Rethinking Autonomous and Robotic Systems in Residential Architecture: Assessing the Motivations and Values of Home Automation

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Our story begins at the turn of the twenty-first century when enthusiasm for all things digital reached a crescendo. Within our modern Western industrialised context, a pervasive sense of optimism surrounded the development of 'smart' technologies, digitally enhanced replacements for earlier products of industry and craft. This exuberance was especially strong at the Massachusetts Institute of Technology (MIT), where we, the authors, found ourselves compelled by a vision of digital futurism that promised nothing short of liberty and prosperity for all.[1] Indeed, the digital revolution had swept through the Departments of Architecture and Media Arts and Sciences, and it would appear irresponsible not to participate in the exploration (and exploitation) of its potential.

Of course, architecture has always been subject to the winds of technological change. Every technological epoch, beginning with the stone age, has influenced how humans construct and conceive shelter; the twentieth century marked a particular acceleration of technological encroachment into architectural theory and practice. Architects like Adolf Loos and Le Corbusier dismissed ornamentation and favoured pure forms that could be perceived day or night, thanks to the invention of electric light.[2] Architectural form was abstracted and decontextualised from local culture to find its expression in the timeless, universal forms of geometry.

Industrial materials like concrete, glass, and steel, along with new universal means of production enabled radical changes in building design and construction. Large window openings supplied ample natural light, air, and view into building interiors, and the electric elevator enabled the creation of high-rise structures, radically changing the urban setting. Walter Gropius and Ludwig Mies van der Rohe enthusiastically embraced these developments. Mies van der Rohe believed that new materials and technologies could help architects to fulfil their social mission: 'We do not need less, but more technology; we do not need less science, but more intelligent science, not less but more mature economic initiatives.'[3]

Le Corbusier's aphorism that the 'home is a machine for living' characterises the modern era. It reflects a fascination with efficiency, reducing design to problem-solving, where proper analysis of function and precise metrics guarantee good results. Engineers are believed to work based on immutable physical laws, distinct and separate from the complex and nuanced reality of human experience. The mid-twentieth-century architecture was an expression of a society organised around technological progress to which everything else had to be subordinated. David Watkin notes that it gradually became essential for architecture to keep 'up to date' and even, where possible, anticipate the future. Buildings started receiving praise not for their quality or imagination but as technological achievements. The architect's role has changed from a person of education, taste and imagination responsible for 'raising our spirits' to an agent through which 'a material problem is resolved'.[4]

Unsurprisingly, this twentieth-century fascination with the mechanical evolved into a twenty-first-century obsession with the digital. Today, we witness the proliferation of digital computing, an eruptive body of techniques, networks, and infrastructures that transform human behaviour. Nicholas Negroponte's declaration that 'computing is not about computers anymore, it is about living' has become an actuality.[5] Residential architecture could not remain unaffected. In the coming years, efforts to facilitate the digital augmentation of homes will continue alongside similar developments in other sectors, such as the automotive and consumer electronics industries.

Two decades into our journeys to this future, we now pause to reconsider some of the assumptions driving our prior work on computationally augmented homes. We will examine and contemplate the implications of this work, aiming to reach conclusions about which aspects of digitalisation are best incorporated into architectural design and which may prove out of scope. In many ways, the history of architecture parallels the history of technology. Designers of buildings and designers of technology are frequent (if unintentional) collaborators in authoring new narratives about everyday life and the future. Sometimes this collaboration is explicit, as in the production of concept homes to illustrate future lifestyles brought forth by technological innovations with impactful potential.

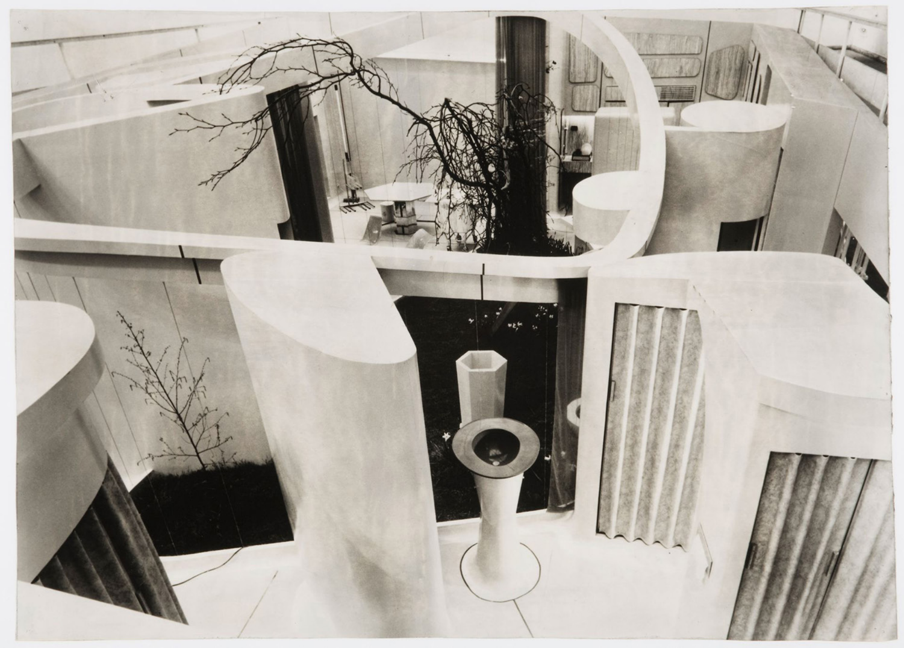
Early prototype houses

The earliest concept homes were built or sponsored by electric appliance manufacturers for advertisement purposes. While these began popping up in the early twentieth century, the most famous examples date to the 1950s. One of these, the Monsanto House of The Future was an attraction at Disneyland, California, in 1957–67.[6] The 120m^2 moulded plastic house was designed by architects Richard Hamilton and Marvin Goody and built by MIT and Monsanto Chemical Company. Monsanto wanted to demonstrate plastic's versatility as a high-quality, engineered material. The house's futuristic fibreglass components were moulded in the factory and assembled on-site. The house was an imaginative projection of what domestic life might look like in 1986. It featured a lot of electric appliances, large-screen video displays, microwaves, and dishwashers that would eventually become commonplace in homes. [Fig. 1]

Another House of the Future was presented at the *Daily Mail Ideal Homes Exhibition* in London in 1956. It was designed by architects Alison and Peter Smithson as a full-scale mock-up projecting how a conventional suburban home might be in the year 1981.[7] Designed around an atrium that supplied natural light and private outdoor space, the house interior was enclosed, without windows to the public street. [Fig. 2] What they called 'wired acoustics' was the only way it interacted with the outside world. The line between commodity and fiction was deliberately blurred. Existing pieces of technology such as a Tellaloud loud-speaking device, kitchen appliances, a closet to dry clothes, and a washing machine were presented alongside imagined devices like after-shower body air-dryers and telephone message recorders.

