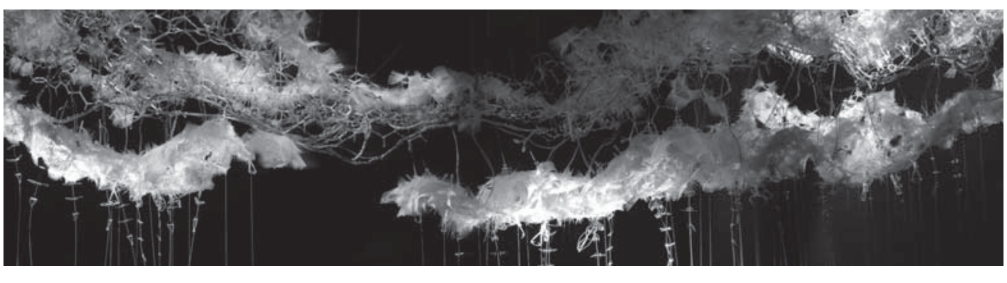
Evolving Cooperative Behaviour in a Reflexive Membrane

Kirsten Robinson University of Waterloo
Robert B. Gorbet Department of Electrical and Computer Engineering, University of Waterloo
Philip Beesley School of Architecture, University of Waterloo

This paper describes the integration of machine intelligence into an immersive architectural sculpture that interacts dynamically with users and the environment. The system is conceived to function as an architectural envelope that might transfer air using a distributed array of components. The sculpture includes a large array of interconnected miniature structural and kinetic elements, each with local sensing, actuation, and machine intelligence. We demonstrate a model in which these autonomous, interconnected agents develop cooperative behaviour to maximize airflow. Agents have access to sensory data about their local environment and 'learn' to move air through the working of a genetic algorithm. Introducing distributed and responsive machine intelligence builds on work done on evolving embodied intelligence (Floreano et al. 2004) and architectural 'geotextile' sculptures by Philip Beesley and collaborators (Beesley et al. 1996-2006).

The paper contributes to the general field of interactive art by demonstrating an application of machine intelligence as a design method The objective is the development of coherent distributed kinetic building envelopes with environmental control functions. A cultural context is included, discussing dynamic paradigms in responsive architecture.



Beesley et al, Detail: *Implant Matrix,* 2006

INTRODUCTION

The *Reflexive Membranes* project focuses on a new generation of reflexive, kinetic design using a program of research and creation to develop new technologies and a new aesthetic of responsiveness. This series proposes interwoven kinetic environments and a new kind of 'geotextile' surface for the earth, offering renewed relationships based on mutual exchanges with the environment. Recent iterations of the textiles have featured collective patterns of movement by mechanical components that respond to occupants moving within the environment. The textiles are composed of distributed sensors, microprocessor-driven actuators, and digitally fabricated lightweight structural scaffolds. The current design adds local machine intelligence to produce an active membrane that can evolve to achieve specific goals. Here the goal is maximizing the movement of air through a space.

The work on these textiles crosses boundaries between architecture, machine intelligence, and the dynamics of organic systems. The project consists of a series of architectural textiles that comprise a set of spatially extended sculptures constructed from repeating, scalable elements. The structures are designed at multiple scales: at the level of the component, intermediate tessellations composed of component arrays, and general structural systems. This paper reviews cultural relationships illustrated in canonical Western paintings and employs these analogically to illustrate intentions in the development of the *Reflexive Membranes* series. Building upon the idea of 'mechanical empathy' derived from these paintings, the paper pursues the possibility of orchestrating the cooperation of component arrays by using machine intelligence. A methodology of genetic algorithms (GA) is described to implement this. A preliminary prototype is presented in which a GA evolves rules that create emergent cooperation in a system composed of spatially distributed and autonomous agents. The character of the assembly emerges from the combined effect of numerous actuators, distributed throughout the structure and controlled locally by microprocessors, acting simultaneously. The rules that the microprocessors use to govern motion are based solely on local information, and impact the appearance and function of the overall structure.

The approach taken is to model the responsive structures using cellular automata and, given a quantifiable objective function reflective of the desired behaviour, to evolve rules for individual automata that optimize global performance. This discussion is framed within the context of the movement away from static 'Vitruvian' architectures based on durability and permanence towards a dynamic and nuanced pattern of interaction between the environment and human subjects.

