Hybrid Sentient Canopy

An implementation and visualization of proprioreceptive curiosity-based machine learning

ABSTRACT

This paper describes the development of a sentient canopy that interacts with human visitors by using its own internal motivation. Modular curiosity-based machine learning behaviour is supported by a highly distributed system of microprocessor hardware integrated within interlinked cellular arrays of sound, light, kinetic actuators and proprioreceptive sensors in a resilient physical scaffolding system. The curiosity-based system involves exploration by employing an expert system composed of archives of information from preceding behaviours, calculating potential behaviours together with locations and applications, executing behaviour and comparing result to prediction. Prototype architectural structures entitled Sentient Canopy and Sentient Chamber developed during 2015 and 2016 were developed to support this interactive behaviour, integrating new communications protocols and firmware, and a hybrid proprioreceptive system that configured new electronics with sound, light, and motion sensing capable of internal machine sensing and externally-oriented sensing for human interaction. Proprioreception was implemented by producing custom electronics serving photoresistors, pitch-sensing microphones, and accelerometers for motion and position, coupled to sound, light and motion-based actuators and additional infrared sensors designed for sensing of human gestures. This configuration provided the machine system with the ability to calculate and detect real-time behaviour and to compare this to models of behaviour predicted within scripted routines. Testbeds located at the Living Architecture Systems Group/Philip Beesley Architect Inc. (LASG/PBAI, Waterloo/Toronto), Centre for Information Technology (CITA, Copenhagen) National Academy of Sciences (NAS) in Washington DC are illustrated.

1 Produced at CITA, this experimental testbed focuses on modeling and form-finding through laser-cut acrylic thermoforming, integrated with computational controls and proprioreceptive functions. The latter functions support cycles of sensor and actuator data which enables it as a physical environment for machine learning.
INTRODUCTION
This paper provides a detailed exposition of physical testbeds, electronics, and software developed as proof-of-concept prototypes for curiosity-based responsive architecture. An interaction algorithm is implemented using distributed machine learning, supported by a distributed system of custom microprocessor electronics hardware integrated within interlinked cellular arrays of sound, light, and kinetic actuators and proprioreceptive sensors in a resilient physical scaffolding system. The sentient canopy system is supported by network communications and real-time visualizations of complex system dynamics. Specialized craft and problems associated with implementation of machine-based curiosity, framed within a general context of complex systems research are described here.

The Living Architecture Systems Group/Philip Beesley Architect Inc. (LASG/PBAI, Waterloo/Toronto) and Centre for Information Technology (CITA, Copenhagen cooperated during 2015 and 2016 to explore machine-based motivation for responsive systems housed within architecture-scale prototype structures. Machine-based motivation for the responsive architecture prototypes was formulated as an internal drive to satisfy curiosity. Workshops staged in November 2015 and February 2016 were staged for development of firmware, software, communications, and coupled dynamic visualizations. Fundamental questions were explored within this cooperative development: how can we design kinetic, living architecture that engages with visitors during extended interactions and enhances human experience in an immersive environment? How do humans respond to these evolving interactions, in a process of mutual adaptation? Such environments present novel challenges of finding new methods of presentation and representation supporting further exploration and study.

Responsive kinetic architecture requires support scaffolds, control systems applicable to distributed organizations, mechanisms and hardware configurations, communication and networking systems, software-based controls, and algorithms for learning, adaptation and human-machine interaction (Spiller 2008; Fox and Kemp 2009; Bullivant 2006). The hybrid physical environments and control systems being engineered by LASG with CITA are accompanied by conceptual models rooted in non-equilibrium systems (Nicolis and Prigogine 1977; England 2012). This emerging field is characterized by systems indeterminacy, requiring cycles of development that test potential combinations of assemblies and interdisciplinary working methods in practical implementations with public occupants.

The current CITA and LASG testbeds are related to a new generation of prototypical spaces developed by LASG containing large arrays of actuators and sensors that are linked together by networks of nodes (Beesley 2010). Specialized development of individual systems within this research includes the iterative whole-systems development of an evolving physical testbed, serving as the integrative platform for individual elements. These testbeds mature into full-scale public prototypes, usually housed in museums or galleries, where observation and data collection allow the validation of prototype function and resilience, responsive intelligent behaviour models, and hypotheses around occupant interaction and reaction.