Other experimental indoor spaces, such as Cedric Price's Generator Project (1976–79), were more conceptual.[8] The Generator was designed to serve as a retreat and activity centre for small groups and sought to create conditions for dynamic interactions in a reconfigurable and responsive architectural environment. [Fig. 3] Price developed a scheme of one hundred and fifty 3.6m x 3.6m mobile, combinable cubes constructed with off-the-shelf infill panels, glazing, and sliding glass doors. The parts could be moved by mobile crane on an orthogonal grid of foundation bases as desired by users to support their activities. 'The whole intention of the project was to create an architecture sufficiently responsive to the making of a change of mind constructively pleasurable', Price explained.[9] The Generator aimed to shift the roles of designers and users, questioning who and what was responsible for interactions and challenging the performance and formal expression of architecture.

Fig.1: Monsanto Plastics Home of the Future, designed by Richard Hamilton and Marvin Goody, Disneyland, 1957. Photo: Corbis, *Wired*, June 2009.



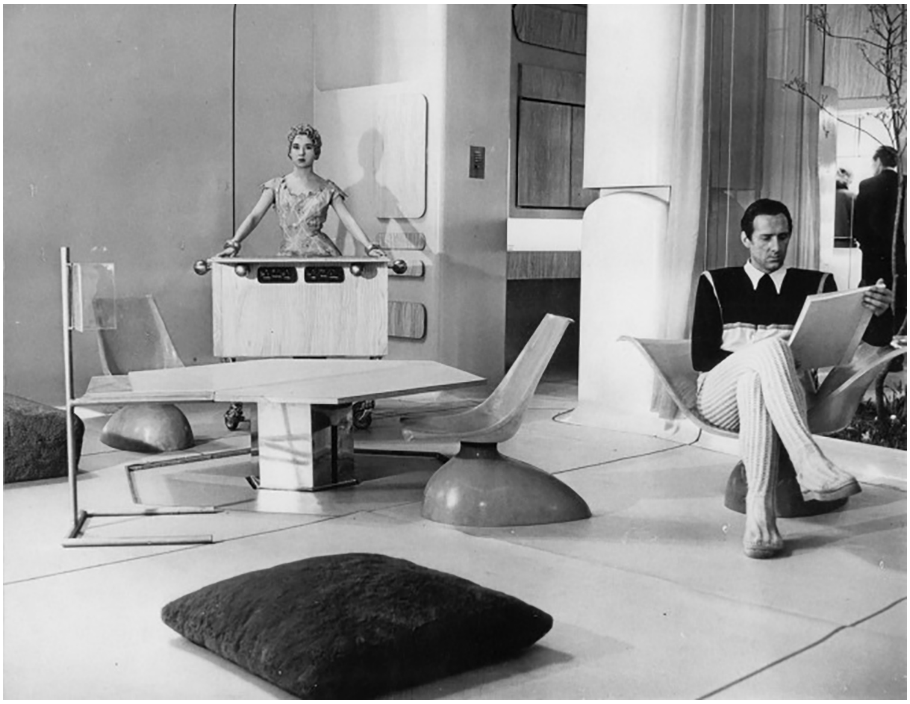


Fig. 2: House of the Future, designed by Alison and Peter Smithson, Daily Mail Ideal Home Exhibition, London, March 1956. Unknown photographer. Source: Canadian Centre for Architecture, Montréal.

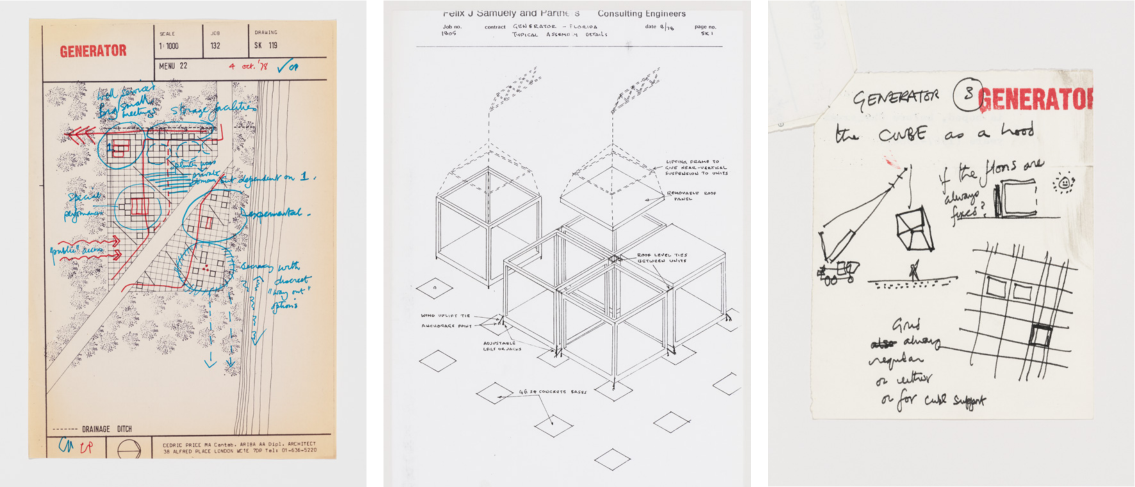


Fig. 3: The Generator, designed by Cedric Price. Site plan, axonometric of assembly principles, and sketch showing frames and grid foundation pads. Source: Cedric Price Fonds, Canadian Centre for Architecture, Montréal.

Digital prototypes

The aforementioned concept homes were largely analogue in character, reflecting the state of the art in the middle of the twentieth century. However, advancements in digital computing rapidly led to a rewriting of the future home concept, where architecture is a platform for an ever-changing array of digitally augmented experiences.

'Ubiquitous computing' is the term coined by Mark Weiser for his vision of the future, where embedded microprocessors with limited computing power populate everyday objects to make them easy to track and perform simple tasks without direct user interaction.[10] Ubiquitous computing devices are network-connected and constantly operating in the background, using processing power hidden in a network. As devices grow smaller, more connected, and integrated into the physical environment, says Weiser, the technologies will disappear and 'weave themselves into the fabric of everyday life until they are indistinguishable from it', making computing an integral, invisible part of people's lives.

