Responsive Architecture: User-centered Interactions within the Hybridized Model of Control

Tristan d'Estrée Sterk
The School of the Art Institute of Chicago, USA
The Office for Robotic Architectural Media, Vancoucer, Canada

In the September 1969 issue of *Architectural Design*, Andrew Rabeneck wrote about the use of cybernetic devices within an automated architecture. He hypothesized that the concept of 'flexibility' was introduced to architecture because existing building technologies were inherently inflexible. He argued that architects should use cybernetic technologies to produce completely new types of increasingly flexible, user-centered, buildings. Three years later, Yona Friedman wrote about the changing relationship between clients and architects. He said that a new design methodology was needed because architects could not assess the future spatial needs of building users accurately enough. Proposing a new model, he split architectural design in two complementary halves, hardware design and software design, reasoning that this would give users the opportunity to adapt built spaces to suit their needs. Both of these ideas describe approaches to the production of an architecture that can change shape and configuration in response to changing patterns of use. Rabeneck's approach illustrates the benefit of predictive technologies and automation, while Friedman's model illustrates the benefit of user intervention and direct manipulation. This paper discusses developments in the field of responsive architecture in relation to two opposing user-centered interaction methodologies. It proposes methods for controlling responsive buildings and suggests that human computer interaction methodologies need to be re-thought and extended when applied within intelligent, responsive, architectures.

Responsive architecture came to the fore in the late 1960s and early to mid 1970s when shortfalls within modern buildings led architects to question the design methodologies that were used within the profession. It was within this context that architects attempted to forge more appropriate forms of architecture and new, user-centered, design methodologies.
Though the development of responsive architecture was first driven by shortfalls within practice, its successes were informed by three forward-thinking ideas. These were: 1) that architects design systems, not just buildings,[1] 2) that feedback could be used as an architectural form generator, and 3) that the profession of architecture must respond to the changes that surrounded its practice.[2]
Supported by relatively recent developments within the fields of Cybernetics and General System Theory, architects were encouraged to think of buildings as dynamic user systems or feedback systems rather than as static objects. This shift enabled architects to rethink the existing modern ideals of form and function within the terms of behavior and fitness for purpose. By employing feedback as a new type of form generator, architects began to conceptualize a new architecture that could tie user needs, wants, and actions directly to architectural form. The realization that the profession of architecture had undergone serious quantitative change added further weight to this shift.
Working from observations about the way architects designed, Yona Friedman proposed the model of participatory architecture. He introduced the model in the belief that modern architects faced many new types of design problems that were caused by increasing client numbers as well as a significant increase in the degree of impact that single design decisions had. From here it was a relatively short step for people such as Nicholas Negroponte to recognize that the profession of architecture needed to change and that the systems and cybernetic approach to design offered a tangible model upon which such change could be based.
As someone interested in designing responsive buildings, I would like to frame this discussion differently to support a more detailed understanding of the systems that are required to actually construct a responsive architecture. Even though the participatory and feedback models of architecture are conceptually very similar one must understand that, at the technological level, both models are actually fundamentally different. They are different because the model of feedback supports arguments of automation while the participatory model proposed by Friedman supports arguments for direct manipulation. Though both models are very useful this paper supports a third model that unites each interaction methodology within a single, hybridized, model.
Hybridized models of control are not without their own precedents. Hybridized control techniques are often used within the field of robotics to produce intelligent machines[3]. These types of models support the use of higher-level reasoning and lower-level responsive processes, often scaffolding each together to produce flexible and robust control systems. Though commonly used in robotics the hybridized model also provides us with insight into the development of new human-computer interaction methodologies that unite direct manipulation and automation within a single interactive process. This paper explores the relationship between direct manipulation[4] and automated interaction methodologies. It discusses how each methodology may be woven together to produce useful hybridized control mechanisms for responsive buildings.

Early models for user-centered interaction in architecture

Architects have long understood that it is possible to change the way that users interact with the spaces and objects that surround them by integrating logical devices within an environment. Only recently have the devices required been cheap, powerful and small enough to be economically used within buildings. So, after four decades since it began, responsive architecture has finally become a sensible topic for designers and architects to explore.
With history in mind, two of the key models that were used by architects to design early responsive systems will now be reviewed. Even though these models are old they do offer useful principles and insights that advance our thinking today.