STANDING IN THE WORLD: CULTURAL CONTEXT FOR THE REFLEXIVE MEMBRANE SERIES

Reyner Banham cited a turning point early in the twentieth century in the 'relationship of men—especially thinking men—and their machines; both were now stripped for action…' (Banham 1960). In figure-ground relationship models, the kind of Existentialist interpretations that Modernist writers such as Banham[1] have favoured tend to isolate figures from their surrounding 'ground', preferring a stripped void to the 'sentimental' environments of the preceding century. In contrast, by drawing upon recent revisionist readings of cultural history, we hope to develop a sensitive vocabulary of relationships.[2]

In the broadest of terms, a Renaissance view of the world might stretch out in a geometric array that reinforces human control. On the other hand, a Romantic stance might see overwhelming presence lurking above and below, far beyond human control. The pursuit of this project is of a hybrid that reconciles these conceptions. A key term for this pursuit is empathy. The use of this term draws upon aesthetic theory that examines nuanced relationships involving projection and exchange.[3] By combining the terms of mechanism and empathy, we hope to develop a stance in an intertwined world that moves beyond closed systems. The pores in *Implant Matrix* might be said to demonstrate 'mechanical empathy': they move the air and are at the same time moved by the air. In the model of figure-ground relationships,

FIGURE 1 Lorenzo di Credi, *Annunciation,* 1480

FIGURE 2 Caspar David Friedrich, *Man and Woman Contemplating the Moon,* 1824

FIGURE 3 School of Fra Angelico., *Madonna and Child,* mid 15th century

the figure is immersed in the world. Instead of unifying or polarizing opposing forces, the Reflexive Membranes project pursues responsive relationships.

A brief review of canonical images serves to illustrate this hybrid stance. One centuries-old attitude that tends to reinforce boundaries is embodied in Lorenzo di Credi's *Annunciation* tempera painting of 1480 (Figure 1). Against an array of landscape and buildings, the figure of the Archangel Gabriel and Mary stand. Their free, relaxed postures are amplified by drapery that swirls around each figure as if caught in the lightest of breezes. The world stretches away behind them, organized by radiant geometry—an inner shell of buildings, with alternating apertures making a gridwork filter that opens out to the surrounding; and an outer natural world, manicured in ordered arbours and garden rows. Mary and Gabriel are confident actors here, expressing vivid freedom and mastery. To them, the world is a servant that offers a reliable stage for their own action. This view holds striking similarities to a confident, Modern cosmology of progress.

Caspar David Friedrich's *Man and Woman Contemplating the Moon* (Figure 2), embodies a distinctly different world. Two travelers stand exposed at the edge of a precipice. Around them at the edge of this uncertain space is a turbulent thicket of branches and giant boulders, relics of upheaval in the ground. Heavy clothing pulled tight around them makes dense silhouettes that contrast with glaring light stretching out into the void beyond. Their stark, outward gaze implies great personal resolve, but no certainty. This space contains powers vastly larger than any human domain. However, while Friedrich's pensive atmosphere might seem opposite to di Credi's confident world, the boundaries are similar. Like di Credi, this Romantic space builds upon distinct divisions between nature and culture and between freedom and order.

A third painting takes a different approach, offering a hybrid world in which those distinct elements combine. The anonymous artist from the school of Fra Angelico, who created the *Madonna and Child* in the middle of the fifteenth century (Figure 3), painted a glittering veil that makes a great sheltering canopy for the scene. In the background and foreground, volatile forces twine together into turbulent clouds that imply the dawn of creation itself. Mother and Child sit sheltered within the veil, their gestures speaking of vulnerable intimacy. The veil is shot through with embroidered intertwining patterns in deep relief. The deep reds and gold rendering of this textile is almost identical to Mary's golden hair and crimson inner tunic. The outer blue cloak that flows around that inner layer spreads out below, collapsing and funneling out into the great clouds of the nascent world beneath. Above, Mary's inner tunic, golden hair, and encircling halo seem to extend into the brocaded canopy. The veil acts like part of Mary's body, an extended physiology.

Similar to the veil in the *Madonna and Child*, the projects that have developed in this series imply an intertwined world that moves beyond closed boundaries.

HISTORY OF *REFLEXIVE MEMBRANES*

A series of works have preceded the current generation of the project. Lightweight structures using lattice and geodesic organizations form the core of a series of installations. Organizing the thematic approach is a program of development moving from individual figures, composed of complex parts assembled into coherent hybrid organisms, to a second stage of immersive landscape-like environments and finally to integrated architectural envelopes including lightweight interior-linings and durable exterior systems. The current project bridges the first and second phases of this research, featuring innovations in lightweight actuated mechanisms organized within an immersive synthetic environment. Further refinements include the incorporation of an ability to filter and trap matter. The current work focuses on integrating sensors, actuators and control systems that activate these structures with decentralized responsive intelligence.

The *Palatine Burial* project of 1995-6 (Figure 4) developed a fabric 'soil', a spreading geotextile reinforcing the soil and fostering new growth. The hollow core of this matrix was detailed to reconstitute the soil by slow mechanical absorption and digestion of organic matter. The structure made a grotto of densely massed barbed wire shards with individual links configured to grasp and puncture adjacent surfaces. The links of this fabric net received special details. To the interior, arrays of transparent vessels were suspended in sprung cushions and fitted with serrated hollow needles. To the outside, angled crampons were set with hair-trigger antennae. Open joints in the enclosing skeleton contained guides that encouraged tangling and automatic assembly with neighbours. The enveloping mass made a fertile turf. This linking and clumping motion tended to accumulate mass that increases over time, controlled at first by the geometric arrays of the structure but growing darker, toward formlessness as matter was ingested and decomposed.