Along these lines, Daniel Cook et al. define 'ambient intelligence' (AmI) as a class of ubiquitous components that are: embedded, integrated into the physical environment; context-aware, able to recognise users and their situational context; personalised, tailored to user needs; adaptive, able to change states in response to users' needs; and anticipatory, able to anticipate user needs without direct input.[11] AmI systems can involve AI agents to perform autonomously, depending on the detected needs and user input or recommendation systems interpreting the user's state and habits and initiating a response.[12]

These visions serve as the foundation for more recent home prototypes. For example, the Adaptive House, implemented by the University of Colorado, is an early neural network home experiment.[13] [Fig. 4] In this home, an autonomous control system manages basic comfort systems like air and water heating, lighting and ventilation, and by tracking the inhabitants' preferences, it learns to cater to their needs. The ComHome (1999), developed by the Interactive Institute of Sweden, was an apartment equipped with video-mediated communication, in which researchers tested modalities of home-based activity such as communication, remote work and social interaction.[14] [Fig. 5] The Aware Home, developed by the Georgia Institute of Technology, was a suburban house based on the 'living lab' and ubiquitous computing concepts.[15] [Fig. 6] The house was aware of itself and the activities of its inhabitants by maintaining continuous high-speed connectivity through cameras, microphones, and sensors. A wireless network enabled communication among devices, and a radio-locating system tracked tagged everyday objects.

The sensing infrastructures underlying these concept homes could be deployed in conjunction with robotic actuators to modify the physical space. Robotic systems are already being promoted in the building construction industry,[16] and integrating robotics in envelopes and interiors could lead to adaptable buildings that address particular needs in sustainability and occupant comfort. In this vein, a preliminary application is Agata Bonenberg's kitchen for parallel use by people with and without mobility problems featuring mobile gesture-controlled modules, enabling plumbing and kitchen adjustment.[17] Likewise, Wada Kazuyoshi et al. describe a multipurpose robotic module for people with disabilities, which can cook, store electric appliances, cooking tools, and tableware, and transform into a dining table.[18]

Each of these prototypes represents a research lineage of over two decades, yet there is no clear consensus over if, when, why, and how to integrate autonomous sensing and actuation systems into residential architecture. Some moderately advanced technologies, including robotic vacuum cleaners, smart speakers, and motion-sensing security cameras, are already gaining acceptance in homes. Their cost is not low, but homeowners embrace them. What about more advanced and expensive robotic options? What if intelligence is

Fig. 4: The Adaptive House, circa 1999. Photo: Mike Mozer.

Fig. 5: The ComHome. A videoconferencing device, Torso, for informal everyday communication and a ComTable for video-mediated communication in a dinner situation. Photos: Stefan Junestrand and Konrad Tollmar.

more seamlessly integrated into the fabric of the home? How do concerns about the future adaptability of spatial distribution influence decisions about integrated home technologies? Moreover, who should decide what technology is brought into the home? Is it the homebuilder? The architect? The homeowner or occupant? We shall consider these questions through a review and contemplation of three ambient intelligence projects in residential architecture designed and implemented by ourselves and colleagues at MIT over the past twenty years.

Case studies

We present three case studies: a Connected Sustainable Home (CSH) aiming at adaptive sustainability, the PlaceLab, a living laboratory for studying health-related home systems, and the CityHome, a series of robotically transformable apartment prototypes. These projects were not conceived of as visions of future technologies that could or should be broadly adopted in the real world. Hence, they are not discussed in such a light now. In truth, they embody a complex network of political, technical, and design choices that, more often than not, are determined by agents beyond the researchers or the architects themselves. Nonetheless, we believe they provide a reasonable basis for discussing design criteria for autonomous systems in residential architecture.

The Connected Sustainable Home

The connected sustainability concept aspires to a vision of dynamic resource management to achieve sustainability in the spirit of the early farm communities. Various energy production, storage, and control systems operate within homes connected to a network to exchange information, manage the community's resources, and allow for dynamic energy sharing and pricing.

The CSH prototype was a testbed for connected sustainability developed by the Design Lab at MIT and the Fondazione Bruno Kessler in Trento, Italy, from 2009 to 2013. Although the project aimed to minimise home energy consumption and maximise comfort, the vision of connected sustainability was akin to broader economic, social, and cultural objectives. Local materials, companies, and building technologies were engaged in the project. The local economy, culture, and living habits were acknowledged in the design. Another goal was to provide an environmentally sensitive mode of building an original tectonic vocabulary aligned with technological innovation. Along these lines, the CSH integrated low-tech and high-tech systems to facilitate management of resources, to reduce performance uncertainty, and to provide intuitive interactions between residents and systems. [Fig. 7]

The CSH is a single-floor, free-standing suburban house with an open-plan layout, ample loft space and an open-view curtain wall facing south. Fixtures organise interior functional zones for living, sleeping, eating, and a patio area. The partitioning is adaptable; the loft can be converted into a temporary bedroom for visitors or a workspace with dividers adjusted manually.

There are four house systems: a) a high thermal mass envelope and base, b) a programmable, robotic solar wall, c) a cogeneration energy production plant, and d) a distributed control system fine-tuning the operation of all the above. Building physics governed many design decisions. A custom simulator computed the envelope's performance based on the features of the materials and the local seasonal conditions. Humidity, illuminance, temperature, thermal comfort and weather information, including statistical data and data produced by simulation, informed the design. Alternative design schemes and combinations of materials were explored through simulation and evaluation.

The plan and section of the CSH reflect energy management concerns. A high thermal mass envelope facing north is placed back-to-back with a programmable, robotic façade facing south. The high thermal mass envelope secures high thermal resistance and low conductivity to sustain heat

Fig. 6: Georgia Tech's Aware Home Research Initiative (1999). Photo: Georgia Tech.

during the winter and prevent excessive heat during the summer. The programmable façade is a matrix of robotically actuated, independently openable windows enabling precise air, visibility, sunlight and solar heat modulation in the interior as needed.

The interior of the CSH would have been unpleasant and energy-intensive without intelligent environmental management. Forcing the residents to perform this management by manually operating the house systems would have been inefficient – integrating a model-based autonomous control that constantly works in the background made human involvement optional. The control compiles data about the weather, temperature and light, the state of the envelope and the programmable façade, the occupants' activities and the energy production system to calculate a predictive plan of operation for all house systems. The plan maximises comfort at a minimum energy cost by setting the tectonic elements to perform and appear variously in response to exterior conditions, preferences, or residents' activities.

Beyond being regulatory, the programmable façade is an expressive tectonic system. Colourful house façade murals engage the eye; this is a traditional decorative practice in Trentino. The dynamic transformation of the pattern, distribution, and degree of chromatism on the robotic façade has a similar effect. Various patterns based on degrees of window chromatism applying to the façade maintain the desired level of illuminance, solar radiation, and visibility in the interior. A visual algorithm generates a façade pattern language in real time based on illuminance and symmetry and dynamically transforms how the public street perceives the house.[19]

The high thermal mass envelope – covering the north, east and west – is made from X-laminated panels, a renewable material produced in Trentino, boosting the local economy. A double layer of fibre gypsum and fibre wood panels of different densities secure thermal and acoustic insulation. The north, east and west walls are 720 mm thick, providing high heat transmission resistance. A theoretically calculated value U = 0.150 W/m^{2}K for the roof and the walls indicates that the envelope performs as a passive structure. [Fig. 8]

The south façade is a matrix of robotic windows. Each window integrates an overlay of two electrosensitive materials, an electrochromic coating regulating natural light and thermal performance and a PDLC (polymer-dispersed liquid crystal) film regulating visibility and view. Each window is driven by its low-level controller, and the house control manages the entire robotic façade.