The testbeds integrate arrays of interconnected, interactive components within lightweight kinetic scaffolds and massively distributed proprioreceptive sensor networks. The vital aspect of proprioreception in these sensor networks is a particular feature of new LASG work providing feedback between sensing and mechanisms and setting the stage for machine learning. Computational functions include layered communication between nodes and interactive curiosity-based learning. The combination of these computational and physical systems creates substantial complexity and unpredictability. Interactions with sensors organized within individual nodes influence the behaviours of actuators within the local node, adjacent nodes, and also within global organizations of the system. Sensors vary from simple range detectors to a vision system with image processing and pattern recognition. Actuators vary from simple LED lights to shape memory alloys and pneumatic actuators with complex dynamics that challenge normal methods of modeling. Interaction between human occupants and neighbouring nodes increase the unpredictability and complexity of behaviours. By studying the technologies and implications of these layered, interdependent systems, insight can be gained that contributes to new discourse examining complex systems and interconnectedness.

A key question when designing interactive installations and environments is the design of the interactive behaviours. The use of learning algorithms for automatically generating behaviours is an active research topic in developmental robotics (Clune et al. 2009) but is still at early stages of implementation within architectural construction systems. In early work by the LASG group, interactive behaviours were designed as reactive programs organized by coupling between distributed nodes. Stochastic variations were included, but those machine-generated random signals were not configured to feed back into creation of new behaviours (Beesley 2010). Those programs included capture of system-wide behaviours, including rapid responsiveness and diffusion over space but they did not include the capability to change over time. The pursuit of adaptation is now a priority for test-beds installed within locations permitting long durations of occupation and study. Interactive behaviours which have the ability to change over time and adapt to users could lead
to hybrid couplings (Cairns-Smith 1982). To this end, we are investigating the use of curiosity-based learning algorithms to automatically generate interaction behaviours.

Curiosity-based learning algorithms were originally proposed in the field of developmental robotics, to enable robots to learn about their capabilities and the environment, emulating childhood development (Oudeyer, Kaplan, and Hafner 2007). We have adapted these algorithms to distributed interactive installations (Chan et al. 2015). The interactive system initiates interaction with and responds to human visitors by using its own internal motivation, formulated as an internal drive to satisfy curiosity. This enables the system to generate continuously evolving interactive behaviours and move beyond purely reactive interaction towards shared-initiative interaction.

**CONTEXT**

A particular focus of the research is the algorithmic development of intelligent behaviour controlling kinetic, light and sound-based responses embedded within these environments. The use of machine learning for autonomous robot behaviour generation has been an active topic in the developmental robotics community (Peteiro-Barral and Guijarro-Berdíñas 2013). For example, the Playground Experiment performed by Oudeyer, Kaplan, Hafner, and Whyte (Oudeyer, Kaplan, and Hafner 2005) was based on a curiosity-driven learning algorithm which tries to select action that can potentially minimize the prediction error in the same sensorimotor context. They implemented and validated the algorithm on a Sony AIBO robot which only had three sensors and allowed three types of actions. They showed that the robot was able to discover complex behaviours which lead to improved knowledge and sensorimotor ability.

Curiosity, in this context, is formulated as a driving force for the learning algorithm to explore motor functions that offer the highest potential for increased knowledge. This means that the learning algorithm is incentivised to explore regions of sensorimotor space that are neither well-known nor seemingly random. One of LASG’s research challenges is to develop a similar learning algorithm that uses this sense of curiosity and apply it to a distributed system with a large number of sensors and actuators. Due to the distributed nature of the system, the algorithm must also deal with the sharing of information among different nodes in the system. Distributed machine learning techniques enable learning from multiple sites while avoiding the need of transferring a large amount of data to be processed centrally in one processor.

**CANOPYPrototype**

The canopy prototype consists of four interdependent layers: a physical structure that forms the space as a forest of deeply
interwoven material; an electronic system that includes sensors, actuators, and microcontrollers; firmware that provides low-level functionality at the microcontroller stage; and software that is executed on a remote computer and provides higher-level intelligence. Together, these layers form a meshwork characterized by resilience and hybrid coupling (Beesley and Macy 2010). The new structural system is organized by a hybrid triangular flexible space-grid, stiffened by expanded-mesh hexapods that support telescoping posts and spires contacting the floor and ceiling for stability. Tensegrity coupling is featured, employing metal rod cores that stabilize the system surrounded by expanded meshwork hyperbolic shells that provide alternating tensile and compressive support. This structure offers minimal material consumption, achieved through efficient digital manufacturing employing laser machining and thermal forming of expanded meshwork.