By adding filtering and clamping elements to this kind of lightweight, landscape-scaled network, hybrid textiles were developed. *Erratics Net* (Figure 5), installed near Halifax in 1998, was an interlinked wire fabric mounted on a glacier-scoured terrain. Layers of new strata floating just above the surface of the land were developed within the foam-like filigree of this textile installation. A soil reinforcing mesh was developed for the ocean shore, a wide-spread net anchoring into the granite surface. This artificial reef encouraged turf growth by means of a myriad of hooked clips catching wind-blown plant matter, holding and amassing a matted matrix serving as synthetic soil. In this state, the textile was organized in a pillowed form of alternating peaks and valleys, presenting barbs outward catching new material and inward for anchoring beneath. These

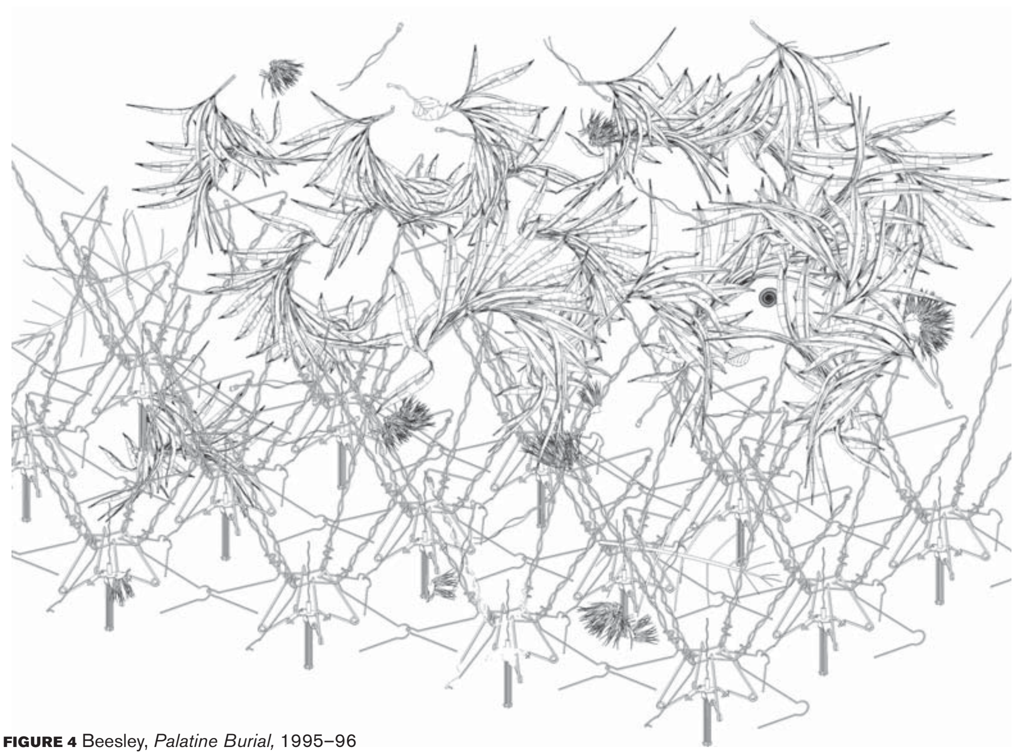


FIGURE 4 Beesley, *Palatine Burial,* 1995–96

FIGURE 5 Beesley et al, *Erratics Net,* 1998

anchors held the net just above the bare rock, making a shallow film of still, sheltered air allowing delicate growth to emerge. The net was made with wire joints clamped by sliding flexible tubes that lock each link to its neighbour making a tough, resilient structure. Responding to times of deep fog where the air stills and the ground is soaked in vapour, the net expanded into multiple layers, each outward facing peak formed within a matrix layer in turn serving as the foot for an inward facing valley of the next layer. A foam-like cellular lattice resulted, a filigree extending throughout the thickened atmosphere. Froth-like natural growth was encouraged by this armature.

More recent generations of this work have employed active sensing and actuator mechanisms. *Implant Matrix* (Figure 6), a temporary gallery installation in Toronto, 2006, was an experimental building skin equipped with layers of miniature valves and clamping mechanisms that might convert surrounding material into a fertile living wall. The work used simple interactive systems controlled by distributed Peripheral Interface Controller 'PIC' microprocessors. These systems supported a primitive intelligence that animated the structure, pursuing a kind of mechanical empathy in which the components reacted to human occupants as prey. By accreting and digesting surrounding matter, the matrix was designed to accumulate a new kind of living turf. The elements were structured using an aperiodic tessellation of rhombic cells with slender acrylic armatures that flexed perforated sheets of mylar. Capacitance 'whisker' sensors, shape-memory alloy (SMA) muscle-wire actuators and toothed mylar filtering valves were included within its lightweight polymer skeleton.