The CSH is powered by a cogeneration heat and power plant (CHP) using solar energy and a conversion system. A custom-made solar-driven cooling and heating machine uses thermal energy stored in microporous material regenerated by solar thermal collectors. A low-level controller monitors the states of the system components under variability of load, seasonal effects, daily effects and user profiles, exchanging data with the house control and realising an adaptive energy production system.

The responsiveness of the CSH relies on control, sensing and actuation networks, aiming at comfort, sustainability, and convenience. Comfort is achieved by letting the residents set their temperature and illuminance preferences, sustainability by minimising energy consumption, and convenience by minimising the user's effort to reach the two previous goals. The three goals are realised through goal-directed planning. Predictive fine-tuning of the air conditioning, the robotic windows and the passive envelope's thermal conservation state secures the servicing of the interior atmosphere at a minimum energy cost.[20] The control operates in a stochastic domain. A probabilistic guarantee that the resident's comfort constraints will not be violated is secured by acknowledging the sources of uncertainty and planning accordingly. This is referred to as risk-sensitive planning.[21]

Schedule and comfort preferences are encoded as time-evolved goals in a chance-constrained qualitative state plan (CCQSP). Time-evolved goals are constraints placed on the system's state jointly with

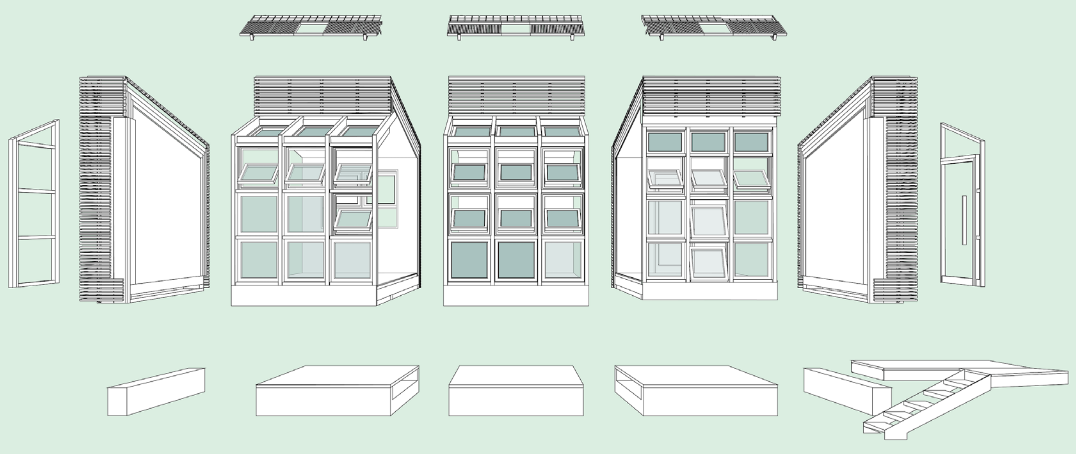


Fig. 7: The CSH prototype in Trento, Italy, 2012. Photo: MIT Design Lab.

Fig. 8: Axonometric diagram of the passive and dynamic components of the CSH envelope. Image: MIT Design Lab.

temporal information describing their timeframe, like: ‘maintain a sleep temperature until it’s time to wake up’ or ‘maintain room temperature until it’s time to go to sleep’. A CCQSP is depicted as an acyclic-directed graph. [Fig. 9]

A room temperature control scenario with a twenty-four-hour planning horizon is depicted in figure 10. The resident wakes up at 08:00, leaves home at noon, returns at 17:00 and sleeps at midnight. During these times, the room temperature is set within specific ranges. The algorithm satisfies chance constraints by setting a safety margin (shadowed areas) along the boundaries.

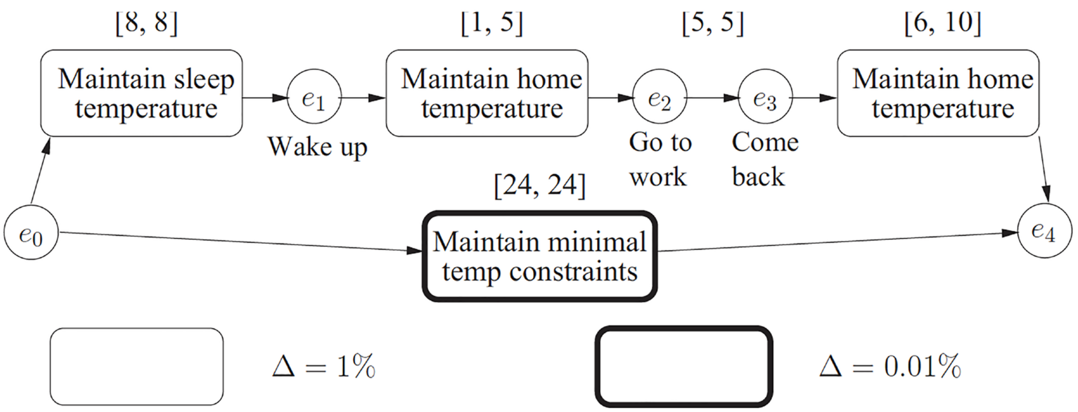
The control is integrated with the physical architecture through sensors performing real-time monitoring and actuators adjusting critical building components. An outdoor weather station performs weather measurements while indoor sensors monitor ambient parameters such as temperature and relative humidity, indicating a value inside or outside a defined wellness area. Luminescence sensors provide a lumen factor to activate the electrochromic windows. The probabilistic control algorithm proactively calculates a state plan for all house systems targeting the residents’ comfort zone. It achieves significant energy savings compared to a traditional PID (proportional-integral-derivative) algorithm: 51 per cent over the PID during winter and 15 per cent, 17 per cent, and 4 per cent during spring, summer, and autumn.

