Architecture and Neuroscience

ANDERS NEREIM
School of the Art Institute of Chicago

In March of 1962, the Industrial Design Education Association held a remarkable meeting in Urbana, Illinois. Funded in part by General Motors and the National Science Foundation, it brought together key architects, designers, critics, and a neuroscientist. We can look back now to the group's published discussion[1] and see signs of some galvanizing trends of the late 20th century. A similar moment exists right now for architecture, as it begins to borrow from more recent discoveries in neuroscience and mathematics.

At that conference Serge Chermayeff and Sibyl Moholy-Nagy represented architecture and the approach of the Bauhaus, as reincarnated at the Institute of Design in Chicago. They had a modernist's belief in the logic and logistics of creativity, exemplified by the way Ray and Charles Eames took wartime inventions of necessity back into the mainstream of peacetime commercial design. Jay Doblin also represented the Institute of Design, but his interests had more to do with strategic planning and what became the savvy marketing critique of the late 20th century. Heinz von Foerster, who had recently perfected the foundation of computer-based vision,[2] begun during his wartime biological, electrical, and cybernetic research, fit right in to their discussions about design and ordering systems. Von Foerster's great-grandfather had been one of the chief architects of the Ringstrasse in Vienna, and the highly organized philosopher (and architect manqué) Ludwig Wittgenstein was a close relative.[3]

Both Chermayeff and Foerster expressed a need to bring together their research on ordering systems, to deal successfully with a radical increase in the amount of information. This was 1962. Just a few years later, the media theorist Marshall McLuhan would rhetorically put this continuing problem into a new and lasting cultural light, suggesting that the intractable medium was in fact the message itself. For the moment of that conference, however, the shared goal was bringing together disparate fields of knowledge about ordering systems — architectural and informational — fields that suddenly seemed immanently meld-able. Given the world's need for designs of all types to deal with its increasing complexity, and given a new (for that time) understanding of exactly how the brain recognizes and processes complex visual images, there was hope for a shared trajectory in the rapid development of intelligent and intelligently designed products and services.

Today's popular designs, such as the cell-phone-PDA and the Internet, clearly respond in their own ways to this shared trajectory. Bots, or active helping agents, and embedded control devices, are an integral part of industrial design's current methodology and pedagogy. Architecture is today at the cusp of a similar development. The work of Greg Lynn has fostered an appreciation of the computation of dynamic systems as a creative tool in its own right. Flash-savvy programmers, conversant in lingo and action-script, crowd our skateboard parks and architectural studios. It is a very small step from this situation to one in which we can develop an event-driven architecture with sensate embedded control devices. We need only a few more insights.

In the 40 years between that prescient conference, and his death at 90 last year, Heinz von Foerster watched over the continued development of information architecture, thinking machines, and the discovery of the mind's own deeper mechanisms for ordering visual systems. Although today it is still difficult to say just how the mind deals with language and abstract non-visual associations, much is known for sure about the processing of images and the organization of our gray matter.[4]

Central Processing Units, or C.P.U.'s, have grown more powerful and smaller, and have been distributed into networks. Throughout this growth and distribution, however, the computational paradigm has remained almost the same, as it was when Foerster's wartime contemporaries conceptualized the first electrical thinking machines. All of these machines rely on a strict, dependable instruction set, whether it is precise, hexadecimal machine language, "C," or natural language scripting.

Today's massively parallel distributed computing still relies on these first principles, even while it resolves the partial differential equations that model dynamic systems like flight through a fluid medium, or explosions of disease or radioactive particles. But still, certain problems seem easy for living systems to compute, while they remain curiously difficult for manufactured computers. New techniques such as fuzzy logic, weighted decision trees, and subsumption architecture have resolved a few of these intractable problems, but other basic and important problems remain curiously un-computable by common methods.

Foerster's early successes with machine vision made it seem reasonable to stick with the same computational paradigm for later research. After all, we think of vision as one of the higher animal functions. And we think of walking as one of the lower animal functions. But this assumption was deceiving. As simple and lowly as walking seems, it has proven devilishly hard to make a machine do it. The variety of gaits used by animals as they negotiate varied terrain was among the most difficult behaviors to model successfully using the old C.P.U. paradigm. It was difficult even when a human was substituted for the C.P.U.