Figure 7 shows the membrane with its identical pores linked in a two-dimensional array that projects downward. Arrays of whisker-sensors and shape-memory alloy actuators were arranged in chained, rolling swells that made subtle grasping and sucking motions. The twitching, billowing motion created diffuse 'peristaltic' pumping that pulled air and organic matter through space.

Each pore (Figure 8) had an SMA wire actuator that contracted when heated to flex the armature. An electric current caused them to heat resistively, allowing them to act like muscles within each cell. The restoring force on the wires was provided by tensions in the acrylic support structure induced by contraction. Contractions pulled the legs together, flexing the mylar pores and moving incremental amounts of air.

EVOLUTION OF *REFLEXIVE MEMBRANES*

The *Implant Matrix* installation included distributed sensing and actuation but retained centralized power, intelligence, and communications. The next generation will evolve towards a decentralized structure in which the entire system is distributed and extensible, based on localized intelligence. The remainder of this paper discusses our initial experiments at evolving cooperative behaviour in a simulation model of this next step in the R*eflexive Membrane* series. In the following section, we concentrate on a detailed description of a GA implementation to be used in the next stage of the project.

In our simulation model, each active unit in the tessellated membrane is modeled as a one-dimensional cellular automaton (CA) having two possible states. CAs are discrete models composed of a regular grid of *cells*, each in one of a finite number of *states.* The state of a cell at time *t+1* is a function of the state of a finite number of neighbouring cells (the *neighbourhood*) at time *t.* This function is the same for each cell and is called the rule for the cell (Crutchfield, Mitchell, and Das 2003). In the example of the *Implant Matrix* membrane, one CA would represent each mylar pore held by its slender acrylic frame and actuated with a segment of SMA wire. This actuator can either be "on" (contracted), or "off" (extended). Each CA has the same two possible states. In our prototype model, the system is modeled as a closed, one-dimensional ring of 25 cells; essentially a chain of connected elements. This can be interpreted either as a one-dimensional system or as a two-dimensional system in which each cell is influenced only by cells on two sides, though there may be other cells adjacent. One-dimensional binary-state cellular automata (CA) are perhaps the simplest examples of decentralized, spatially extended systems in which emergent computation can be studied (Mitchell, Crutchfield, and Das 1996). Despite their simple underlying structure, CAs display complex dynamic behaviors when modeled on a large scale (Ilachinski 2001).

Determining appropriate rules for individual automata which will achieve the desired global behaviour is a complex, non-intuitive design problem, particularly as the size (number of cells) and complexity (states, dimensionality) of the structure increases. Here, we apply a genetic algorithm (GA) to evolve appropriate rules for individual CAs, with the desired global behaviour being to move air coherently through the membrane. The movement of air is used here as conceptual inspiration, evoking possible functions of a new kind of architectural envelope.

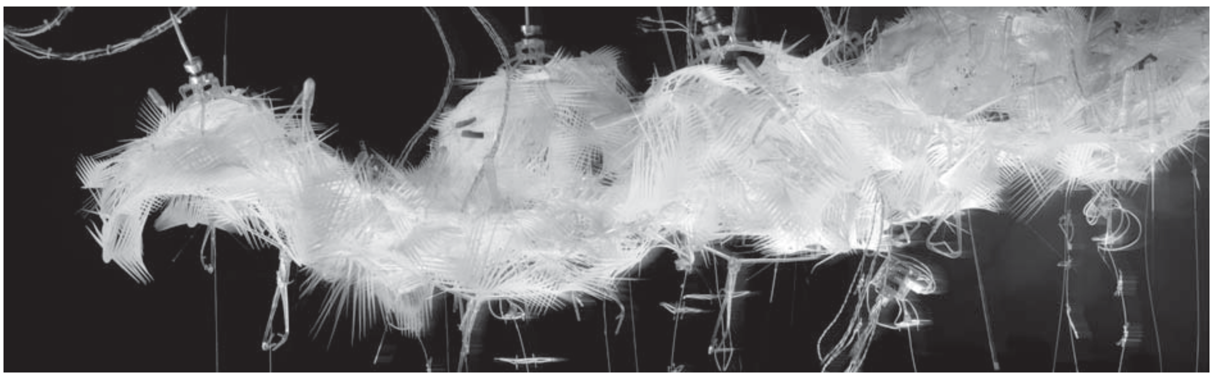
GAs are stochastic search methods in which rules, represented as "chromosomes," are evolved from a base population using biologically-inspired principles: inheritance, selection, crossover and mutation (Haupt and Haupt 1998). GAs are particularly attractive for distributed systems like reflexive membranes, which mimic organic forms where the size of the solution space expand rapidly with dimensionality and neighbourhood size and where complex non-obvious patterns emerge with even simple rules. The work builds on research by Crutchfield, Mitchell, and Das (2003) in evolving rules for spatially extended dynamical systems, and also by Tomassini (2005) where the system is modelled with CA.