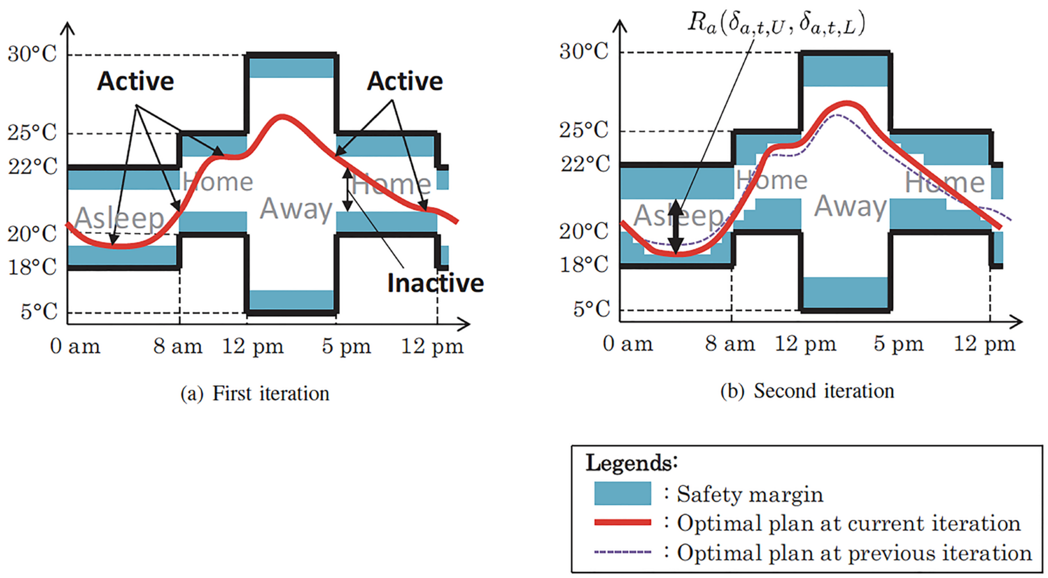
The robotic façade exploits the high thermal conservation capacity of the passive envelope. A window can be opened at precise angles so that the permeability of the façade to airflow can be adjusted. Setting the electrochromic material fully coloured – to its minimum solar transmittance value (3.5 per cent) – protects the interior from sun exposure during hot summer days. Setting the electrochromic material transparent – to its maximum solar transmittance value (62 per cent) – exposes the interior to the warm winter sun during winter days and enables solar heat storage. The PDLC film is independently controlled to supply the desired privacy and view. [Fig. 11]

These operations illustrate the necessity of trade-offs and clear objectives when automating a home for something as ambiguous as human comfort. As the CSH demonstrates, this is likely only possible through the synthesis of low-tech and high-tech systems. The performance of a high-tech, high-cost system like the robotic façade depends on the performance of the low-tech, low-cost envelope (thermal inertia, resistance, diffusivity). Different design configurations or material combinations yield different outcomes. It seems within the purview of the architect to determine a desired synthesis based on technical, aesthetic, cultural, and socio-economic criteria, though the specific interplay between low- and high-tech systems would best be determined with the assistance of physics engines plugged into computer-aided design software. Architects might then be free to explore the aesthetic impact of technological innovation on the users, residents, and the broader community. Orchestrations of dynamic visual elements such as robotic windows can be composed at design time by the architect, and experienced later by the inhabitant in response to specific physical or social conditions. As many façade configurations meet the performance requirements at any moment, the controller can choose from a library of compositions provided by the architect to evoke responses of delights and surprise from inhabitants and the public. [Fig. 12]

The PlaceLab

Operated from 2004 to 2008, the PlaceLab was developed as an apartment-scale shared research facility where new technologies and design concepts could be tested and evaluated in the context of everyday living.[22] It is now recognized as one of the first instrumented ‘living laboratories’ and was one of the most highly instrumented living environments ever built.[23] The 90m^2 one-bedroom home integrated hundreds of points of sensing, allowing researchers to study many aspects of life in the home.[24] PlaceLab experiments focused on building





(a) First iteration

(b) Second iteration

Fig. 9: A CCQSP illustrated by an acyclic directed graph depicting the resident’s schedule. Image: MIT Design Lab – Autonomous Systems Lab.

Fig. 10: Overview of the iterative risk allocation algorithm. Image: MIT Design Lab – Autonomous Systems Lab.

infrastructure and energy conservation, proactive health and disease management, and user interfaces. [Fig. 13]

The PlaceLab design included a backbone system that distributed data and power to modular 'infill' cabinets customised to accommodate sensors. Each infill cabinet contained a microcontroller and network of twenty-five to thirty sensors. Environmental sensors included floor and ceiling air temperature and humidity as well as ambient light sensors. Small wired and wireless movement sensors were located on nearly every object people touch and use, including cabinet doors and drawers, controls, furniture, passage doors, windows, and kitchen containers. These sensors detect on-off, open-closed, and object movement events, allowing researchers to infer occupants' activities according to which objects were currently in use. [Fig. 14]

An audio/video capture system processed images captured by architecturally integrated cameras and microphones. The video recordings enabled the creation of detailed descriptions of activities and annotations that researchers used to generate machine-learning models for home activity recognition. The rich sensing and observational records allowed researchers using the PlaceLab to focus on interesting research questions rather than the technical challenges associated with custom sensor deployments.

The PlaceLab, though conceived as a research facility, was not intended to be experienced as one. In contrast to most other ubiquitous computing research laboratories, the PlaceLab was not located on a university campus or in an office park; it was one unit in a newly constructed residential condominium building located in a vibrant and diverse neighbourhood. All other units in the building were inhabited by owner-occupants or lessees. The PlaceLab was constructed following contemporary residential development standards but was not an architectural experiment per se. Its focus was on living. The interior design of the space was contemporary, offering all of the typical amenities one might expect in an extended-stay flat. Participants, whose stays ranged from several hours to several months, sometimes likened the PlaceLab experience to staying in a well-appointed hotel suite.

During the years of its operation, PlaceLab served many research projects and generated thousands of hours of data recordings. To illustrate the nature of these studies, three examples are offered: 1) an evaluation of a context-aware temperature control system, 2) an exploration of technologically enhanced medication reminders, and 3) a study of a 'persuasive' remote control to change television viewing patterns.

Context-aware thermostat. Using ten weeks of data from a couple living together in the PlaceLab, researchers analysed the potential for context-aware power management to reduce energy expenditures for heating and cooling. The participants were unaware that their Heating, Ventilation, and Air Conditioning (HVAC) use was being monitored for this purpose and thus were unlikely to have modified their behaviour in ways that might not be representative of typical patterns. Researchers identified opportunities to save on heating and cooling using a proposed just-in-time thermostat that uses travel distance computation from GPS-enabled mobile phones to predict arrival times at the PlaceLab. Knowing arrival times allows the system to preheat or pre-cool the space, achieving the setpoint just as the resident arrives home.

Analysing GPS travel data from eight participants (for eight to twelve weeks each) and heating and cooling characteristics from four homes, researchers found potential energy savings that could augment existing manual and programmable thermostats. Although manual and programmable thermostats can save considerable energy when appropriately used, studies have shown that over 40 per cent of US homes may not use energy-saving setbacks when unoccupied. A temperature setback is a pre-programmed time window there the heating or cooling system is set to turn off or operate less frequently when the home is expected to be empty.