But years of trying to model, in a programmed C.P.U., certain processes that are common in living, walking, and swimming organisms — such as the variety of locomotion that is so necessary for their survival — led to few new insights. Advanced biological research was unable to isolate the necessary and sufficient electrical data for walking, in part because that data was always dirtied up by all of the other things an animal was doing and thinking about. Walking always seems to come along with a noisy higher purpose.

These standard robotics investigations, focusing on programming and biological measurements, needed a breakthrough for an adequate understanding of the workings of a set of legs. That breakthrough happened with purely mathematical investigations of strange attractors. It was the nature of oscillations, their variety, and their manner of supple change across this variety, following on developments in chaos theory that gave the necessary insights, which came about ten years ago to Ian Stewart among others.[5] It is important to remember that the main popular insight about chaos is that it is just pattern by another name, only sliced from reality in a different direction, that's all. Coupled with this was another insight: that walking was fundamentally a lower behavior, not located in the brain like the visual cortex, but more likely in the spinal cord, involving a much simpler electrical activity than the associative processes we use in our minds to recognize a building by Le Corbusier, for instance.

To better understand this elusive simplicity, we can look at the growth of nerves in very primitive animals, starting with the first evidence of coordinated nervous activity in cells. The ancestors of neurons were slightly differentiated cells in ancient creatures that were like today's sponges, jellyfish, polyps, and hydras. Curiously, some of these creatures are more like neighborhoods of cells than a singular organism. They can be pushed slowly and gently through a very fine screen, until the creature gets dissociated completely into its separate cells, without killing it exactly. If that weren't amazing enough, these cells can then, all by themselves, reconstitute their "animal" through a variety of chemical traces, with each of the three types of cells taking up their proper location in the expanded field that is the organism. The more nervous cells are mixed with, and only slightly differentiated from, the rest of the cells.

They take a leading role in the over-all contractions which happen as a slow propagation of electrochemical waves passes, for a period of about three seconds, through the creature — or the neighborhood — while it feeds and respires, which are, happily for the simple creature, the same thing.

The beginning of an identifiable and functional nervous net ring, and its useful regular nervous oscillation, occurs in jellyfish, which are only slightly more complicated than sponges. Rhythmically ingesting water and food, and moving to facilitate that, all at the same time, the jellyfish needs a coordinated set of nerves that communicate with each other. In the coelenterate, propagating nervous waves spread at about 20 cm. per second,[6] throbbing or oscillating slowly, and it is this which allows the free-swimming jellyfish to move and eat as it goes.

Although these nervous oscillations are very slow to propagate compared to the reaction time of a sports star, they can oscillate like that for days on end, while continuously traveling over 450 miles. The behavior of this nervous net can be approximated with very simple circular chains of inverting electronic buffers, with variable propagation delays introduced with simple capacitor and resistor which holds and then release the electrical pulse. The symmetries of these chains, as

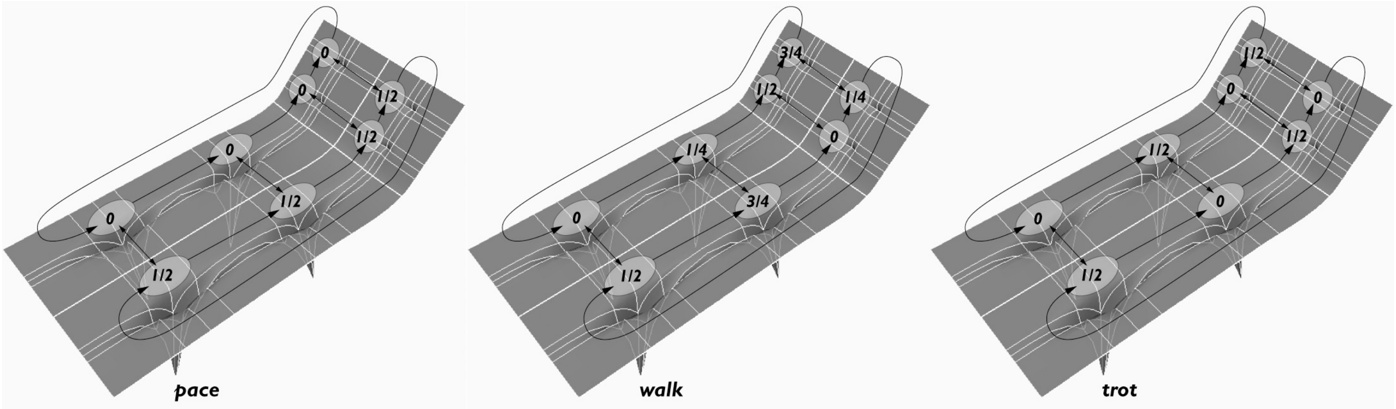

Fig. 1. The neural topology and mathematics which underlie the various gaits of animals.