In our model, the next state of each cell is determined by its current state and the states of its two neighbors. With two possible states per cell, this results in eight possibilities for current state, each having associated with it a "next state." If binary encoding is used to represent state, the complete rule for a CA can be specified in eight bits, as shown by example in Figure 9. Thus, the rule, or "chromosome" is encoded using a 8-bit binary number, and there are 256 possible rules for the CA in our model.

Left	Me	Right	Next
0	0	0	0
0	0	1	1
0	1	1	1
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	0

FIGURE 9 Sample rule for a CA

The goal of the GA is to choose a single rule for the CA from the entire search space of 256, which generates behaviour which maximizes the airflow through the membrane. The GA operates as follows. A starting population of 100 rules is chosen at random from the total of 256. In turn, each rule is applied to all the CAs in the model and the behaviour of the model is simulated for 50 time steps using a random initial state for each of the 25 CAs. A fitness function is used to evaluate the outcome and assign a quantitative score to the simulated rule. The simulation and evaluation of the entire population of 100 rules is called a *generation.* At the end of a generation, the 20 rules with the highest scores survive into the next generation. Pairs are then randomly selected from the



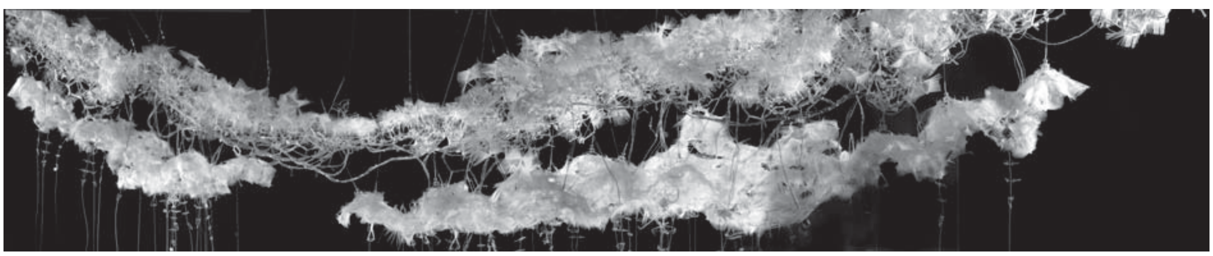


FIGURE 6 A AND B Beesley et al, Detail and General View, *Implant Matrix,* 2006

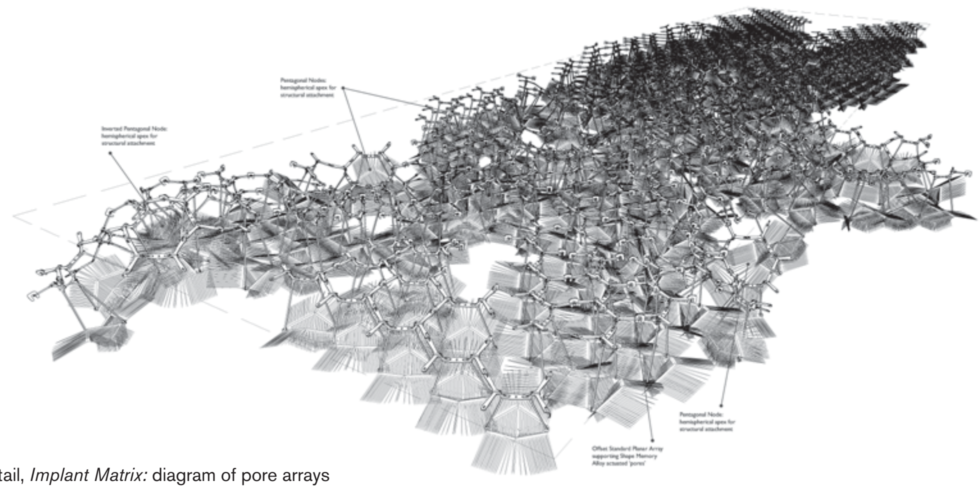


FIGURE 7 Detail, *Implant Matrix:* diagram of pore arrays

remaining 80 rules and "mated" through a crossover process, to create 80 "offspring". In crossover, the two parent chromosomes are divided into two segments of random (but equal) length and each segment is joined with a segment of the other parent, creating two new rules. Finally, each of the 100 new rules is subjected to a probability of mutation (a bit-flip) at each bit position. This new population of 100 rules is then the basis for the next generation, and the GA runs for 100 generations or until the search converges on a solution. The rule with the highest score after 100 generations, or at convergence, is the *solution* for that iteration of the GA, and is stored. This entire process was repeated 500 times independently, generating 500 solutions, in order to identify patterns in the emergent behaviours of the systems. These are discussed in a section below.