The electronics form the basis of the interactive system that imbues the canopy with a prototypical sentience. A portion of the canopy’s primitive intelligence is distributed throughout its structure in a series of connected nodes. These nodes are each built around a Teensy 3.1/3.2 microcontroller, an Arduino-compatible platform that provides the low-level interface to an array of sensors and actuators. These sensors and actuators form the canopy’s perceptive and reactive body and are configured to allow the canopy to perceive and influence its own physiology as well as its environment. This ability to self-sense is called proprioreception and is an essential capacity for an intelligent system that can understand itself within the context of its environment.

Proprioreceptive signals—both sensing and actuation—are first produced at the firmware level. Firmware refers to the portion of code that is written for and executed on the Teensy microcontroller. It is installed onto every node and performs low-level processing of actuation commands and sensor data. Simple behaviours, such as the generation of fades and activation envelopes for the various actuators, are produced at the firmware level. Furthermore, sound production is handled entirely by the firmware, though the actual triggering of sound can be communicated from the software layer. The firmware also plays the role of translating raw sensor data into filtered and error-corrected signals that can be used by the software as representations of the sensed environment.

The supervisory layer is executed on a remote computer and implements the learning algorithm, named the curiosity-based learning algorithm (CBLA). The CBLA engine aims to learn about the relationship between its actions and its sensory observations. At each time step, the engine considers a set of behaviours and predicts the outcome of each of the behaviours. It then chooses one of the behaviours to execute, observes the outcome and compares its prediction to its observations. The agent’s curiosity is highest for those actions which are likely to lead to decreasing prediction error. This means that it specifically selects actions that are outside of its past experience and for which its predictions of the outcome are mostly likely to be incorrect. This configuration ensures that the canopy and its nodes do not simply settle into routines of recurrent action and response, but continue to find and explore unfamiliar territory.
Each node learns and explores its own subset of the system. The distributed nodes are coupled to each other both physically, by sharing sensors, and virtually, by considering node outputs as inputs to other nodes in the system. This coupling creates the potential for neighbour and group behaviour by connecting the perceptive spaces of each node. In addition to running the CBLA learning process, the Python-based software also passes signals from the sculpture over the Internet and local networks via UDP. This UDP connection exposes the data from the canopy for analysis and visualization outside of the CBLA software and opens the canopy’s actuators to external control. The data streaming capability is used to drive a Grasshopper-based parametric model for the canopy’s 3D Rhino model. This dynamic 3D visualization of the testbed’s live operations is a valuable tool for the analysis and study of the canopy’s behaviour and its evolution over time.

**TESTBEDS**

Three new testbeds based on this new control framework are currently installed in the PBAI and CITA studios, and at the National Academy of Sciences in Washington, D.C. In these prototypes, the pre-programmed behaviours seen in the preceding Series 2 (Beesley 2014) have been replaced with supervisory adaptive behavioural algorithms based on the work of Oudeyer et al. (2007). The aim is to improve the behavioural and perceptual capabilities of the interactive sculpture systems through developing learning algorithms that can acquire novel and engaging behaviours through their interactions with the users.

These algorithms require that the system is able to detect and monitor its own activity as well as changes in the environment. This ability, equivalent to proprioreception in animals, plays an important role in enabling the sculpture to generate a model of itself and the world and thereby learn. The current design includes three main types of actuators: high power LEDs, Shape-Memory Alloy (SMA) fin mechanisms, and custom-made speakers. Actuators are paired with proprioceptive sensors in order to provide feedback on their behaviour for the CBLA algorithm. The kinetic SMA actuator is equipped with an accelerometer which provides feedback on movement caused by either the SMAs or external interactions such as a person touching the fin. The LED is paired with a phototransistor that provides feedback on ambient and actuated brightness. The sound modules are paired with nearby microphones that pick up ambient noise as well as sounds produced by the sculpture.
In the case of all of these sensor-actuator pairs, the sensors are able to register a change in their state when their actuator is triggered by the CBLA system. At the same time, they can register environmental changes that move the CBLA system into a new sensorimotor zone that it is able to then explore.