evidenced by their behavior, are apparently remarkably invariant over the entire animal kingdom, according to Ian Stewart.[7]

Similar circuits comprised of decentralized ganglia, or groups of coordinated if relatively unintelligent neurons apparently underlie locomotion in animals from across the phyla — from the speedy cockroach, to the swimming lamprey, to the graceful higher mammals. I say apparently, because these ''central pattern generating'' ganglia have only recently been definitively identified and physically isolated in the lamprey.[8] But the mathematical topology that for all appearances now seems to underlie these neural mechanisms is known, and has even been physically modeled.

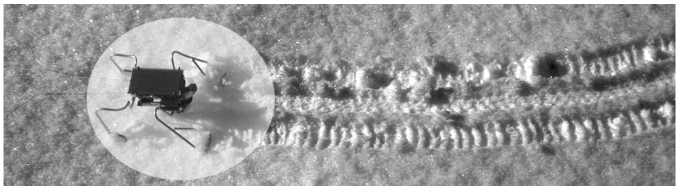

Fig. 2. Walking gait has been physically modeled using very simple electronics.

These constructed models, based on preliminary work by Mark Tilden of the Biophysics Division at the Los Alamos National Labs, have improved the performance of artificial walking locomotion by an order of magnitude over a wild variety of terrain. Tilden's physical models do not involve computing the way a C.P.U. does it, via precise hexadecimal digital instructions. They make use of central pattern generators, which can be influenced by adjacent connected CPG's and sensors.

They adapt their oscillations to work efficiently in different loading conditions.[9] They are in a sense tuned, rather than programmed. To hear Tilden describe the robust adaptive advantages of these potentially microscopic entities[10] is to understand for a moment some of the fears conjured up by Michael Crichton in his recent book ''Prey.'' In truth, while the military obviously has its eyes on this technology, Tilden is also very interested in its use for walking minesweepers, wheelchairs, gurneys, and stretchers.

Tilden's electronics represent a radical repurposing of very simple items designed for different uses, and they occupy an order of functionality just below the microprocessor and the memory chip. They involve an electrical behavior that is not exactly digital, although it underlies much of what we think of a digital computing.

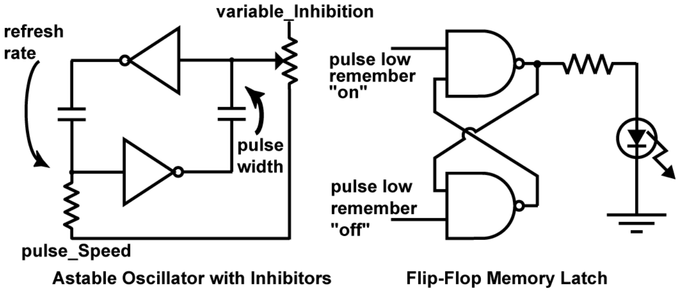

Fig. 3. Tilden's simple neural net electronics exhibit electrical behavior that is not exactly digital. A flip-flop (1 or 0) memory element has been configured to emphasize digital behavior.

This is behavior that needs to be tuned, like a very old radio, rather than instructed. It is somewhere between analog and digital behavior — somewhere definitely similar to the behavior of living neurons. It should be noted that radical repurposing of genetically predesigned mechanisms is at the root of most of evolution, according to Richard Dawkins[11] and Stephen Gould.[12] How we understand this type of autonomous lower nervous behavior, and use it in our designs, will determine the development of an architecture of wider material investigations — one that is driven by event.

It has become easy to think of most new products that make use of electronics, such as a DVD player, as belonging to the order "electronics." Appliances like refrigerators which we already knew "how to use" before the advent of embedded electronic control systems are more difficult for us to re-categorize, for the moment.

