Adaptive Distributed Robotics for Environmental Performance, Occupant Comfort and Architectural Expression

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Abstract

The integration of adaptive distributed robotics in architectural design has the potential to improve building energy performance while simultaneously increasing occupant comfort. In addition, conceiving buildings as dynamic systems with the ability to adapt to the changing environments in which they exist, opens new aesthetic possibilities for designers. As the façade of a building is a common place to address issues of energy performance and occupant comfort, this paper presents a first prototype of an adaptive solar envelope (ASE). Its functions are to provide distributed shading, solar power generation through integrated photovoltaics, and daylight distribution. We describe the interdisciplinary design process, and illustrate the architectural possibilities that arise from a distributed systems approach. The ASE is expanded to work in parallel with an adaptive artificial lighting element. Rather than being preprogrammed, the systems adapt their behavior through interaction with the environment and building occupants. This adaptation to the user’s wishes is demonstrated successfully for the artificial light controller. We argue that with presently available technology and an increased exposure of architecture students and practitioners to adaptive design techniques, adaptive architectures will soon become a regular element of the built environment.
1. INTRODUCTION

Buildings account for over 40% of CO₂ emissions generated by western
nations. [1-3] Passive techniques, such as natural ventilation, solar
orientation and thermal mass storage, and active strategies, such as
photovoltaic (PV) elements and heat pumps have the potential to reduce
demand for heating and cooling, as well as artificial lighting in sustainable
architecture. For design, building simulation tools, such as the Design
Performance Viewer (DPV) [4], can be used to predict how a building will
perform energetically. As simulations are based on a series of assumptions
and simplifications, they can only offer educated guesses about the real
world performance of a building, and thus, fail to reflect the dynamic day-to-
day conditions that make up the environment in which a building will exist.

In addition to the previously mentioned approaches and applications,
building automation systems can be programmed to follow certain rules to
improve occupant comfort and building energy performance. For example,
moderating heating and cooling temperatures when buildings are assumed
to be unoccupied or lowering shutters at certain times of day to reduce
heat loss or gain. However, such automated building shading systems are in
most cases optimized based on preconceived notions of occupant desires
and for energy efficiency, rather than actual occupant desires. This is neither
a prerequisite nor is it an appropriate goal in and of itself. The system, while
having the potential to reduce energy consumption, should also take into
consideration the desires of the occupants for whom the building is (in
theory at least) designed for and around. [5]

In current systems, if a change in building use or occupancy pattern
occurs, there is no possibility for the building and its automation system to
adapt without the intervention of a specialist for reconfiguration. The main
reason for this is the understanding of a building as a static system, i.e., it is
built and programmed for a certain function, and then basically left
untouched for the rest of its lifetime. However, if we move beyond this view
of a static building, and conceptualize it as a dynamic system, we gain the
potential for increased energetic performance, increased occupancy
comfort, and new aesthetic possibilities. We believe that the technology and
capacity to design buildings from the outset as dynamic systems is currently
available, and thus, a building should be conceptualized with the ability to
adapt to shifting external and internal conditions.

Our understanding of an “adaptive” system is very specific and goes
beyond the typical architectural notion of preprogrammed motion, termed
“kinetic”, or systems that move based on sensor readings, termed
“responsive”. Responsive systems are often referred to as being adaptive
because they execute an action due to a certain sensor input, e.g., “if the
temperature drops below 19°C, close the window”. In terms of a robotic
system, this is a simple control law, and there is no adaptation. However, if
over time the control law evolves to “if the temperature drops below 17°C,
close the window”, i.e., the threshold temperature is changed without explicit human reprogramming, then we speak of an adaptive control system. Note that the responsiveness is still there, but in addition, adaptive control allows the automatic reprogramming of the responsiveness. We will employ this notion of “adaptive” for the remainder of this paper.

Adaptivity in architecture allows buildings to change their behavior in response to real world events as opposed to preconceived assumptions, and therefore offers context appropriate performance. Improving building energy performance can and should be done in a way that does not have negative consequences for building occupants. Ideally, the systems could learn through user interaction, and thereby adapt their behaviors to the desires of the occupant(s) over time. The system would be free to optimize itself for energy performance when the space is unoccupied, or could even nudge an occupant toward “greener” habits by testing the boundaries of what the occupant is willing to accept. In essence it would be an ongoing dialogue between occupant(s) and building, navigating their sometimes shared and sometimes contradictory desires. This ascription of desire to the building is legitimate as it helps us to conceptualize the building and “understand [...] its past or future behavior”. [6]

Adaptive architectural systems can be deployed at various scales and locations depending on the goal of the system. We believe that a distributed approach allows for local variation in response to internal and external factors, and thereby offers the most probability of negotiating the often conflicting goals of energy performance and occupant desires. The building envelope, acting as a buffer between interior and exterior environments, is a common place to address issues of energy performance in architecture. The envelope, or façade, is also a very important area in terms of architectural design as it is in essence the public face of a building. As shown in Figure 1a and 1b, the envelope can mitigate solar insolation, thereby offering reductions in heating/cooling loads, and improve distribution of daylight.