In addition to the sensors that provide feedback on the actuators, there are sensors that provide information about the environment that the system is in. The Infrared (IR) proximity sensors are currently the only type of sensor in this category and are located on the sound modules as well as the tentacle nodes. These sensors provide feedback on the observers in the vicinity of the system. This system offers a unique, physical kind of machine vision that offers complex responsive kinetic functions. For example, occupants interacting with this system could find arrays of individual fronds following their motions accompanied by outward-rippling motions. Increased complexity approaching peer-like playful kinetic responses could, with further development, result from this arrangement. Proprioception necessitates a vast expansion of the sculpture's sensing capabilities in comparison to previous generations of sculpture hardware, with a corresponding radical increase in the amount of data that is generated in each control cycle. The communication system plays a central role in ensuring that all of the data generated by these expanded sensor systems are able to be used for modeling and visualization.

### DIGITAL COMMUNICATION

Previous generations of this work within LASG have established a communications protocol designed to facilitate the transmittal of sensor information and control signals between the Teensy-based nodes and the laptop-based CBLA software. The inclusion of a model-based graphical visualization of the system necessitated a re-design of this protocol and the addition of a system for forwarding signals to a remote computer to perform visualization. The new communications protocol uses a predefined message format to execute a set of designated commands on specific end-points within the canopy. For example, the CBLA software may request the value of a sensor at a particular address on a particular node, or it might direct a specific LED to fade out over a given timespan. These commands are purposely not limited to being used in the USB communication system that connects the hardware nodes to the computer running CBLA. Using the protocol it is possible to extend the communications system over other channels.

A new event-based communication protocol was created for this prototype, following a query-response schema. In order to efficiently organize large exchanges of individual messages required by this approach, pre-programmed behaviours are configured...
for each hardware node within the installation. This nested hierarchical organization shifts a portion of response to local controllers, reducing the necessity for high-frequency messaging with the central CBLA engine and easing the load on the USB communication system. User Datagram Protocol (UDP) provides the interface between the model/visualization space and the CBLA software. UDP is formulated as a low-latency transport layer, making it well suited for near-real time connections and supporting rapid development of new interfaces for the canopy system. The UDP component for Grasshopper is used to link the firmware-software messaging system with the parametric controls that Grasshopper provides for the 3D Rhino model of the system. A custom message parsing component processes messages in the communications protocol format and then uses those values to drive the visualization in the model space. The initial steps described here anticipate significant further development exploring complex interactions and learning processes within these environments.

SOFTWARE COMPONENTS

The software is structured as a modular hierarchy, consisting of a low-level layer and a high-level layer. The two layers are connected physically through USB. A low-level layer of firmware written in C++ runs on the Teensy 3.1/3.2 USB-based development boards which interface with the peripherals that connect with the actuators and sensors. High-level software written in Python runs on a central computer. The use of the central computer as a development platform provides flexibility for development free from the limited processing power and specialized functions inherent to the Teensy microcontroller hardware. Moreover, Python is cross-platform and supports multi-threading, permitting operation within many operating systems and allowing multiple sets of software instructions to be executed in parallel. In this configuration, it is possible to use the connection to the sculpture for multiple simultaneous but independent applications. For example, a CBLA learning engine may read the sculpture data and send control signals, while a visualization is run using the same sculpture data stream.

In previous installations, the interactive behaviours of the sculptures have been pre-scripted. Each node responded to the occupants and influences the behaviours of its neighbouring nodes in deterministic ways. As described above, the software and hardware platforms were updated in the current series in order to allow the more demanding CBLA to be implemented. However, the new systems also support the design and implementation of pre-scripted behaviours that can run alongside or in place of the CBLA learning engine, depending on the desired mode of operation.
COUPLED VISUALISATION
The real-time visualisation of information provides opportunities to observe, analyse or even feed back into and affect a dynamic system. The system-level view that one can attain in the virtual space provides a fundamentally different way of experiencing the canopy from a sensorially immersed presence within it. Through the UDP communication system, Grasshopper is able to access information about sensors, actuators, and the state of the learning system and translate them into a rich visual representation of the canopy’s current state. The basis for the visualisation is a spatially explicit 3D model of the canopy. As real-time sensor and actuator data are passed to the model, Grasshopper allows for the recording and visualization of the canopy’s behaviour.