Our current perception of the realm of architecture and its materials is even more difficult to change in this light. We have all heard about the smart house, one that has been colonized by a junta of appliances — some hidden, some out in the open — that communicate by radio waves about our needs. Signaling secretly right through our power systems and the air we breath, they purport to solve simple problems for us, all the while keeping us entertained and educated via broadband. This sort of intelligence, however, is based on the old paradigm of C.P.U.'s, however fluidly they communicate over their various networks.

The research I have been describing, which began to achieve coherence across disparate fields, and produced results only over the last decade, involves examining the way decentralized weak computation and autonomic nervous systems can be modeled and used. My theory is that this mode of autonomous control will pay benefits of robust behavior in an event-driven architecture, for the same reasons that it has paid dividends in walking systems. These are systems too simple to get so confused that they need to be rebooted. They are like your heart — which operates on similar principles — which is the reason not too many of us ever need to feel the high voltage paddles on our chests.

The cost per transistor in our computers is dropping down to the point where we might want to consider just imbedding a PC wherever a simple task needs to be done — any task. But these silicon-based electronics, while definitely solid-state material, currently have their own specialized manufacturing processes that are separate from those which lead to architecture. While we can conceive of embedding the foreign computational device, as I have in some of my own previous projects, we don't yet conceive of its integral manufacture as an indivisible part of a building product, like the paper on the back of insulation.

The necessary integral manufacturing processes are being developed in other economic arenas, however. The E-Ink business venture relies upon a modified ink-jet printer technology to imprint very simple electronic circuitry and reflective display technology directly into and onto paper.[13] Paper is a widely used product that has a place in both architecture and product design. It is this seamlessly embedded intelligence that will bring the most interesting changes in how we conceive of a sensate, alert, and responsive architecture.

In my research, I still need to use common separate electronic components, so I can wrap my fingers around them, but I try to conceive the work in a way which points toward a time when these electronics can be manufactured as an integral part of the building component we want to make sentient, alert, and responsive. I am also interested in deploying these sentient systems within energy grazing systems that use only what they can get easily and naturally — parasitic when necessary, but low impact in general. I want to conceive of these new projects as feeding naturally rather than being fed intravenously.

I have previously designed somewhat autonomous responsive systems that relied on CPU's and were fed intravenously, or plugged in to the wall.

This is a piece of furniture born out of the pain in the back of the neck which I experience typically when writing a paper this long, while sitting in front of a laptop computer. It is very easy to ignore a message popping up on the screen, telling me to take a break and stretch, because it never comes up at the right time in the flow of my thoughts. Someone can even tell me that dinner is waiting, and I still put off getting up until a series of thoughts is finished. Someone walking up and grabbing me by shoulders will do the trick, however. Physical intervention will most effectively interrupt my slumping, hunching, frozen up behavior. This piece of furniture is designed to notice that particular unhealthy behavior pattern, in which only my wrists and fingers are moving slightly for long periods of time, and offer me a physical invitation to correct my posture.

In its initial construction and beta testing, the piece fell into the central processing rut I alluded to earlier, by relying on machine vision and the exact correction of a user's posture. A simple camera designed to recognize and count blobby beans on a conveyor belt, and a direct descendant of Heinz von Foerster's machine vision research, would watch the user and send precise numerical data about the slumping head blob and shoulder blob.

The furniture would then move you to a scientifically determined correct posture. The recognition of the individual blobs, and their numerical interpretation and communication, is today accomplished in a tiny, relatively inexpensive amount of hardware. Fifty years after von Foerster's breakthroughs, this part no longer needs to be programmed at all — it's available burned into a chip.