Figure 1: Various states of building envelope components: a) closed state, reflecting solar radiation, b) open state, allowing views and bouncing daylight into the interior, c) solar tracking state, optimizing for maximum power generation if PV elements are integrated, and d) “mixed state”, allowing multiple functions to be fulfilled simultaneously. It is the flexibility of the mixed state that gives a system the ability to adapt to user desires.
This paper describes the design of an adaptive solar envelope (ASE) that integrates the key functions of a façade into a distributed adaptive robotic system for the purpose of increasing on-site renewable energy production (Figure 1 c) and enhancing occupant comfort (Figure 1 d). In addition, we argue that approaching the design of buildings from an adaptive distributed systems standpoint opens new aesthetic opportunities. The paper is organized as follows. Section 2 reviews background and current trends of robotic systems in architecture. In Section 3, we present the concept, the potential and the current state of the ASE prototype. Followed by Section 4, which describes the adaptive control strategy. Finally, Section 5 concludes the paper.

2. ARTIFICIAL INTELLIGENCE / ROBOTICS IN ARCHITECTURE

There exists a long and rich history of integrating artificial intelligence and robotics into architecture. Some well-known examples are the works of Pask, Brody, Eastman, Rabeneck, Price, Negroponte, and Frazer. [7-8] While their ideas were well developed at various points from the 1960s to the early 1990s, it wasn’t until the mid 1990s that computational power became affordable enough for physical exploration to be widely available to students and practitioners of architecture. A rise in accessibility and affordability of microprocessors, such as the Arduino prototyping environment [9], has generated an explosion of kinetic, responsive, interactive architectural projects in recent years. [8] Many of these projects deal with issues of kinetic, solar tracking, and/or computationally driven facades, some examples include Hyposurface [10], Helioptix [11], and Adaptive façade [12]. As our approach addresses adaptive distributed systems in general and uses the façade as one possible incarnation of such a system, details on façade construction, functions and typologies are beyond the scope of this paper. The interested reader is referred to texts such as Facades: Principles of Construction [13] and ClimateSkin [14].

Parallel to the development of interactive architecture has been the development of Intelligent Environments (IE) or Smart Homes. Some notable projects from this field include the TRON Intelligent House (Roppongi, Tokyo), the EasyLiving project (Microsoft), the AwareHome (Georgia Tech.), the House_n project (MIT), and the Neural Network House (University of Colorado). [15] The later is of particular interest in its approach to balancing energy performance and occupant desires. The house is controlled by a centralized computer running a neural network which receives and processes sensor input in order to predict occupant behavior and adjust lighting, heating and shading in response. [16] The system adjusts its performance based on direct user input (turning lights on/off, adjusting heating, etc.), and predicts occupancy patterns through occupancy sensors and historic use patterns collected over time. This system embodies the
core aspects of our understanding of adaptivity, and offers many insights into how adaptive systems may be implemented in architecture. [5]

The work done in the IE sphere has tended to focus more on the networking of devices and multimedia applications, and has not focused on architectural design per se. There is, of course, blurring of boundaries, and this blurring is exactly what we are interested in. How can we integrate the creative design process of architecture and the visual and spatial effects of kinetics with the computationally intensive techniques of the IE community in order to create new architectures that are more sustainable and increase user satisfaction?

In order to succeed at increasing user satisfaction it is also important to consider how users will interact with an adaptive system. In our concept of an adaptive system the role of the occupant goes beyond the capacity to override the system. In fact, the very act of overriding is in itself an integral component in “training” the system through direct interaction (See also Section 4). We strongly believe that how the user interacts with the system should be “natural”. As Adam Greenfield wrote on the topic of ubiquitous computing, which he refers to as ‘everyware’:

In all of these scenarios there are powerful informatics underlying the apparent simplicity of the experience, but they never breach the surface of awareness: things just work. Interactions with everyware feel natural, spontaneous, human. Ordinary people finally get to benefit from the full power of information technology, without having to absorb the esoteric bodies of knowledge on which it depends. [17]