FITNESS FUNCTION

The *fitness function* used to evaluate a CA rule assigns a quantitative score for each rule that rewards the desired collective behaviour observed during model simulation. In this case, the fitness function rewards efficient pumping of air. The function calculates the score by estimating how much air each cell moves in each time step during transitions from one state to the next, and summing over all cells and all time steps. Figures of merit representing "air moved" in each possible state transition are shown in figure 10. The two left columns indicate the transitions of left and right neighbouring cells, and the remaining columns indicate the figure of merit given the transition of the central cell. A cell receives a positive score for moving air "forward" (the "on" direction) and a negative score for sucking it back. Note that it is the cumulative effect of the neighbours that influences air moved, so that spatial order doesn't matter (i.e., neighbour transitions "↑–" is equivalent to "–↑").

Left Cell	Right Cell	Centre Cell		
		↓	↑	–
↑	↑	3.0	0.5	0.25
↑	–	1.5	0.25	-0.25
↑	↓	0.5	0.0	-0.5
–	–	0.5	0.0	-0.5
–	–	0.25	-0.25	-1.5
↓	↓	-0.25	-1.0	-3.0

FIGURE 10 Look-up table for the fitness function: "air moved" given transitions of neighbouring and middle cells. "↑" represents an off-on transition, "↓" represents an on-off transition, and "–" represents no transition during that time step.

The absolute numerical values in figure 10 are arbitrary. It is the relative values in each of the cells in the table that impacts the rule score. The table entries were derived using heuristic rules based on expected outcomes. For example, cells move most air when a group of three neighbours moves together, hence the strong positive score in the upper-left entry and strong negative score in the lower-right. If a cell's two neighbours move against it, it is counter-productive and the cell receives a lower score.

EVOLVED STRATEGIES

Five hundred independent iterations of the GA were run with different starting populations, each resulting in a single evolved rule: the solution. In the five hundred trials, only nine different solutions were evolved. Because ICs were selected randomly for each iteration, each time a rule was evaluated it produced a slightly different pattern and earned a different score.

Figure 11 shows five images that illustrate the patterns of emergent behaviour. Each column represents one

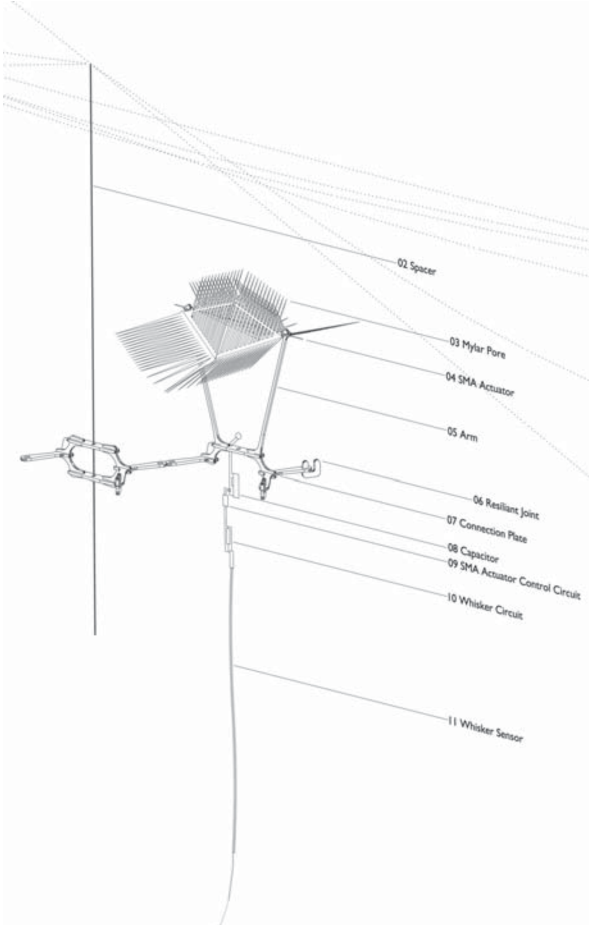


FIGURE 8 Detail, *Implant Matrix:* pore components with actuator and sensor

time-step, and each row traces the state of a single pore through time. Black squares represent cells in the "off" state and white squares represent cells in the "on" state. When a cell goes from black to white (a "↑" transition), the actuator contracts and the pore pushes air forward. Similarly, the extension of the actuator pulls air backwards, represented by a change from white to black.

Solutions produced three main types of behaviour over time in the membrane. Some simply oscillated back and forth creating a *checkered* pattern of "on" and "off" cells. Others formed more complicated patterns consisting of *right-angled* or *isosceles triangles.* The isosceles triangles perform best followed by the right-angled triangles and finally the checkered pattern.

The first image shows an example of a solution that produces a checkered pattern. The behaviour over most of the field is relatively simple. Each cell turns "on", moving air forward when its right neighbour has just turned "on". It then turns "off" either immediately or after a few turns, once the neighbour has turned "off". The emergent pattern appears as small waves traversing the membrane.

The second solution earns a higher score. The interesting feature of this approach is the emergence of larger stationary oscillations, two or four cells wide, represented by horizontal bands of repeating patterns. In this strategy, several cells move forward together to propel air. Cells at the edge move back first then the central cells drop back. The strategy lets cells work together pushing outward. They then take turns returning to the "off" position so that air can leak past them. This approach is advantageous because movement forward is rewarded and movement back penalized.