1 Pask, G., 'Architectural Relevance of Cybernetics', in: *Architectural Design* (1969), September, pp. 494-496.
2 Friedman, Y., *Towards A Scientific Architecture*, MIT Press, Cambridge Massachusetts 1975 pp. 1-4.
3 Coste-Manié, E. and Simmons, 'Architecture, The Backbone Of Robotic Systems', in: *Proceedings of the 2000 IEEE International Conference on Robotics & Automation*, San Francisco, California 2000, pp. 67-72.
4 'Direct Manipulation vs Interface Agents', Excerpts from the Ben Shneiderman and Pattie Maes debates at the Intelligent User Interfaces Conference, 6-9 January 1997, and at CHI 97 in Atlanta, 22-27 March 1997. Reprinted by The Association For Computing Machinery.

The feedback model and adaptive-conditional architecture:

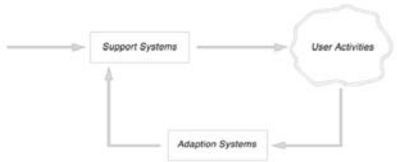
The model of Adaptive-Conditional Architecture was developed by Charles Eastman in 1972. The model built upon a lineage of ideas for automation that were first explored in the 1950s by the cyberneticist Norbert Wiener. Wiener's works were well accepted within architectural circles in the 1960s and 1970s as well as by computer scientists like Warren Broody who were interested in developing responsive systems, structures and objects.

When applied to buildings, the cybernetic model enabled architects to begin thinking of spaces and users as complete feedback systems. In these systems two-way relationships between users and spaces existed such that a user's influence upon a space did not go without the user being simultaneously influenced by the space. At that time, applying these types of ideas within designs that could adapt and change was all the rage. For example, in a September 1969 article in Architectural Design,[5] Andrew Rabeneck wrote that the basic aim of design is to avoid uncertainty through prediction. He reasoned that in order to design a building that has a longer useful lifespan architects needed to make predictions about the future needs of a building occupant. He hypothesized that any technological aid that could be used to assist in this process would be very useful to architects. From this position Rabeneck quickly carved a very elegant argument for the application of cybernetic technologies within an automated architecture, noting that both the fields of architecture and cybernetics seek to produce predictive mechanisms that solve real world problems. Charles Eastman described a slightly different version of this model in 1972, supplementing it with case studies of automation that were already in use.[6] With examples in hand he, like Rabeneck, made the bold proposal that feedback could be used to control an architecture that self-adjusts to fit the needs of users.

Eastman described the application of automated systems and used them to improve the fit between the needs of a building user and the spaces they occupy. He argued that automated systems could control building responses just as thermostats control the temperature of a room. Using this analogy he described an automated responsive system that consisted of the following components:

1 A series of sensors that would be distributed through an environment to monitor its change.
2 A control mechanism or algorithm that would run in conjunction with sensors, reading their output and comparing it to a predefined instruction.
3 An actuator. Actuators are devices that do work to change the environment. By their nature actuators must be distributed throughout an environment.
4 A setting for users to enter their preferences. Within the thermostat model this device is typically integral with the control mechanism however this relationship has been completely overturned in recent years.[7] In figure 1 the control setting and mechanism are bundled together under 'Adaption Systems'.

fig. 1 Eastman's model of adaptive conditional architecture.

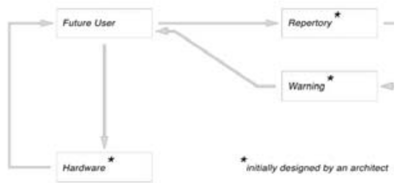


The model of participatory architecture:

The model of participatory architecture[8] introduces direct manipulation methodologies to design. Within this model, intelligent systems give users a means of directly controlling the outcomes of design processes without the use of automation. The model depends upon design process being split in two interconnected halves those being a 'hardware' and a 'software' system. By networking a hardware system to a software system, Friedman provided a model of architecture that gave users an interface for controlling buildings responsively. He believed this type of system would provide users with a means for adjusting spaces to meet their changing needs. He also believed that these systems would enable buildings to change over the long term on a tenant-by-tenant basis, as well as over the short term on a need-by-need basis. The components of his system were divided into the following parts:

1 A Repertory. As a part of the building's software system the repertory was designed to contain a list of spatial configurations that users could select in order to modify a space.
2 A Warning system. As a second software element, the warning system was designed to provide feedback that would inform users of the impact that their selection (from the repertory) would have upon the space or building structure.
3 A hardware system. Buildings aren't buildings without the physical things that hold them up, as such, Friedman proposed that building hardware consist of any physical building structure, envelope or internal partitioning system. He proposed that these components be as mobile and flexible as possible so that the software selections made by users could be reproduced within the building itself.

fig. 2 Friedman's model of participatory architecture.