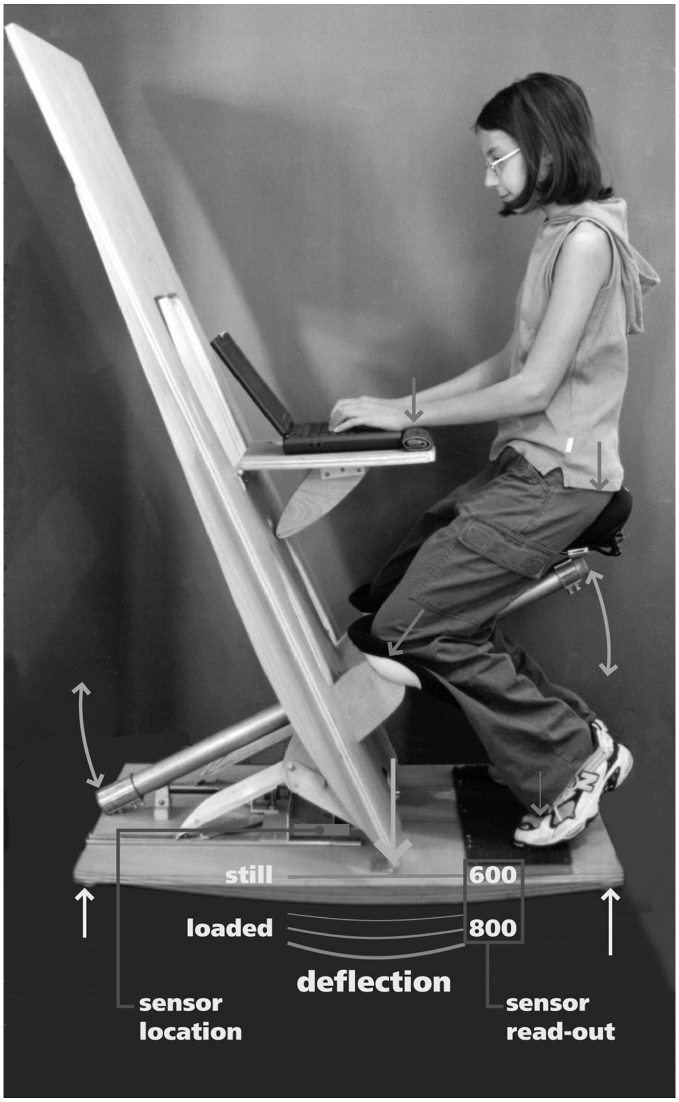

Fig. 4. The Laptop Easel ©™ uses an embedded controller to correct bad posture.

Immense amounts of computation were still needed, I thought, to determine the natural correct posture of each different person using the piece, but I was wrong. As it turned out in beta testing, the mere physical suggestion of big body-scaled movement — for instance lifting the body by the knees — was enough to cause every different size of user to correct their own posture, without interrupting their flow of work. Tracking the vibration in the piece was all that was finally necessary, in order to watch for an unhealthy posture and working behavior

This responsive furniture is like an extension of the user's autonomous nervous system, because its activity occurs below the level of conscious thought. An analogy for this is the way a bicyclist balances while concentrating on traffic and other thoughts. That balance relies on interplay between the physics of the gyroscopic bicycle wheels, and the "body memory" of the rider. It is not done at the fully conscious level, unless a big problem or pothole requires intervention. This intervention, by the way, is similar to the subsumption architecture described by Rodney Brooks.[14] It can be adapted to the interplay between very complicated digital computation, and its interaction with less "conscious" autonomic systems that are not exactly computing in the purely digital manner.

With that lesson fresh, this next piece, an architectural component, attempts to distribute the sensing, logic, power usage, and power collection, into a field of small units distributed throughout the piece.

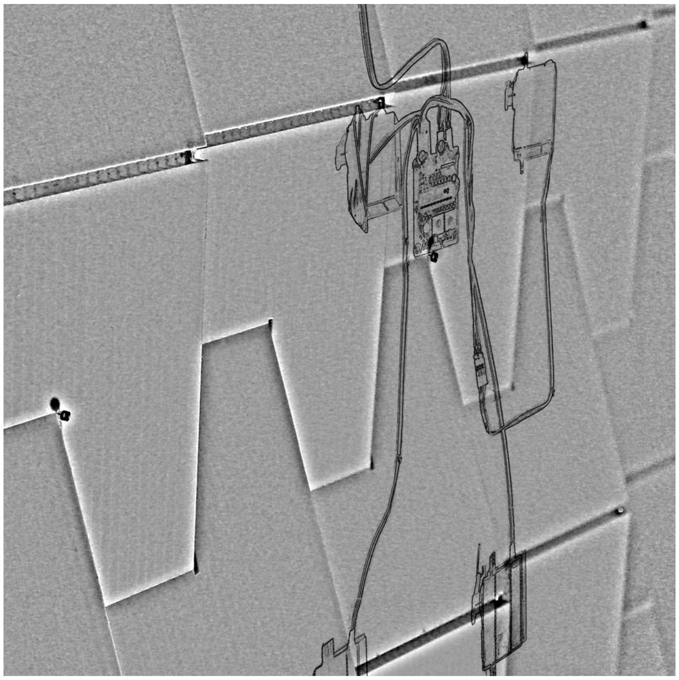

Fig. 5. Sensing, logic, power usage, and power collection are distributed into a field of small units.