The third and fourth images show larger stationary oscillations but also illustrate wasted opportunities. In the third figure, the actuators only turn "off" from one side, producing *right-angled triangle.* Since it takes twice as long for all the cells to turn "off," the cycle repeats less frequently and the membrane moves less air. The fourth image illustrates large isosceles triangles, but there are regions of ineffective cooperation between and within the large triangles that develop. It seems as though the triangles are too big.

The final image represents the pattern with the highest score. It achieves relatively regular oscillations over the entire surface and proves most effective in pushing air through the space. The pattern appears as small densely massed *isosceles triangles.* Interestingly, the triangular patterns in images four and five can emerge from a single rule, depending on the ICs.

Figure 12 records the performance of each of the nine individual solutions evolved over the 500 independent iterations of the GA. A point (x,y) on a line corresponding to a specific solution represents the score (y) achieved in the xth run won by that particular strategy. For example, 11001001 dominated, winning 251 of the 500 trials, with scores ranging from 300 to 430. The second highest score was achieved by strategy 10000001, scoring between 280 and 380 in 150 winning trials of the 500 total. The next most successful solution, 11101001, won relatively few rounds and generally scored less than the two higher solutions.

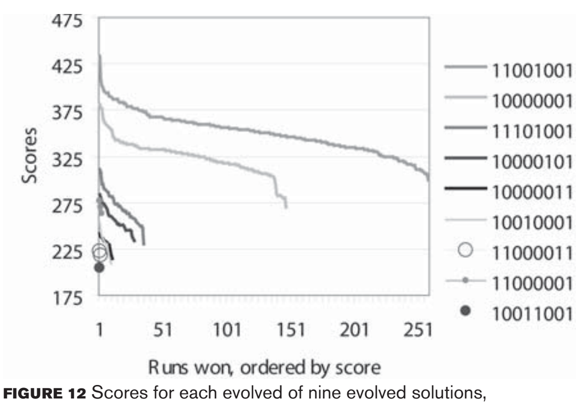


FIGURE 12 Scores for each evolved of nine evolved solutions, in each of the runs won by that solution.

FUTURE WORK

In this work, a simulation was used to model the evolution of distributed intelligence in a tessellated membrane. This application of GAs to the design of distributed intelligence could progress in a number of directions, including:

- increasing the realism of the simulation by refining the implementation of the fitness function to better approximate the movement of air.
- extending the model to study the effect of changing the number of states, the number of neighbours, or the dimensionality of the model.
- exploring the possibility of evolving rules to perform different tasks, such as controlling the passage of light.
- replacing the simulation entirely and evolving the rules using the GA *in situ.*

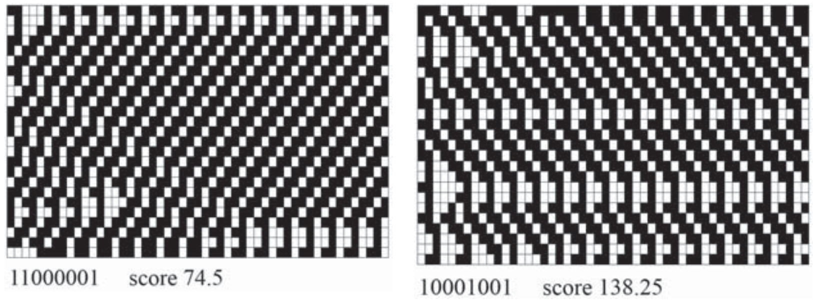
This extension would involve integration of sensors responding to variables of air movement and illumination within the structure, developing an embodied intelligence (Floreano et al. 2003). The fitness function would be adapted to use actual sensor readings, meaning that the system could evolve strategies to suit the actual physical environment rather than an idealization. This flexibility is desirable in an extensible architectural membrane because different installations could evolve rules to suit the specific conditions of their installation without reprogramming.

CONCLUSION

In the prototype a GA is used to evolve rules that maximize the air moved forward by a distributed architectural membrane. The model represents the membrane using one-dimensional cellular automata. Each cell represents a single pore in the membrane and is modeled as having two states. The pore's SMA actuator is contracted and the pore pulled forward in the "on" state and it is extended back in the "off" state. Each cell determines its next state using a rule based on its current state and the states of its two nearest neighbours.

The GA evolves rules for the automata using an objective function that approximates the amount of air moved through the space using a simplified model. In the model, the cells move significantly more air when they move at the same time than when they move separately. Five hundred independent trials of the GA were executed and nine independent strategies evolved, each of which shows a characteristic pattern of behaviours when tested with random initial conditions.