The network that Friedman formed between hardware and software systems was composed of two interconnected feedback loops that converge upon the user. It is worth noting that unlike Eastman's model of an automated architecture, Friedmans' model requires a relatively sophisticated computer interface for users to make selections from. It is also worth noting the communicative nature of Friedman's model and its dependence upon symbolic, mixed initiative, interactions.

The link between old and new interaction methodologies:

Both Eastman and Friedman's models for interacting with responsive buildings suggest that new relationships between people and space will form when responsive systems are integrated within buildings. Each model enables people to manipulate the environments that they live within through a series of responsive actions.

Cybernetic theory describes how these actions work through the principle of dynamic stability. Dynamic stability is found within all feedback systems. It is present whenever two bodies interact with each other to achieve a task. One can witness it working between people and their tools, be these anti-aircraft guns, boat rudders, car brakes, or buildings. Cybernetic theory harnesses dynamic stability to increase the accuracy of automated systems, achieving this by enabling a system to rock back and forth between two op-posing states of correction. The simplest example of a dynamically stable system is a boat moving toward a target by carefully oscillating its rudder from left to right in order to find a common heading. Similar concepts apply to the temperature control of a room, or in the frequency control of a car's anti-skid braking system.

As a concept dynamic stability can be used to enable a very simple feedback device to automate simple tasks that help free people from work that they would otherwise need to perform. To go further, dynamic stability also enables an automated system to outperform a person who is doing the same job, improving the systems overall performance or safety. For example by removing the need for a driver to concentrate upon controlling a car brake skillfully enough to prevent its wheels from skidding, drivers who have cars with anti-skid braking systems are left with a single very simple operation to perform – 'braking.' As such feedback mechanisms can be used to encapsulate many complicated operations into a single, symbolic action. It is

5 Rabeneck, A., 'Cybermation: A Useful Dream', in: *Architectural Design* (1969), September, pp. 497-500.
6 Eastman, C., 'Adaptive-Conditional Architecture ', in: Design Participation, Proceedings of the Design Research Society's Conference Manchester, September 1971, Academy Editions, London 1972, pp. 51-57.
7 Once integral, control settings are now often removed from the control mechanisms that they interface with to control mechanisms. Today we can often provide preferential settings remotely, for example via telephones and or TC/IP connections.
8 Friedman, Y., 'Information Processes for Participatory Design', in: *Design Participation, Proceedings of the Design Research Society's Conference Manchester*, September 1971. Academy Editions, London 1972, pp. 45-50.

here where older, well-established concepts such as dynamic stability meet current human-computer interaction methodologies in a compelling way and where mixed initiative interaction methodologies take over. From this point we may wrap up some of the key similarities and differences between the Eastman and Friedman models and begin to seriously ask about how responsive architectures are going to be built today.

Control as a product of feedback and direct manipulation

It is clear that both Eastman and Friedman's models provide different approaches to solving the same problem and that each model has its strengths and weaknesses.

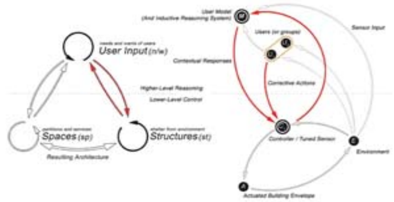
Eastman's model for automation provides an example of a machine led, systems approach to control that is suitable for producing simple logical responses, while Friedman's model for participation provides an example of user led control. Eastman's model relies upon many hundred or thousand low-level distributed devices running in parallel, while Friedman's model relies upon centralized high-level devices that are highly communicative and capable of performing symbol manipulation activities. Eastmans model, with such a weighty dependence upon distributed computing demands a new type of coordinating control architecture, while, Friedman's model as a communicative system depends upon mixed initiative interaction methodologies. Today methodologies from human-computer interaction, artificial intelligence and robotics provide models that can unite these approaches into a single model. These methodologies realize that each form of interaction; direct manipulation (deliberative control) and automation (reflexive control) have a useful purpose. Hybridized models combine each to produce a model that is both self-regulatory and participatory.

As a background note it is worth mentioning that hybridized methodologies were developed when conventional programming techniques struggled to process environmental and user input in real-time. As such the development of responsive architectures strongly follow the development of robotic systems because each type of system must be capable of analyzing stimuli from numerous parallel systems quickly and accurately. Recognizing that Eastman's and Friedman's models provide us with opposing but complementary solutions to the same goal we now ask: can a hybridized approach help us produce a new control system for responsive architecture?