In other words, a window should work like a window, and a door like a door. A touch screen is not needed as an interface, and there is no need for a user to understand the internal mechanism. Take the example of a dual door-opening device invented by Thomas Jefferson and integrated into his home in Monticello, illustrated in Figure 2. When a user pulls open one door, its paired door automatically opens in unison. “As the device was concealed beneath the floor, its principle was not known until it was uncovered in 1953”. [18]

Figure 2: Jefferson’s dual door-opening mechanism. Adapted from [18].
While certain aspects of adaptive systems in architecture have little or no impact on design, for instance an adaptive control strategy for a traditional climate control system (the Nest learning thermostat [19] for example is a product placed in the building after construction is finished), others are intimately related with design decision making. Material choices, sizing and spatial configurations are extremely important in the design and function of these systems and can have a strong impact on the aesthetic result of the design. These decisions should be approached from a design perspective, not solely from a technical perspective, so that they may garner public approval and thereby ensure implementation of such non-traditional architectural projects. Engaging architects is the only way to develop the aesthetic potential of these systems in the built environment.

The following section will delve into the design process engaged in developing the ASE prototype. We will explore the development of the basic module and its behavior, and how that module scales from an individual component to a multi-agent system at the level of the building envelope. We will further explain how we see this distributed adaptive system interacting with other distributed systems that can be integrated into architectural design.

3. ADAPTIVE SOLAR ENVELOPE DESIGN PROCESS

The ASE 1:1 scale prototype, shown in Figure 3a, was developed to explore multiple aspects related to the implementation of adaptive robotic systems in built architecture. As shown in Figure 3b, this project is highly interdisciplinary, integrating concepts of renewable energy, kinetics, user interaction, adaptive control and architectural design.

Figure 3: a) ASE 1:1 prototype, b) interdisciplinary nature the ASE project.
The prototype is 2.25m high by 1.25m wide, and consists of 36 modular robotic components (See Figure 3a). The movement of the components can be defined by user control, by a solar tracking behavior, or run in a preprogrammed series of movements. The prototype was conceived as part of a network of interacting adaptive distributed systems that could be implemented at varying scales and locations within an architectural design. (See also Section 4)

The basic module of the ASE consists of a pair of stacked servos paired with light sensors, a microcontroller and a solar thin film cell. The various elements of the basic module are shown in Figure 4a-c. The stacked servo pair is mounted with pan-tilt brackets giving the module two degrees of rotational freedom, shown in Figure 5a-b. Figure 5c shows the hemispherical operational boundary allowed by the set-up. This freedom of rotation gives the components the flexibility to track solar movements throughout the course of the day/year.

Such a dual axis solar tracking device has been shown to increase daily power production from photovoltaic (PV) systems by 35-40%. [20] In addition, the energy production from solar tracking as opposed to static PV systems is more evenly distributed through the course of the day, as shown in Figure 6, which is beneficial in balancing energy production patterns with energy consumption patterns. While solar tracking systems offer substantial increases in PV productivity some of the produced energy will be consumed...
by the actuators. Further research for efficient actuation systems and mechanisms is needed to ensure net energy production, and thus, for such distributed systems to be feasible within an architectural context.

The initial inspiration for our solar tracking module came from Valentino Braitenberg’s Gedankenexperiment *Vehicles: Experiments in Synthetic Psychology*. [21] Braitenberg described how through building simple sensor/actuator relationships “behaviors” could be observed in man-made artifacts. One of the vehicles developed conceptually in the book used a pair of light sensors to drive a pair of motors. As shown in Figure 7, depending on the relationship of the wiring between the sensors and the motors the vehicles would express a “light loving” behavior or a “light phobia” behavior.

We adapted the basic set up for a Braitenberg vehicle by replacing the two motors with a servo motor. The rotational direction of the servo is defined by comparing the readings from two light sensors. As with the Braitenberg vehicle, by switching the relationship between the sensors and the servo, the behavior switches between a light tracking and a light avoidance...
behavior. Once a single Braitenberg servo was operating a second servo with the same setup was stacked on top of the first in a pan-tilt arrangement (See Figure 4b). This setup gives the component the ability to track solar movements without preprogramming solar tracking paths based on geographic location. The behavior of the module makes its installation location independent of programming, and also means that its behavior responds to local instances of overshadowing. This localization of behavior is essential in adapting to site specific and time specific events.

Once the solar tracking module was functioning we looked into applying the module to an architectural scale not by increasing it in size, but by increasing its numbers. The module can act autonomously, but it can also be clustered into small groups. Likewise, groups of clustered modules can relate to a window or particular interior spaces. These in turn, if proliferated, could make up the façade, or entire envelope of a building (See Figure 8).