The emergent behaviours range from simple patterns of oscillating cells to patterns in which groups of cells move forward at once to maximize forward air movement then fall back one by one to avoid pulling air back. The



FIGURES 11 A TO E Patterns of emergent behaviour

coordinated patterns scored significantly better against the objective function. When plotted against time, the most successful strategies showed patterns of dense regular white triangles. The appearance of the base of each triangle corresponds with a localized expulsion of a stream of air.

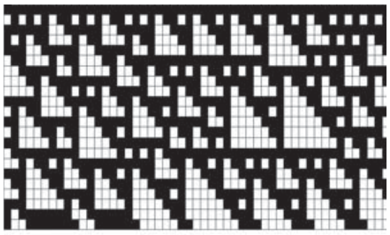
The integration of distributed machine intelligence into the *Reflexive Membranes* project is part of the project's evolution towards open responsive systems. The simulated prototype of a system with machine intelligence demonstrates the potential for developing emergent cooperation. The painting by Di Credi discussed within this paper serves an analogy for this kind of architecture. It offers a world in which 'figure' and 'ground' are dynamically connected. The prototype described demonstrates the feasibility of using a GA to evolve behavioral strategies for responsive distributed elements in an architectural textile.

ENDNOTES

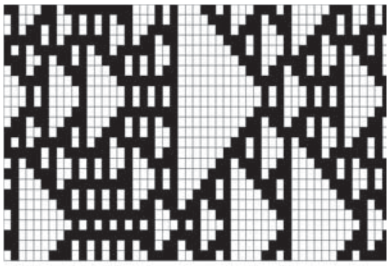
1. Banham is arguably a transitional figure whose interest in architectural mechanisms distinguish him from canonical Modern architecture.

2. This interpretation owes much to Christine Macy and Sarah Bonnemaison's Architecture and Nature: creating the American Landscape, 2002, and Detlef Mertins' 'Bioconstructivisms' 2005 thesis.

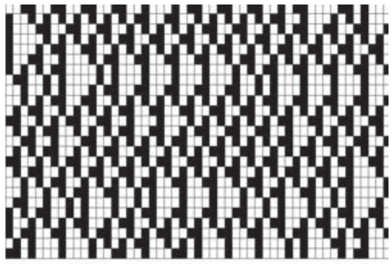
3. Organicism forms the context for this approach. While organicism is sometimes viewed as a late 'romantic' mode opposed to modernism (among canonical works:Worringer, 1904), this movement can also be seen as an ongoing tradition embeddded in twentieth-century and contemporary culture.



11000011 score 219.5



10000001 score 266.75



11001001 score 364.5

REFERENCES

Banham, Reyner. "Theory and Design in the First Machine Age", Second Ed. MIT Press/Architectural Press, 1960, p. 11

Beesley, Philip 1995-96. "Palatine Burial". Prix de Rome (Canada). Rome, Italy.

——— et al. 1998. "Erratics Net". Halifax, Nova Scotia, Canada.

———. 2005-06. "Implant Matrix". InterACCESS Gallery. Toronto, Ontario, Canada.

Crutchfield, James P., Melanie Mitchell, and Rajarshi Das. 2003. "The Evolutionary Design of Collective Computation in Cellular Automata." In *Evolutionary Dynamics—Exploring the Interplay of Selection, Neutrality, Accident, and Function*, edited by James. P. Crutchfield and Peter Schuster, 361-411. New York: Oxford University Press.

Floreano, Dario, Francesco Mondada, Andres Perez-Uribe, and Daniel Roggen. 2003. "Evolution of Embodied Intelligence." In *Embodied Artificial Intelligence: International Seminar, Dagstuhl Castle, Germany, July 7-11, 2003, Revised Selected Papers*, edited by Fumiya Iida, Rolf Pfeifer, Luc Steels, and Yasuo Kuniyoshi. Berlin: Springer-Verlag.

Floreano, D., F. Mondada, A. Perez-Uribe, and D. Roggen. 2004. *Evolution of Embodied Intelligenc*e. Lecture Notes in Computer Science. (3139):293-311.

Evolution of Embodied Intelligence

Haupt, Randy L. and Sue Ellen Haupt. 1998. Practical Genetic Algorithms. New York: John Wiley & Sons.

Ilachinski, Andrew. 2001. *Cellular Automata: A Discrete Universe*. Singapore: World Scientific Publishing.

Macy, Christine and Sarah Bonnemaison. 2003. "Architecture and Nature; Creating the American Landscape". New York. Routledge

Mertlef, Detlef. 2005. *Bioconstructivisms* in "Nox", edited by Lars Spuybroek. 2New York: Thames and Hudson.

Mitchell, Melanie, James P. Crutchfield, and Rajarshi Das. 1996. Evolving Cellular Automata to Perform Computations: A Review of Recent Work. In *Proceedings of the First International Conference on Evolutionary Computation and its Applications (EvCA '96).* Moscow: Russian Academy of Sciences.

Tomassini, Marco. 2005. *Spatially Structured Evolutionary Algorithms: Artificial Evolution in Space and Time.* Berlin: Springer-Verlag.