The hybridized model of control:

The hybridized model of control is useful to responsive architecture because it enables both lower-level processes such as those employed within simple (automated) feedback systems to be incorporated with higher-level (deliberative) intelligent processes. [9] More importantly the hybridized model can also be used to produce responses that have adjustable response criteria, achieving this by using occupant interactions to build contextual models of the ways in which users occupy and manipulate space.

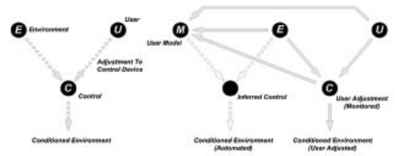
fig. 3a (left) and 3b (right) – Interactions Within The Hybridized Model Of Control (Sterk).



The hybridized model of control (shown within 3a) has three major parts, two types of connections between parts, and one implied connection labeled 'resulting architecture'. The parts consist of: 1) user input, which provides users with the means of controlling or manipulating responses as well as a model of the user and their interactions within an environment; 2) a building structure that has a responsive capability which enables it to respond directly to environmental loads; [10] and 3) spatial responses that are used to control the partitioning and or servicing of internal spaces. To add further detail to the model we can now describe the connections between responsive technologies and occupants. The base upon which higher-level systems and occupant interactions are situated is a simple feedback system. For clarity, figure 3b depicts just one base system, and categorizes it as a lower-level element. One should note that, as within Eastman's model, a typical building would require several hundred lower-level systems to work in parallel and simultaneously. These low level systems are composed of three parts, 1) a sensor within an environment, 2) a digital or simple analogue control device such as a bank of tuning resistors that are assembled to work with the sensor, and 3) an actuator that is controlled to do physical work within the environment. Both the sensor and the actuator must be positioned within a common environment for the system to work as a self-regulating and dynamically stable feedback device. Upon this lower-level system, two higher-level forms of interaction are now discussed, these are: user interactions, and user models. When considering the precise relationship between a user and a lower-level system one may conceive of users' interactions as being corrective. For example a user will typically correct or adjust the behavior of a lower level system (such as a thermostat) to meet perceived changes within comfort at a particular time and within a particular context. Figure 3b depicts these interactions and labels them as 'corrective actions.' Corrective actions are instances of direct manipulation that help simpler, automated systems perform well.

A 'User-Model' provides the hybridized model of control with yet another level of responsiveness. By watching an occupant interact with a space and by collecting environmental data about a space, a contextual model that describes occupant interactions can be produced. Figure 3b locates this process within the 'User-model' while figure 4b describes the logical structure of the user-model as an inference engine. The user model is linked into the larger control system in two ways, firstly through a series of sensors that collect: information about the environment, and secondly though a series of sensors that collect information about the corrective actions made by a user. By collecting these corrective actions (also shown as 'adjustments' within figure 4a), and by noting the environmental context that surrounds a corrective action, inductions about individuals and groups can be made. These inductions are important because they help the complete system produce responses that are contextually appropriate.

fig. 4a (left) and 4b (right) – Logical structure of the 'user model ' to produce inferred & contextual responses.



The principles that drive the user model are shown within figure 4a and 4b. Figure 4a reiterates the general case of a user interacting with a control mechanism while figure 4b expands the case to illustrate the logical structure of the user model as an inference engine. The inference engine performs operations on tables of data that are collected from different types of environment information (i.e. temperature, time, wind speeds, air pres-sures, internal and external light levels), user information (i.e. non-personalized space use patterns, degrees of activity, locations and time of activities), and data about corrective actions made to lower level control devices, (i.e. any adjustments made to devices such as light switches, thermostats, air conditioners or automated blinds). By collecting all of this information inferences may be made about the context in which users are likely to interact with and adjust their environment. These inferences can be used to produce contextual responses that lower level systems are incapable of generating by themselves.

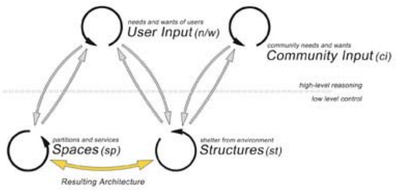
9 Coste-Maniè, E. and Simmons, R., 'Architecture, The Backbone Of Robotic Systems ', in: *Proceedings of the 2000 IEEE International Conference on Robotics & Automation*, San Francisco, California 2000, pp. 67-72.

10 Sterk, T., 'Using Actuated Tensegrity Structures to Produce a Responsive Architecture ', in: *Proceedings of the 2003 Annual Conference of the Association for Computer Aided Design in Architecture*, Indianapolis, Indiana 2003, pp. 85-93.