Fig. 11: The dynamic façade permits the regulation of visibility, incoming sunlight, and heat. Photo: MIT Design Lab.

Fig. 12: The CSH aimed to provide novel home experiences of privacy and display. Photo: MIT Design Lab.

Unfortunately, setbacks are often not used because they are difficult to programme, or because it's hard to predict when the home will be unoccupied. However, the PlaceLab study showed that using a GPS-enabled thermostat might lead to savings of as much as 7 per cent for households that do not regularly use the setback features. Significantly, these savings could be obtained without requiring any change in occupant behaviour or comfort level, and the technology could be implemented affordably by exploiting the ubiquity of mobile phones.

In the case of the context-aware thermostat, the individual's location in the world outside of the home becomes engaged in a feedback loop with the home's heating and cooling systems. In many ways, this relationship makes sense. The structure of the building has specific properties – solar gain, insulation, thermal mass – that influence the performance of its mechanical systems and can be optimised with more information about the occupancy status of the space. Notably, the absence of context awareness results in default to baseline performance levels. In this way, the system can be described as fail-safe. Introducing additional input that improves the ability of the mechanical systems to provide comfort is just another extension of a technological throughline that started with chimney flues and moved toward increasingly sophisticated and efficient central heating systems.

Context-aware medication reminders. In 2005, PlaceLab was used to evaluate an experimental adaptive reminder system for medication and healthcare practices.[25] The system consisted of three major components: 1) a handheld interface like a smartphone for providing reminders, 2) the *PlaceLab* sensor subsystem and 3) a central server that manages medical tasks and reasons over sensor data in real-time. Operating in consort, these components optimise the timing and location of the reminders to increase effective compliance. A volunteer participant was recruited and asked to adhere to a complex regimen of simulated medical tasks. The participant was presented with both context-sensitive and scheduled reminders at fixed times during the day. The degree of adherence to the regimen, and the participant's assessment of the usefulness of each reminder (while blinded to the reminder strategy being used), were evaluated over the course of a ten-day study. Quantitative and qualitative results allowed comparison of the efficacy of context-sensitive reminders over fixed-time reminders for adherence and perceived value.

By contrast to the case of the context-aware thermostat, the feedback loop for context-aware medication reminders cannot be fully articulated, as the universe of potential contexts is much greater than the binary distinction of 'at home' and 'away'. In this study, the participant received two types of technology-delivered reminders: reminders based on both place and activity and reminders based on fixed time intervals. The results suggest that the contextual reminders were more helpful overall, but both types tended to fail in the edge cases, where the participant's behaviour (for example, sleep schedule) did not match expectations. Further work would be required to tweak the reminders' parameters to address these issues and tailor the system to the user's idiosyncrasies. It is unlikely that a fully fail-safe context-aware system could ever be defined; the nature of medication schedules is such that a fallback to time-based reminders is inevitable.

Persuasive television remote control. In a 2006 study of media consumption, researchers explored how strategies for motivating behaviour change might be embedded within usage patterns of a typical electronic device.[26] In the contemporary world, daily screen time with computers, televisions, smartphones, and entertainment systems continues to rise, with potential adverse health effects. However, ubiquitous computing technologies also create new opportunities for preventive healthcare researchers to deploy behaviour modification strategies using those same devices. To explore these ideas, the PlaceLab sensor infrastructure was combined with a handheld smartphone-style universal remote control for a

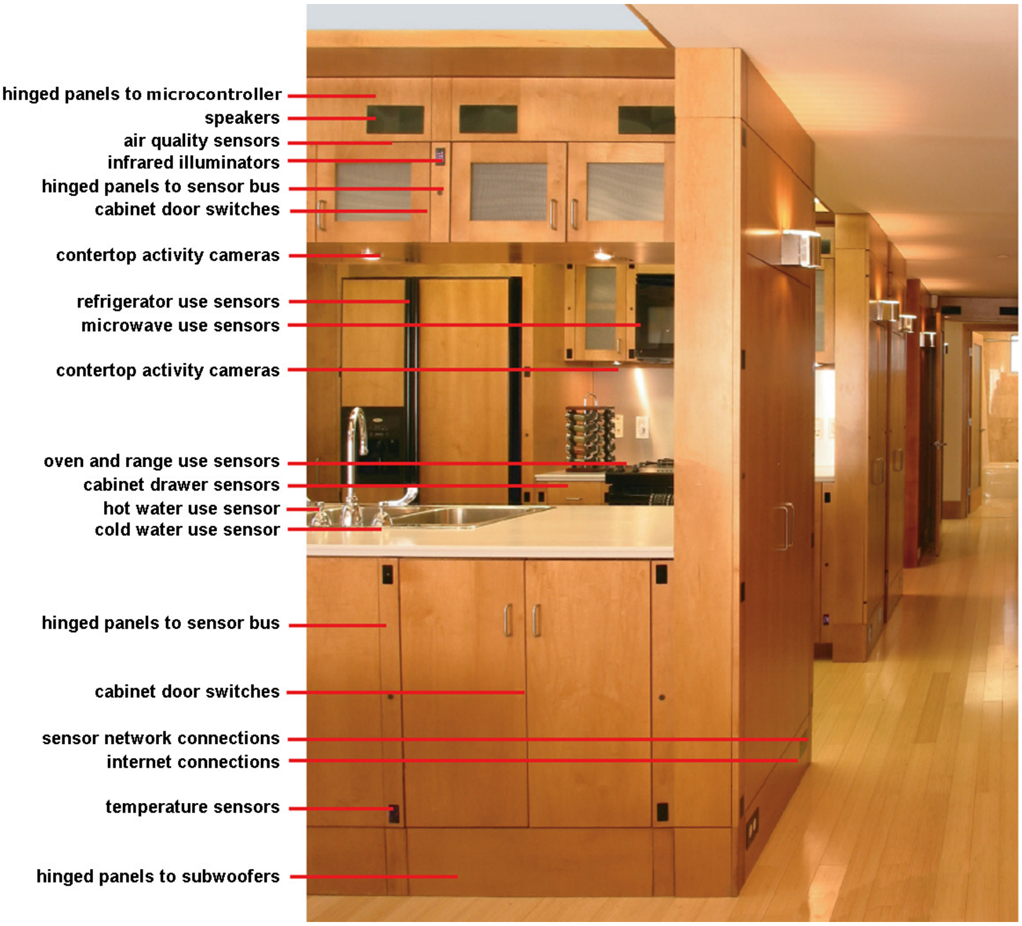


Fig. 13: The PlaceLab: a highly instrumented living laboratory to study the interaction of people and prototypical systems. Photo: Kent Larson.