The tiling pattern of the modules is not confined to a predetermined size or geometry. Solar thin film manufacturers offer the production of custom geometries, and an increasing number of colors and degrees of translucency, which widens the design palette open to architects. Triangles, squares and hexagons are the three basic nesting tiling geometries, shown in Figure 9, but semi-regular tiling patterns offer increased visual complexity without the need for entirely non-standard production of components.
In order to explore the aesthetic potential of custom solar thin film geometries, we selected a semi-regular tiling pattern, as shown in Figure 10, to develop into the built prototype. The pattern produces a high degree of visual interest through the use of only two repeating geometries. The semi-regular tiling pattern was also responsible for defining the underlying support structure, as the center point of each module defined a connection location between it and the support structure.

Figure 9: Regular tiling geometries, a), b) and c). Semi-regular tiling geometries, d), e) and f).

Figure 10: a) semi-regular tiling pattern chosen for ASE prototype, b) structural geometry defined by center points of tiling pattern, c) cluster of modules with support structure, d) geometric pattern of the support structure, e) proliferation of modules.
Because the components move independently of each other, and in response to varying internal and external environmental influences, complex surface patterns can emerge without the need to design and fabricate complex geometries. The complexity of the system is generated through its behavior rather than through non-standard components, as seen in Figure 11. Even with a simple tiling pattern many potential variations are possible.

The production of scale models and the iterative exploration of module mounting solutions was carried out through the use of CNC fabrication techniques including laser cutting, milling and 3D printing. The rapid back and forth between design and physical prototype allowed for the quick development of a custom mounting solution that was easy to assemble and install (See Figures 12 and 13).
The finished prototype ran as an installation for one month. At various times it operated in solar-tracking mode, user controlled mode, or ran a preprogrammed series of movements to demonstrate its various possible configurations, shown in Figure 14. [22]

We envision the ASE as one of multiple adaptive systems that could interact with each other in an architectural context. In the following section we will look more closely at our adaptive control strategy as implemented in an adaptive lighting node.
4. ADAPTIVE SYSTEM

As mentioned in the previous section, and shown in Figure 15, the ASE is part of a larger network, which at its current state is conceived of as having power generation, shading (both provided by the ASE), and artificial lighting components. The objective of this network is to provide adaptive light control in an office environment without compromising on the requirements of the user for shading and light levels. At the same time, power should be generated through the PV cells whenever doing so does not conflict with the desires of the user.

We emphasize that we do not envision a high-level controller to coordinate the interaction between the artificial lighting, the shading, and the power generation components of our system. Rather, each component is given individually the ability to adapt to its environment, which is composed of the respective other components, as well as the user. Since the desires of the user are by their nature unpredictable, and may even vary over time, the controller has to operate in an uncertain environment that can not be modeled. For these situations, Reinforcement Learning (RL), a type of Machine Learning, has been proven successful to find the optimal control law. [23] Simply put, RL finds the optimal control policy by trial-and-error, very similar to how a human would learn a new task: as shown in Figure 16, the controller (or agent) is presented with a state $s$ of the environment, it takes an action $a$ based on its current knowledge. After executing the action, the agent receives a reward $r$ representing how good or bad it was to take this particular action $a$ for the given state $s$. This reward is then used by the agent to update its knowledge about the environment, which is then available for the next decision point.
Several methods to store and update this knowledge have been proposed, out of which Q-learning has been well established, and empirically successful. [24] In essence, Q-learning tries to learn the value $Q(s,a)$ of a state-action pair $(s,a)$ by updating it as in Eqn (1)

$$Q(s,a) \leftarrow (1-\alpha) \cdot Q(s,a) + \alpha \cdot (r + \gamma \cdot \max_{a'} Q(s,a'))$$

where $0<\alpha<1$ is the learning rate, $0<\gamma<1$ is a discount factor, and $\max_{a'} Q(s,a')$ represents the maximum Q-value for that particular state for all possible actions. The learning rate $\alpha$ controls how fast new knowledge is acquired: if $\alpha$ is close to 1, previous knowledge is forgotten quickly, whereas if $\alpha$ is close to 0, the update is very slow. With $\gamma$, we can control long-term rewards: if $\gamma$ is close to 0, we are only interested in immediate rewards: if $\gamma$ is closer to 1, potentially large future rewards are taken into consideration.