It is designed to sense the light and cold conditions as they change around a glazed building, and open or close its "fabric" as appropriate to let in light and prevent excessive radiant heat loss. An analogy for the intent of the design is the way in which stoma open up on leaves, as the conditions and respiration needs change around the perimeter of a tree.

The basic nervous net in this piece normally oscillates at a rate that provides a wave pattern that a standard servo motor (which is adapted from radio-controlled airplanes) can interpret, in its hardware, as a request to move to a particular rotation point. Because the servo involves a gear motor, its position can be held for a long time even without electricity. Power can be intermit-

Fig. 6. Light provides the trigger and the motive power to open the wall system.

tently applied, and it can also be gathered very slowly and intermittently, and stored for short bursts of nervous activity and motion.

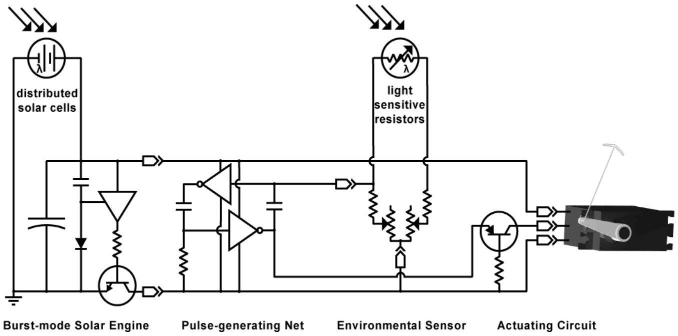

Fig. 7. The Solar Burst Engine ©™ powers an oscillator which varies its pattern based on sensors, and it drives a servo gear motor to a particular position.

Changes in light and temperature that move along the fabric of the piece during the day are interpreted by different kinds of variable resistors that sense (or respond to) these environmental qualities. The changing resistance to an electrical pulse, when coupled with a simple capacitor, or charge-storage device, gives a variable pulse delay that can be fed into the basic nervous net. This causes the pulse widths to vary, and that changes the angle of gear motor rotation, which modifies the openings in the fabric of the piece.

The basic nervous net is adapted directly from the simple locomotion nets invented by Mark Tilden ten years ago. In a sense they represent a benign colony of the entities he conceived as independent agents. They share his idea of simple variable oscillation rates in a chain of simple buffers or ''artificial neurons'' using only dozens of transistors.

Dozens of transistors can ultimately be printed onto a variety of building materials. To me this is a very interesting alternative to the heavy hand of the Central Processing Unit. It is well documented how much more robust these systems are in contradistinction to a microprocessor, even a tiny one with thousands of transistors, and thousands of lines of instruction code. To quote Tilden, his ''control architectures focus first on adaptive survival rather than the performance of specific tasks. Once survivability is under control, goals can be superimposed and the machine used as a platform to carry sensors and if needed, more conventional electronic intelligence.''

This research is essentially an investigation concerning solid-state materials with integral, quantitative, and dynamic flows of electrons, which carry information into and out of the material in real time. It is concerned with the way in which that information causes the material arrangements to reorganize. It is concerned with the performance of those materials, as indexed by