Fig. 14: PlaceLab infill cabinets showing locations of sensing components. Photo: Kent Larson.

home entertainment system. However, this device's interface was designed to unobtrusively promote a reduction in the user's television viewing while encouraging an increase in the frequency and duration of non-sedentary activities. This device tracked daily activity patterns and used behaviour modification theories to persuade users non-intrusively to decrease their daily television use while increasing physical activity. Results from a fourteen-day case study evaluation revealed examples of how persuasive interface design elements might influence user outcomes without inducing a burden of annoyance.

This study provided evidence that behaviour modification strategies can fundamentally change the participant's behavioural patterns when embedded in an activity. While the study showed a reduction in time spent watching television (over seven days), the long-term impact of such an intervention is questionable. In the years since this work, there has been a trend in the reduction of television viewing overall,[27] but this has largely been offset by increases in the use of other screens, notably those of social media apps that use the very same persuasive strategies employed in this study to systematically increase engagement and screen time. These are examples of the unintended consequences that apply to the design of all systems that attempt to modify human behaviour.

CityHome

Shifting away from the live-in laboratory model of responsive architecture, we and colleagues began exploring robotic furniture to develop more dynamic urban housing that responds to changing needs of city dwellers. One concept for this, the CityHome*,* consists of a standardised building chassis and personalised, technology-enabled, transformable infill. It integrates new materials and systems to create urban dwellings that function as if they were much larger than their footprint suggests and strives to create rich living experiences for the occupants.

The chassis of a CityHome provides an efficiently built, open loft living space that contains all the fixed, long-life building elements with carefully located interface connections for power, data, plumbing and climate control. The construction method may vary depending on local codes and accepted design and construction processes. The infill of the CityHome consists of highly personalised, technology-enabled elements that can be rapidly configured and installed at the point of sale or lease in a matter of hours. Experimental infill prototypes include walls, tables, beds, and other furniture that translate and transform to minimise their footprint when not required by current activities. CityHome implements much of the sensing infrastructure developed for the PlaceLab to respond to the activities and needs of the occupants. Tiny wireless accelerometers, passive infrared sensors, and other data collection technologies are integrated into furniture, cabinetry, and other objects that people interact with. Activity recognition algorithms can determine basic activities of daily living, allowing the home to dynamically adjust the natural light, artificial light, audio environment, temperature, and configuration of spatial elements in response to the location and activities of people.

CityHome 200sf, the first CityHome Lab, was an 18.5m^2 prototype designed to develop, deploy, test and evaluate the mechatronics of hyper-efficient transformable infill and new home interfaces that allow easy transition between the functional states provided by the system. In this prototype, a central transformable unit encapsulated furniture for cooking, dining, sleeping, entertaining, working from home and more. A robotic wall system incorporated electric motors and pressure sensors for effortless reconfiguration, and a locking mechanism stabilised the system for seismic loads and delivered low-voltage power to electronics in the wall unit. [Fig. 15] A spatial user interface used voice and gestural control to allow customisation of the environment to current needs and preferences.[28]

CityHome 300sf (28 m^2) extended the dynamic multi-function living spaces model, emphasising vertical transformations.[29] A central living space featured a queen-sized bed, full-sized sofa, and

Fig. 15: Functional prototype of an 18.5 m² robotic apartment. Photo: Kent Larson.

Fig. 16: Functional prototype of a 28 m² robotic apartment. Photo: Kent Larson.

dining table to emphasise that comfort need not be sacrificed to live in small spaces. [Fig. 16] Underutilised space above the living area served as a docking location to store the furniture elements when they were not in use.

The concept of cleverly designed, transformable furnishings to improve the utility of small living spaces is not new. CityHome proposes better integration and, ultimately, standardisation of the components needed to realise visions of responsive homes. In some ways, this vision looks like a traditional home with easier-to-move furniture. This is perhaps the ideal representation of responsive homes, as the physical characteristics and aesthetics of the home are already well established, and the actuation enhances the flexibility of existing living patterns. However, as had become apparent in the PlaceLab case studies, challenges emerge when automation relies on predicting human behaviour, requiring ever more tweaking to handle the edge cases where the human response does not match expectations. In CityHome and related robotic design projects, significant engineering work was required to handle safety concerns encountered when humans, pets or other objects impeded the path of a robotic transformation. It was determined that human actuation is ultimately the safest mechanism and that electromechanical devices should be applied in an assistive capacity.

Discussion

Buildings often embody specialised technological innovation in response to particular conditions and problems. In some cases, this intervention is evident, determined by physical properties that provide measurable and predictable paths toward the intended outcomes. This attitude is exemplified by the CSH and Context-Aware Thermostat projects. Optimising for energy efficiency is a straightforward and largely responsive – as opposed to predictive – undertaking. Whenever prediction is used it is used in a fail-safe manner. Successful prediction accrues greater efficiency benefits than would be lost in cases where the prediction fails.

The accumulation of a high volume of precision data on the association between people and their environment may allow incremental improvements in the predictive ability of autonomous systems. However, high-tech interventions will remain less effective at increasing energy efficiency without the support of low-tech architectural improvements in the building envelope and mechanical systems. Furthermore, the practical approach is to design living environments that support adjustment of comfort and performance by managing the physical envelopes and systems, not the occupant's behaviour. In the CSH, the efficiency gains were achieved by active exploitation of the thermal properties of the passive envelope. It is critical that the intelligent control systems sense and manage the envelope and ultimately respond to changes incurred through human activity without trying to shape this activity.

There is a clear and present risk that autonomous systems are beginning to blur the distinctions between behaviour and performance. When an autonomous system is designed to achieve an outcome that incorporates human behaviour as an input, it will – no matter how 'intelligent' it may be – always resort to treating behaviour as a parameter to be optimised in achieving its target outcome. Wiegerling argues that AmI systems are reshaping the world without enabling human control over this process.[30] While in traditional system design, the performative premises of a system are determined in advance, and the evaluation of success or failure is straightforward, in complex autonomous systems involving intelligent agents the interactions between the system and the user remain open-ended. This fact leads Streitz et al. to argue for a complete reconsideration of the implications of intelligent environments.[31]

Ultimately, advancing and adopting such systems is a multifaceted issue depending on sociodemographic and personal preferences regarding privacy, security, trust, individualism, diversity, mobility, and lifestyle. For this reason, we contend that autonomous technology might best be reserved for control systems managing building physics parameters. We have shown how building physics will likely benefit from technological intervention, and autonomous agents could be constrained to operate on measurable ambient properties. The impact of this could extend to the aesthetic experience as well. Comfortable temperature, air quality regulation, responsive lighting and visual access can significantly benefit the quality of user experience while improving energy performance.