Networks of hybridized control:

Aside from offering a mechanism that controls the responses of a single building, space, or element, the hybridized model also can be extended to control responses across networks of buildings, or across multiple boundaries that separate spaces within a building.

fig. 5 – The networked model of hybridized control (sterk).

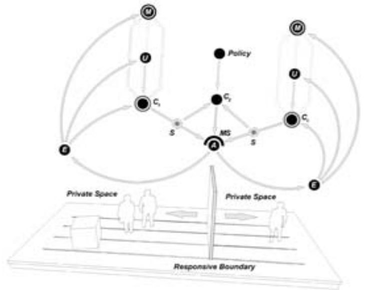


While the extended model of control (fig. 5) maintains the structure of the hybridized model it also supplements it with a second, community driven, control process. This second tier of control is required to coordinate two unique types of responses that are produced within the network: 1) responses upon coincident boundaries, and 2) responses across adjacent spaces or building elements. In each case different relationships between spaces and the lower-level components embedded within them determine the shape of network.

Coincident boundaries consist of any physical boundary that separates two or more spaces. Responses at coincident boundaries must be coordinated to ensure that boundary responses do not negatively impinge upon any space. For example, consider a moving (shared) partition wall that separates two unique spaces. Note, the actuator or actuators located within the shared wall are accessible to two independent control processes that need to be coordinated to ensure that the most appropriate boundary is maintained. One can conceive of an independent control process that coordinates the boundary as a community process (C2). This process works by building a secondary control loop that monitors actuator use and restricting it when required.

One should note that this is essentially the same process for scaffolding simple control devices to produce complex behaviors that Rodney Brookes outlined within his theory of subsumption architecture.

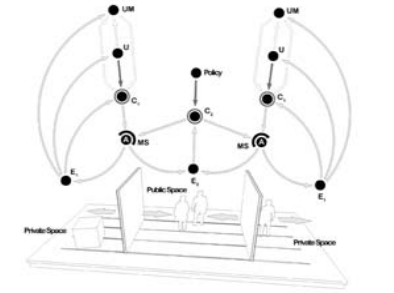
fig. 6 The networked model of control for coincident private bounaries.



Responses between adjacent spaces and elements differ significantly from the previous case (fig. 6) because the division of space no longer results in two control mechanisms sharing a common actuator. The significance of this change is outlined within a new principle. That for links between responsive networks to be made, some form of common element (i.e. a sensor or an actuator) must be present. For example, when two spatial boundaries are coincident an actuator becomes the common linking element, while when adjacent spaces or elements are present the common link becomes a sensor that monitors the shared space or element.

When responses are networked across spaces, the shared environment generates a network condition in which at least two new lower-level feedback systems provide the link between networked responsive systems. Figure 7, depicts an instance of this case and illustrates the relationship between another higher-level community control mechanism (shown as a policy) and the lower-level control policies used to condition the space. To better imagine how this system would need to operate, think of a public corridor within

fig. 7 The networked model of control for intermediate elements and public spaces.



a building that must coordinate and maintain several boundary conditions. In this instance, the coordinating control system must ensure that individual boundary responses do not negatively impact upon a common space. To do this a second tier control device (C2) must moderate each system with sensor data collected from the common environment. This example can be rethought and applied to many aspects of a building, for example instead of considering the protection of a common corridor space one may think of applying this system to a common structural element and the impact that two responsive building envelopes might have upon that structural element. In either case these models enable responsive elements to be controlled such that the integrity of a larger system is maintained.

The precedent model of participatory architecture and the notion that feedback can be used as a form generator for architecture both held significant positions within the discipline during the late nineteen sixties and early nineteen seventies when architects questioned the design methods they used. Though these models did not spawn a new architectural industry for us to build upon, they have provided us with a foundation upon which understandings of responsive architecture may be built and critiques of current architectural design methodologies can be made.

This paper, after examining two important precedent models of user-centered architectures, proposes a third model, the hybridized model of control, to illustrate how the principles of direct manipulation and automation can be applied to produce more sophisticated architectural responses that are both participatory and automated in nature. The paper also briefly examined some of the principles that enable the hybridized model of control to be extended into a networked model of control, and illustrated the need for responsive architectures to seriously evaluate the role of communities within new types of responsive processes.

Finally, after illustrating the impact that responsive systems have upon buildings and building occupants the paper suggests that human-computer interactions within responsive environments are much more stratified than precedent models and current human-computer interaction methodologies have suggested. As such it is becoming increasingly apparent that new human-computer interaction methodologies are needed and that the issues presented within responsive architectures could well provide the driving influence of these developments.