To enable real-time linking between the physical and virtual, a custom ‘listener’ software module links a 3D Rhino model to the communications protocol described in a previous section. As events occur in the physical installation, relevant information propagates into the virtual model through a series of interlinked parametric data filters configured within Grasshopper software. In the case of light visualisation, for example, values received from photoresistors positioned adjacent to each LED actuator are decoded. These values are assigned to spatially explicit 3D points corresponding to the location of the particular LED. The model-space below the installation is discretized into a matrix of points, and fall-off from the LED input values is calculated across this point matrix.

With more development, the parsing and spatial mapping process described here can provide a means for the predictive simulation and testing of different behaviours. The eventual aim of a digital representation is not only to visualize the physical effects and learning status but to support an informational space that can act as an interface capable of controlling the physical system. The real-time visualization of phenomena such as light, sound or the learning process can feed back into the physical installation and modify its learning pattern or trigger actions based on emerging patterns discovered within the digital visualization. This can provide an alternate pathway for exploration of the canopy for both researchers and participants and open exciting new modes of understanding the drivers behind the canopy’s actions.

DISCUSSION
The responsive functions implemented within the testbeds described here are organized by both prescripted and curiosity-based behaviours. The prescripted system is deterministic, involving predictable behaviours employing actuation tightly coupled to sensor stimulus, linear translations of sensed data into actuation response, propagating into neighbour and global responses, modified by timings and filtered damping. In addition to sensor stimulus, background behaviours provide orchestrated cycles of actuation. Prescripted behaviours include combinations that include highly responsive behaviours akin to reflexes, directly associated with gestures and positions of the viewer, and also intermittent events occurring within the surrounding environment. Some background behaviours are coupled to viewer activations, with long echoing cycles of response associated with prior action. Complex actuations occur as a result of the interaction of multiple overlapping viewer stimulations in combination with these background behaviours.

In contrast, the curiosity-based system involves exploration by employing an expert system composed of archives of information from preceding behaviours, calculating potential behaviours together with locations and applications, executing behaviour and comparing result to prediction. Machinic decision processes involves searches for new information with reward structures implemented for behaviours yielding new information. When new actions become reliable with stable stimulus, the reward recedes and the system narrows its response, stabilizing its searching functions. It then eventually shifts to searching for new behaviour. Changes in sensor values tend to introduce new sensorimotor context placing the system in new states for exploration. When a viewer triggers a sensor, initial responses involve diverse possible reactions within the system at widely varying levels. If a viewer maintains a stable behaviour with relatively consistent sensor stimulus, activity levels associated with that stimulus will eventually drop, corresponding to machinic understanding of its new environment. If a viewer continues to explore with widely varying stimulus, the system may continue to explore the context with a wide spectrum of potential behaviours.

While both prescripted and curiosity-based responsive systems offer open-ended exploration for viewers, experience of primary implementations of these two states tends to be widely polarized. Notwithstanding the prescripted behaviours embedded within these environments, the open-ended spatial field offered to viewers appears to support highly involved responses by viewers, who tend to associate the environments with empathetic, mutual responses. In contrast, the behaviour manifested by machinic curiosity can be perceived by viewers as random, even alienating. However, when viewers interact with sustained attention to this implementation of curiosity-based machinic interaction, certain patterns can become apparent. When viewer behaviours are held to highly predictable states, the expert system guiding machine selection of behaviours is configured to connote relatively comprehensive ‘understanding’ and in turn actuations tend to cease. Memory functions are configured within the expert system, imparting states of ‘forgetting’ that,
over time, allow the environment to re-explore and re-engage viewers with interactive cycles.

Next stages of development would involve hybrid coupling in which prescripted behaviours could be combined and adapted by curiosity-based learning. We anticipate that this combination would impart visibly coherent nuanced action to the system, employing reflex-based responses enriched by machinic exploration.

CONCLUSION
The Sentient Canopy implementation described here integrated the new features rendering the system capable of both self-reflexive internal sensing and externally-oriented sensing for human interaction. A number of specialized technical refinements were developed during this phase of research covering key parts of the system including communication, firmware, electronics, and proprioceptive sensing. These innovations help support precise manipulation of this relatively unstable software routine and open the system to new methods for visualization and analysis. The communication system was re-implemented to use an extensible protocol with data transmitted over a USB connection.