The goal of the agent is to maximize its reward. When it is presented with a state $s$, it has two options: it can take the action that will lead to the highest return, i.e., that has the maximum Q-value, as in Eqn (2)

$$a = \arg\max_{a'} Q(s,a')$$

and thus, the agent “exploits” its current knowledge of its environment to maximize its reward. Or, it can choose an action randomly from the set of all the possible actions $A$, as in Eqn (3)

$$a = \text{rand}(A)$$

in which case, it “explores” the environment. This combined exploitation and exploration ensures that the agent tries different actions in order to find the optimal one.

As a demonstration of the artificial lighting component of our system, we implemented the lighting control strategy similar to that of the Neural Network House [25] for a desk light. The unit has a motion sensor to detect presence, a light sensor to monitor the ambient light, and a button for the user to turn the lamp on or off in a natural way. The hardware and software integration was done using the Arduino prototyping platform.
Q-learning was implemented using two tables, one for when the user is present, and one when the user is absent. In the former case, the states of the system are ranges of light levels, in the latter, the states are whether the lamp consumes energy or not. In both cases, the available actions to the controller are to turn the light on or off, and the respective Q-values are initialized randomly. When the user pushes the button, a penalty signal is generated, indicating that he was not satisfied with the last action of the controller, and an update of the respective table is performed. If the user is not present, the agent receives a penalty should it decide to turn the lights on.

Figure 17 shows an example for the learning process. For the occupied table and a light level that is too low for the user, the Q-values for turning the light on and off are shown. We can clearly identify the learning, or adaptation, of the light controller to the user. At the beginning, due to the random initialization, the agent believes it is better to turn the lights off, as $Q(\text{dark}, \text{light OFF}) = 4.2 > 1 = Q(\text{dark}, \text{light ON})$. This is against the desire of the user, who wants more light, and, thus, turns the light on, thereby penalizing the agent’s action. Due to the interactions, the Q-value for turning the light off decreases rapidly below the Q-value for turning the light on. Afterwards, the agent has learned the simple control law that “if the light level is in this range, the light should be turned on”. Note that no preprogramming of threshold values, or educated guesses of those values was necessary to obtain this rule. This demonstrates successful adaptation to the desires of the user.

Similarly, we have implemented Q-learning for solar tracking capabilities onto a single solar thin film module equipped with four in-plane light dependent resistors (LDRs) in a cross arrangement. [26] The servos were

![Figure 17: Learning progress of a desk light agent (for Occupied Q-table).](image-url)
allowed to rotate in steps of +/- 10° at each instant and the agent received a reward when each resistor reached the same value, meaning that the module is facing the sun. The agent has learned that its goal is to turn towards the sun, thereby demonstrating its location-independent programming.

Our current focus is on integrating these and additional systems into a larger office environment to demonstrate adaptivity in architectural and building systems at a large scale. Extending the ideas of adaptivity beyond artificial lighting control, we envision an even larger network of interacting adaptive systems co-evolving their behaviors with each other and building occupants, as sketched in Figure 18.

5. SUMMARY / CONCLUSIONS

The ASE project integrates techniques from robotics, machine learning, ubiquitous computing, and sustainable architecture in order to move toward architectural systems with the capacity to learn through experience, i.e., adaptive architectural systems. The distributed combination of these systems in built architecture has the potential to minimize artificial lighting, reduce heating/cooling demands, optimize on-site PV power generation, and increase occupant comfort. We have demonstrated that this approach also opens new aesthetic opportunities through the expressive nature of dynamic buildings that change their behavior over time. In order to explore the aesthetic potential of adaptive systems in architecture, we believe it is important to prototype them at a 1:1 scale. This importance arises not only in the complexities involved in developing working kinetics and electronics, but also to test the adaptive nature of the systems with human interaction.

While the integration of adaptive robotic systems into architecture holds great potential in relation to environmental performance, user
satisfaction, and aesthetic possibilities, it remains an area of architecture that is largely unexplored. This may be due to the steep learning curve of its interdisciplinary nature, but as an increasing number of architecture students and practitioners are exposed to these concepts and techniques adaptive architectures are bound to become commonplace in the near future.

Quoting from Stewart Brand’s How Buildings Learn: What Happens After They Are Built,

Two quotes are most often cited as emblems of the way to understand how buildings and their use interact. The first, echoing the whole length of the 20th century is, “Form ever follows function.” Written in 1896 by Louis Sullivan, the Chicago highrise designer, it was the founding idea of Modernist architecture. The very opposite concept is Winston Churchill’s “We shape our buildings, then our buildings shape us.” These were clairvoyant insights, pointing in the right direction, but they stopped short. [27] Maybe Brand also stopped short…

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