gestures. Right: the actual implementation of the Dynamic Façade in Trento north Italy.

6.3 Supporting Individual Expression

At any moment numerous façade configurations meet the efficiency requirements. This allows satisfying performance and individual preference related to privacy, visibility, comfort and view. The façade becomes a medium of self-expression mirroring the dispositions of the residents to the urban landscape (Fig. 21). The variety of façade configurations was approached as a visual language, and it was mapped through the conventions of a generative grammar producing a large number of patterns based jointly on properties of symmetry and performance [14]. In this way, comfortable interior conditions are maintained while a range of distinct patterns is formed. The reconfiguration of the façade can also happen in response to the presence of a passer-by or to specific gestures that are tracked by the embedded network of sensors. The interactive mode allows the façade to react to gestures, events and conditions like the sunrise or sunset, etc. (Fig. 18). On the transparent façade a patch of PDLC cells can conceal a moving person from the public view, while leaving the rest of the façade transparent.

Fig. 18. The Dynamic Façade responding to sunrise at waking time.

7 Autonomous Control

The values of the house microclimate, such as temperature, humidity, natural light, etc., are monitored and energy consumption is controlled by the autonomous control. This system was developed by the Mobile Experience Laboratory and the Model-Based Embedded and Robotic Systems (MERS) group of MIT. The goal was to develop an intelligent control able to respond to user needs, optimize energy consumption and comfort without direct user input. The autonomous control [17] engages a wireless network of sensors (WSN) that is suitably distributed in the walls, ceiling and window frames of the house. The sensors capture data relevant to user behavior and energy consumption, while an HTTP server enables the exchange of information between the control and all the systems of the house (Fig. 19).

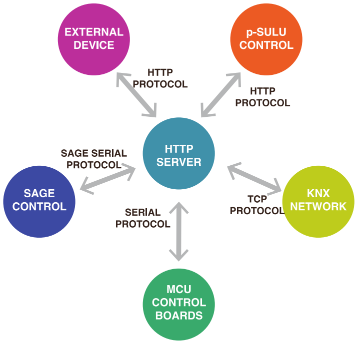

Fig. 19. Diagram of the implemented communication apparatus of the connected home.

The p-Sulu system (Probabilistic Sulu) is a risk sensitive model-based plan executive that controls the home's systems. It combines feedback from sensors, statistic information compiled by a weather station, and environmental data, to evaluate performance in real time. By combining these data with schedules, long-term goals, and preferences, p-Sulu evaluates the risks and predicts the future behaviors to produce a chance constraint qualitative plan executive. This plan is specified as a sequence of state and time constraints (Fig. 20). The control operates to satisfy these constraints while tracking the actual conditions and performing rescheduling as needed.

The intelligent house control p-Sulu takes a threefold approach to optimize comfort: Firstly, it minimizes the use of artificial lighting, heating and cooling by managing the incoming sunlight and heat; Secondly, it exploits the high thermal capacity of the envelope to store solar heat; And thirdly, it helps the residents to choose energy-saving behaviors. A key innovation behind p-Sulu is that it is able to leverage flexibility in a resident's schedule to achieve reduction in energy consumption.

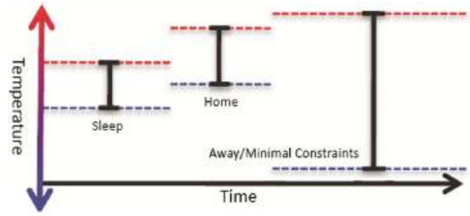

Fig. 20. Simplified diagram of a chance-constrained state plan. The control "drives" the operation of all systems within an upper (red) and a lower (blue) boundary of constraints. (Color figure online)

Fig. 21. Left: day view of the Dynamic Façade with all the electrochromic windows tinted. Right: night view of the Dynamic Façade with the pattern "MIT" formed by the windows.

Finally, the intelligent control informs and empowers the occupants to adjust their behavior to lower energy consumption. The information provided by the intelligent control educates the users and enables them to become more aware regarding the environmental impact of their habits. The house encourages the users to progressively adopt environmentally friendlier practices and at the same time progressively adapts to better serve their needs. By tracking the patterns of use the intelligent control enables an increasingly more effective long-term management of the available resources, while optimizing user comfort. We can therefore say that the dynamic living environment of the connected sustainable home acts as an assistant and a tutor. In the end the users remain always free to follow or overwrite the recommendations of the intelligent control with their behavior.

8 Conclusions

The trajectories of two design projects were described. The first resulted to a new scenario of user experiences for the Atlas Service Center at MIT; the second to a full-scale prototype for a Connected Sustainable Home. The two projects demonstrated possibilities of novel experiences through the integration of dynamic digital systems in physical space. It was also examined how the transformations in user behavior caused by digital media leads to new user expectations and to a need for reconsidering spatial organization. Multi-functionality, connectivity, interaction and symbiosis between users in space, have been supported in both projects. The physical-spatial features of architecture are enhanced by the means of Information Communication Technologies that activate new spatial dynamics. Radical changes take place in the contexts of the design process, performance prediction, and user experience, leading to the generation of new families of physical artifacts. The process of designing becomes more transparent and open-ended to incorporate new technical expertise. Technological change and new tools play important role in the course of ideation. Designers adopt new sets of creative constraints and aim at new objectives. Still, they have always to mediate the needs of the user and to synthesize the technological complexity into a human centric experience, in physical space. Along these lines, the built environment turns into a dynamic interface. At best this interface places the individual at the center of interaction, as the main actor within various contexts. Multiple new territories of exploration open up to design research, like the optimization of energy efficiency and comfort, the integration of intelligent building systems in various social and cultural contexts, the improvement and simplification of services, and the introduction of new aesthetic values and symbolic connotations to the built environment.