A modular, object-oriented framework was developed for firmware that allows for rapid extension and configuration of nodes. An Arduino-compatible node-based electronics system was designed and implemented that exposes dense sensing and actuation capabilities to a flexible array of sub-node (device) level modules allowing for the inclusion a wide range of low-voltage peripheral devices including shape-memory alloy and DC motor-based mechanisms, amplified sound, and high-power LED lighting. Proprioception was implemented by producing custom electronics serving phototransistors, microphones, and accelerometers for motion and position, each coupled to sound, light and motion-based actuators and additional infrared sensors designed for sensing of human gestures. This configuration provides the machine system with the ability to calculate and detect actual behaviour, and to compare this to behaviours predicted by the system’s knowledge to date, allowing the system to explore and experiment with new behaviours. The configuration supports machinic introspection.

Physical interconnection of light, sound and motion-based sensor and actuator systems can result in hybrid relationships. Within these testbeds, coupled relationships have been observed in which vibration from sound emissions have resulted in stimulation of accelerometers originally designed to track the motions of adjacent kinetic devices. Similarly, motion-based sequences designed to act in response to sensor stimulus tracking gestures of human occupants have been discovered also resulting from self-stimulation resulting from stray mechanical movements in adjacent mechanisms. Cycling patterns of feedback result, creating emergent behaviour.

Discussion of hybrid couplings has significance for study of evolving life. Canonical discussions such as Cairns-Smith’s Genetic Takeover and the Mineral Origins of Life (Cairns-Smith 1982) have suggested that highly circumstantial couplings could well explain key relationships within the complex systems of organisms. By observing and analyzing the patterns of behaviour seen within the sentient canopy prototypes illustrated here, insight might be gained in ways that responsive architectural environments might relate to living systems evolved by natural processes. By coupling the kind of intelligent virtual models described here with their corresponding proprioceptive dynamic physical environments, and by visualizing and analyzing the behaviours that they contain, increasingly complex hybrid relationships can become legible. These visualizations offer practical means for working with the systems indeterminacy that tends to challenge control of interactive systems by designers, and could help support skills for the rapidly emerging field of design of near-living systems.
NOTES

1. The findings presented here are the result of collaborations between the Living Architecture Systems Group (LASG) at the University of Waterloo, the Center for Information Technology and Architecture (CITA) at The Royal Danish Academy of Fine Arts (KADK) and Philip Beesley Architect Inc. (PBAI), drawn from a workshop series in late 2015 and early 2016.

REFERENCES


IMAGE CREDITS

Figure 1, 2: Anders Ingvartsen, 2016
Figure 3–13,17: PBAI, 2015
Figure 14–16: CITA, 2016

CITA is an innovative research environment exploring the intersections between architecture and digital technologies. Identifying core research questions into how space and technology can be probed, CITA investigates how the current forming of a digital culture impacts on architectural thinking and practice. Using design and practice based research methods, CITA works through the conceptualisation, design and realisation of working prototypes. CITA is highly collaborative with both industry and practice creating new collaborations with interdisciplinary partners from the fields of computer graphics, human computer interaction, robotics, artificial intelligence as well as the practice based fields of furniture design, fashion and textiles, industrial design, film, dance and interactive arts.

Living Architecture Systems Group, associated with the University of Waterloo, is an international consortium of pioneering academic, institutional and industry partners in a multidisciplinary research cluster dedicated to developing built environments with qualities that come close to life—environments that can move, respond, and learn, and which are adaptive and empathic towards their inhabitants. The LASG partnership is focused on developing innovative technologies, new critical aesthetics, and integrative design working methods for working with complex environments. LASG’s work spans a broad field of specialized disciplines, but is firmly situated within the context of responsive architecture, an emerging sub-discipline, that responds to building occupants. Specializations within the group include advanced structures, mechanisms, control systems, machine learning, human-machine interaction, synthetic biology, and physiological testing.

Philip Beesley Architect Inc. is an interdisciplinary design company located in Toronto, Canada. PBAI specializes in architectural design of public buildings, public art and experimental installations. The group is closely associated with the multi-partner Living Architecture Systems Group, the School of Architecture and Faculty of Engineering at the University of Waterloo, the architectural practice of Pucher Seifert, and Riverside Architectural Press. Sculptural work in the past two decades has focused on immersive textile environments, landscape installations and intricate geometric structures. The most recent generations of these works feature interactive sound, light and kinetic mechanisms with distributed control systems. Studio research focuses on aesthetics, technology and craft of responsive envelope systems including digital fabrication of extremely light-weight, flexible component arrays containing embedded sensors and actuators.