What remains to be answered is how thoroughly and productively functionality and utility might be transformed by integrating sensing and actuation technologies in architecture. Designing and implementing intelligent systems remains challenging because it is hard to determine their evaluation criteria. More importantly, these criteria have no precedent. They cannot be extrapolated from the mechanical paradigm or general theoretical speculation. Perhaps a comprehensive narrative will be provided someday after the fact.

Individuals have widely varying needs, preferences, and dispositions in constant flux. It is inconceivable that a single back-end utility could provide a sufficient mechanism for implementation across homes, users, and living circumstances. Substantial work on ambient intelligence and wellness applications enabled by PlaceLab illustrates the primary challenge: the system must be carefully and explicitly tailored to the disposition of the individual user, or it will sometimes fail. The undesired alternative is to shape the user's behaviour to conform to the system's expectations. This entails reducing behavioural freedom of expression, a compromise at odds with most human value systems.

A further challenge to human values arises from the opacity and complexity of autonomous systems and the users' inability to comprehend how they work. Because ambient intelligence technologies operate constantly and invisibly in the background, there is no transparency about what information is being recorded and to what degree residents have control over this information. Apart from privacy implications – especially as control applications are increasingly outsourced to third-party providers – the lack of transparency over what is being transmitted or manipulated leads to a form of cognitive dissonance that cannot be resolved through architecture.

This is not to say that utility or socio-economic values cannot be addressed through automation. As smartphone technologies have progressed in sophistication, they provide countless examples of how data-driven applications offer practical benefits to billions of users worldwide. However, a smartphone is not a home; it can be turned off and put aside. A home is different. It is meant to be a place of shelter and respite from the world's complexities. We contend that collecting and using home data for behavioural applications violates this sanctity and falls outside the purview of architecture. As tempting as it may be to introduce behaviour-tracking technologies into the home's fabric, there are many good reasons to advise against this practice.

Even if we forget the concerns about privacy and transparency for a moment, there are other practical challenges to overcome. For example, there is a considerable mismatch between technological and architectural lifecycles. Whereas the timeframe of the architectural renovation cycle is in decades, the average lifecycle of a consumer smartphone is approximately two years, and the useful lifespan of a home automation system is probably not much longer.[32] There are also concerns about the right person to select which systems and applications would be deployed in the home. Is it the architect or the homeowner? In PlaceLab, this decision was deferred to the participant, who gave informed consent before participating in the research. In the real world, this decision is obscure, as residential spaces are frequently turned over to new inhabitants, and visitors to instrumented homes are immediately subjected to home system observation.

There are additional philosophical objections to integrating general-purpose sensing infrastructures in architecture. There is an increasing awareness that the digitalisation of behaviour patterns can have significant psychological and social implications, such as the atomisation and polarisation of communities and the perpetuation of biases locked into untransparent artificial intelligence algorithms.[33] Algorithms rest on socio-political premises that remain invisible and may have obscure origins. Furthermore, the resolution of digitalisation can be poor. The nature of digitalisation is to sample phenomena and take momentary snapshots of the state of the world as it is available to the existing points of sensing.

Consequently, the machine's view of the world is profoundly reductive and lacks the nuance of human perceptivity. As Meredith Brousard explains, 'data is socially constructed', and it is dirty, too: 'Data is made by people going around and counting things or made by sensors that are made by people. In every seemingly orderly column of numbers, there is noise. There is mess. This is life.'[34] Because dirty data does not compute, technologists often have to make things up and purify the data to enable their programmes to run smoothly and thereby distort reality in favour of digital expedience. This makes reasoning possible on the average case where a clear yes/no answer can be provided but effectively eliminates edge cases that belong to the grey areas.

An alternative to integrating general-purpose behavioural sensing in architecture is embracing the standing condition. Today, the distribution of home automation and intelligent assistive devices is based on the consumer model. A device is brought into the home and configured by the end user. Users who no longer wish to engage with the device can disable or remove it from the space. As these units are self-contained, they are also fail-safe. Hence, removing devices does not create safety hazards; they only lose their prior utility. The alternative of consumer-based robotic systems was adopted in the robotic façade of the CSH and the CityHome. In both studies, the robotic components use sensing and actuation infrastructure to facilitate operation. However, they are still independently operable by the users as mechanical devices if desired or during power disruptions.

These findings are consistent with our home automation strategy tests in the CityHome, PlaceLab, and CSH experiments. We argue that residential architecture could employ AI and robotics when the parameters of sensing and actuation target measurable, tractable aspects of building physics, efficiency and ergonomics rather than less tractable aspects like social impact and user behaviour. Nonetheless, integrating these more personal technologies into our living environments remains compelling, despite the potentially negative impact on privacy, well-being and social interaction. In any case, a consumer-based distribution model is more appropriate for these applications, as it affords properties that limit the risks to home occupants.

We contend that this position is consistent with historical thinking about the role of architecture and its association with human behaviour. Rasmussen approaches architecture as an artificial environment intimately connected with daily human life, shaped around us, and configured to be used and lived in.[35] The architect intervenes as a theatrical producer who plans the setting for the actors (the ordinary users of the space) and must be aware of the natural course of human actions. The actors respond to staging and the script, but the interaction remains always one-directional. The script does not change in response to the actors' motivations, as this would result in improvisational chaos.

Architecture is, in many ways, synonymous with the stability derived from material design constraints. Buildings are big, heavy, and monolithic. However, autonomous robotic systems can quickly override these constraints unless deployed with deliberation and well-determined outcomes in mind. Designing and implementing intelligent systems that target human behaviour remains outside the realm of architecture. One reason is that such systems lack clear evaluation criteria. Their failure or success cannot be determined by means of the mechanical paradigm or historical and theoretical speculation on the architectural effects of the machine age. Autonomous robotic systems are unprecedented. A corollary of this newness is that robotic architecture and responsive environments are currently explored in the absence of a theory adapted to the new circumstances or a vocabulary of terms for describing their effects and consequences at the architectural level. Keeping a clear mind on the role of aesthetics, functionality, and performance in architecture, rather than relinquishing it to untested and unspecified artificial bits of intelligence, is a conservative but necessary step in maintaining domestic stability.

Notes

The order of the authors of this paper, Kotsopoulos and Nawyn, was selected arbitrarily.

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Biography

Sotirios Kotsopoulos is a researcher, designer, and educator working at the interface of design and computation. As an associate professor at the National Technical University of Athens and a research associate at the School of Architecture of MIT, he contributes to the research area of computational design and shape grammars, and explores applications of networked technologies, electro-sensitive materials and artificial intelligence in architecture.

Jason Nawyn is a research scientist at MIT, where he was a member of the team that built the PlaceLab during his post-graduate studies in human-computer interaction. His current work investigates the relationship between humans and the built environment, with a focus on the ways in which digital technologies shape human experiences and decision-making.