In the context of working and service environments the design proposal for the Atlas Center shows that user interaction can acquire greater efficiency and invigorating social character. Services can be simplified and a new type of physical/digital interaction can be developed. The integration of Information Communication Technologies in physical space and the critical aspects of space distribution, augment the functionality of the built space and improve user experience by making the interactions simpler and more transparent.

In the context of domestic living, rethinking the problem of optimizing energy performance and user comfort through responsive living environments leads to more efficient management of the available resources and better quality of life. Educating the users through preventive, symbiotic architectural systems, like these of the connected home, simplifies human-machine interaction, and transforms the home-living experience. Long term monitoring of the patterns of use by intelligent domestic systems can lead to improvements in the well being of the inhabitants.

Interdisciplinary approach, collaborative design processes, multi-communication design tools come to the definition of hybrid environments applicable to all human living contexts, from domestic, to working and social.

Acknowledgments. Acknowledgement is due to all the MIT Mobile Experience Lab members involved in the Atlas Center and the Connected Sustainable Home. The Connected Sustainable Home research was conducted within the Green Home Alliance between the MIT Mobile Experience Lab and the Fondazione Bruno Kessler, in Trento, Italy.

References

1. Van Berkel, B., Piber, A., Lodi, F.: Designing with the immaterial. In: Proceedings of the 2nd Media Architecture Biennale Conference, MAB 2014, Aarthus, Denmark, World Cities, p. 84 (2014)
2. Bullivant, L.: 4dspace: Interactive Architecture, 1st edn. Academy Press, Cambridge (2005)
3. Alavi, H.S., Lalanne, D., Nembrini, J., Churchill, E., Kirk, D., Moncur, W.: Future of human-building interaction. In: Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems, CHI 2016, pp. 3408–3414. Association for Computing Machinery, New York (2016)
4. Velicov, K., Thün, G.: Responsive building envelopes: characteristics and evolving paradigms (Chap. 1.3). In: Trubiano, F. (ed.) Design and Construction of High-Performance Homes: Building Envelopes, Renewable Energies and Integrated Practice, pp. 75–91. Routledge, London (2012)
5. Aish, F., Davis, A., O'Malley, M., Papalexopoulos V., Foster + Partners: Designing the infrastructure of human building interaction. In: Proceedings of the CHI Conference Extended Abstracts of Future of Human-Building Interaction a CHI Workshop, CHI 2016, San Jose, CA, USA, 7 May 2016
6. Chilana, K., Casalegno, F.: Hermes: hands-free authentication in physical spaces. In: Tryfonas, T. (ed.) HAS 2016. LNCS, vol. 9750, pp. 15–24. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-39381-0_2
7. Walker, W., Sung, H., Ong, C.K., Casalegno, F.: Exploring spatial meaning with tangible map. In: 6th ACM International Symposium on Pervasive Displays Proceedings, 07–09 June, Lugano, Switzerland (2017). Article No. 6
8. Kotsopoulos, S.D., Farina, C., Casalegno, F.: The three autonomous architectures of a connected sustainable residential unit. In: Energy Procedia, International Conference on Applied Energy (ICAE 2014), vol. 61, pp. 1496–1500 (2014)
9. Scagnetti, G., Casalegno, F.: Social sustainability in design: the window as an interface for social interaction. In: Rau, P.L.P. (ed.) CCD 2014. LNCS, vol. 8528, pp. 321–330. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-07308-8_31
10. Kotsopoulos, S.D., Casalegno, F., Hsiung, B., Graybill, W.: A prototype hut for the post-digital age. In: Proceedings of the 30th International Conference on Education and research in Computer Aided Architectural Design in Europe (ECAADE 2012), 12–14 September 2012, Prague, Czech Republic, pp. 307–316 (2012)
11. Kotsopoulos, S.D., Farina, C., Casalegno, F., Briani, A., Simeone, P., Bindinelli, R., Pasetto, G.: A building system for connected sustainability. In: Proceedings of the 14th World Conference on Timber Engineering 2012 (WCTE 2012), University of Auckland - New Zealand Timber Design Society, 16–19 July 2012, Auckland, New Zealand, pp. 271–279 (2012)
12. Kotsopoulos, S.D., Casalegno, F., Ono, M., Graybill, W.: Windowpanes become smart: how responsive materials and intelligent control will revolutionize the architecture of buildings. In: Proceedings of the First International Conference on Smart Systems, Devices and Technologies (SMART 2012), 27 May–1 June 2012, Stuttgart, Germany, pp. 112–118 (2012)
13. Kotsopoulos, S.D., Cuenin, A., Telhan, O., Casalegno, F.: Personalizing thermal comfort in a prototype indoor space. In: Proceedings of the Eighth International Conference on Simulation in Architecture, SIMUL 2013, 27 October–1 November, Venice, Italy, pp. 178–186 (2013)
14. Kotsopoulos, S.D., Cara, G., Graybill, W., Casalegno, F.: The dynamic façade pattern grammar. Environ. Plann. B: Plann. Des. **41**(4), 690–716 (2014)

15. Lyndon, D., Moore, C.W.: Chambers for a Memory Palace. The MIT Press, Cambridge (1996)
16. Kotsopoulos, S.D., Farina, C., Casalegno, F.: Designing an interactive architectural element for a responsive prototype house. In: Proceedings of the XVI Conference of the Society of Digital Graphics (SIGRADI 2012), Fortaleza, Brazil, pp. 369–372 (2012)
17. Kotsopoulos, S.D., Casalegno, F., Ono, M., Graybill, W.: Managing variable transmittance windowpanes with model-based autonomous control. J. Civil Eng. Archit. **7**(5), 507–523 (2013). Serial No. 66