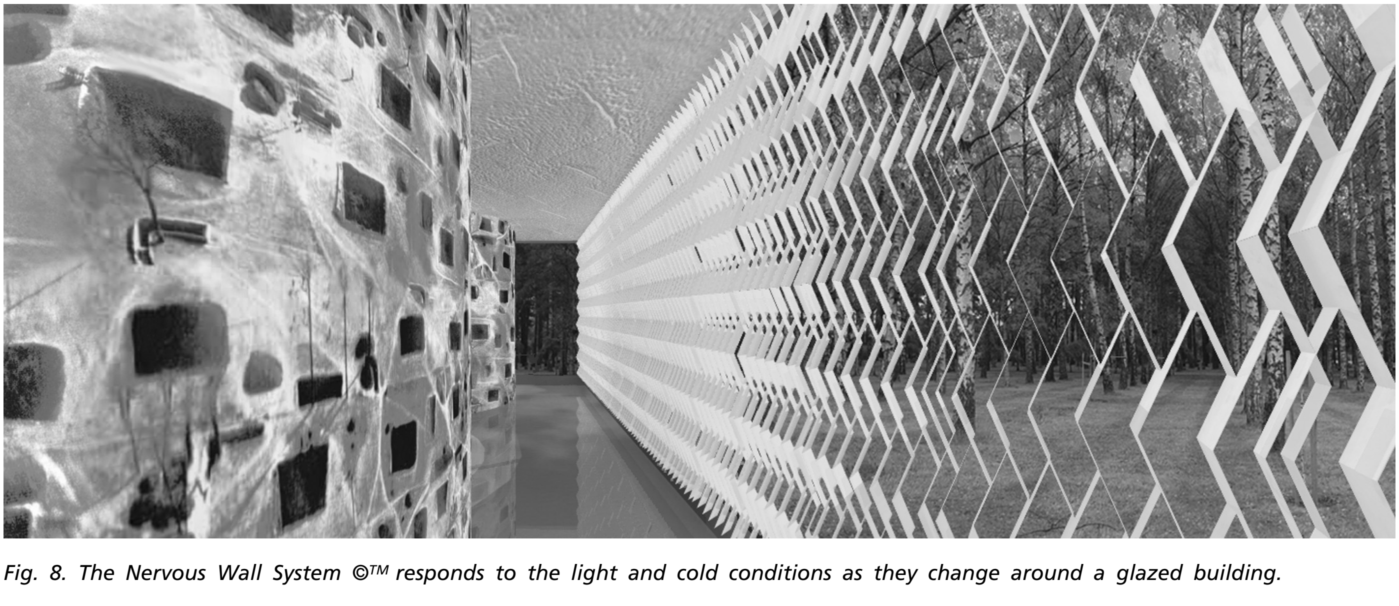

Fig. 8. The Nervous Wall System ©™ responds to the light and cold conditions as they change around a glazed building.

waveforms legible on an oscilloscope, and by the observed behavior of the material in real time. It is an open avenue for architecture's development.

If 40 years ago the question was how to organize a surprising new surfeit of information, today the question is how to navigate more gracefully through an amazingly ungovernable welter of information. The artificial neural nets I've been describing are ideally suited for today's task. They ignore information they can't use, and they listen effectively for the information they can use.

NOTES

[1] Edward J. Zagorski, ed., *Chermayeff, von Foerster, Caplan, Moholy-Nagy: A Panel Discussion* (Urbana: Industrial Design Education Association and University of Illinois, 1962).

[2] P. Weston, ''Photocell Field Counts Random Objects,'' *Electronics* (Sept. 22, 1961): 44-6.

[3] John Markoff, ''Heinz von Foerster, 90, Dies; Was Information Theorist,'' *NYT* (November 9, 2002): 20

[4] Frances Crick, *The Astonishing Hypothesis: The Scientific Search for the Soul* (New York: Simon and Schuster, 1994).

[5] J. J. Collins, and I. N. Stewart, ''Coupled non-linear oscillators and the symmetries of Animal Gaits,'' *Journal of Nonlinear Science* 3 (1993).

[6] Joseph Altman, *Organic Foundations of Animal Behavior* (New York: Holt Reinhart and Winston, 1966): 104

[7] Ian Stewart, *Life's Other Secret* (New York: John Wiley and Sons,1998): 183

[8] Allyn Jackson, ''Lamprey Lingo,'' *Notices of the American Mathematical Society* 38 (1991): 1236-1239.

[9] Mark Tilden, *Patent No. 5,325,031* (United States Patent Office, June 28, 1994)

[10] Tilden, Hasslacher, Mainieri, and Moses, *Autonomous Biomorphic Robots as Platforms for Sensors* (U. S. Department of Energy Office of Scientific and Technical Information,1996)

[11] Richard Dawkins, *River Out of Eden* (New York: Basic Books,1995)

[12] Stephen J. Gould, *The Structure of Evolutionary Theory* (Cambridge: The Belknap Press, 2002)

[13] Neil Gershenfeld, *When things Start To Think* (New York: Henry Holt and Company, 1999): 17

[14] Rodney Brooks, ''A Robust Layered Control system for a Mobile Robot,'' *IEEE Journal of Robotics and Automation* RA-2 (1986)