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Evolving Systems within Immersive Architectural Environments: New Research by the Living Architecture Systems Group

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Canada’s Living Architecture Systems Group (LASG) combines scientists, engineers, architects and artists working together to create large-scale prototypes of immersive architectural spaces with qualities that come strikingly close to those of living systems. ‘Working in interdisciplinary groups combining architects, engineers and scientists, LASG is building environments that can move, respond, and learn; environments that renew themselves with chemical exchanges and that are adaptive and empathic toward their inhabitants. This paper provides a detailed review of the history and current research of the group, including a detailed case study of Epiphyte Chamber, a complex immersive environment presented at the new Museum of Modern and Contemporary Art in Seoul, 2014; a context of precedents in the rapidly evolving field of responsive architecture; and a description of the current implementation of a new proprioreceptive distributed control system employing a curiosity-based learning algorithm. Also included are detailed reviews of industrial design methods and digital fabrication of specialized structures and mechanisms. The paper is illustrated with industrial design drawings, interactive system design documents, and photography of a series of current environments and test-beds authored by the group.

Keywords: responsive architecture; curiosity-based learning algorithms; machine learning; human-computer interaction; living architecture

1. Introduction: The Living Architecture Systems Group

> *[These] interactive installations - part creatures, part environments; part mechanical, part biological - remind us that the cosmological point of reference for architecture has shifted from the human to the non-human: from the Vitruvian man, inscribed in a circle and a square as the guarantor of universal validity, to the tangled web of creatures and environments within which humanity lives a promiscuous life.*
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> -Detlef Mertins, preface to ‘Hylozoic Ground: Liminal Responsive Architecture’, Riverside Architectural Press, 2010

Can architecture integrate living functions? What are fundamental qualities that living architecture might offer? Canada’s Living Architecture Systems Group (LASG) combines scientists, engineers, architects and artists working together to create large-scale prototypes of immersive architectural spaces with qualities that come strikingly close to those of living systems. ‘Living Architecture’ encompasses a new generation of architectural design based on functions and qualities that approach definitions of life itself. By integrating emerging life-like technologies in computation and synthetic biology with next-generation physical structures, a revolutionary living architecture could emerge. Working in interdisciplinary groups, LASG discovers, develops, and implements techniques to create built environments with qualities that come strikingly close to life; environments that can move, respond, and learn; environments that renew themselves with chemical exchanges and that are adaptive and empathic toward their inhabitants. Human relationships with buildings could be transformed, giving buildings a kind of 'agency' that creates active conversations and exchanges with their occupants, greatly enhancing the quality, the economic value, and the technical performance of the built environment.

Fundamental questions are raised by this emerging work. 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? Answers to these research questions could offer practical methods for working with our increasingly complex and fragile built environment. In contrast to other scales in which automated kinetic functions are well established, the field of interactive robotics and related controls applied to architecture is novel, with relatively few precedents. New technologies and new design working methods are needed for this emerging field. Development of architectural scales of responsive, robotic functions that can effectively function within the public sphere of architecture requires specialized expertise that draws from multiple disciplines including professional architecture, systems design engineering, electrical and computer engineering, mechanical engineering and industrial design. 'Responsive' kinetic architecture requires:

- effective mechanisms and support scaffolds
- control systems applicable to distributed organizations
- mechanism and hardware configurations
- communication and networking systems
- software-based controls
- algorithms for learning, adaptation and human-machine interaction

The hybrid physical environments and control systems being engineered by the LASG are accompanied by conceptual models rooted in non-equilibrium systems. 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. Specialized development of individual systems within this research normally includes degrees of participation in 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 prototypical spaces developed by the LASG use arrays of interconnected, interactive, intelligent components, interconnected within lightweight kinetic scaffolds and integrated with massively distributed proprioreceptive sensor networks. Synthetic biology is housed in fluid-bearing vessels supporting first generations of chemical metabolisms. The interactive environments contain large arrays of actuators and sensors that are linked together by networks of nodes. Figure 1 depicts the Hylozoic Ground installation.

Figure 1 - Hylozoic Ground explores a new generation of responsive spaces. The interactive geotextile mesh environment includes embedded machine intelligence and 'living' chemical exchanges, conceived as the first stages of self-renewing functions that might take root within the architecture. Hylozoic Ground, Venice Biennale, Italy (2010). Photograph: Philip Beesley

The vital aspect of proprioreception in these sensor networks is a particular feature of new LASG work providing feedback between controls 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. For example, interactions with the sensors at one node influence the behaviours of the actuators both locally and globally. The complexity of the sensors varies from a simple range detector to a vision system that can involve significant image processing and pattern recognition. Likewise, the types of actuators vary from a simple LED light to shape memory alloys and pneumatic actuators with complex dynamics that challenge normal methods of modeling. In addition, the interaction between the users and neighbouring nodes increase the unpredictability and complexity of the 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. This paper describes the design and evolution of the specialized systems including controls and resilient physical scaffolds used within these environments. Two recent systems are described in detail, including the 2014 installation entitled Epiphyte Chamber at the National Museum of Modern and Contemporary Art in Seoul, and a new system entitled Sentient Canopy, currently in development within Waterloo and Toronto testbeds.

1.1. Research Context: Emerging Conceptions of Responsive Architecture

LASG’s work occurs within the context of ‘responsive architecture,’ a conception of architecture that stands in marked contrast to longstanding paradigms of architecture based on permanence and separation from the dynamics of human action. This conception is resulting in a new generation of architecture that actively responds to building occupants. These environments often employ sensor-based systems that enable buildings to adapt in form, shape and function to occupants and the surrounding environment. An optimism prioritizing the ‘performance’ of architecture may be perceived accompanying this emerging work. Supported by design methods involving cycles of dynamic visualization and simulation, and enhanced by new design tools employing generative and parametric software, this emerging movement tends to proclaim expanded qualities of a new ‘instrumental’ architecture validated under a broadly-defined rubric of 'performance'.[1] Recent prominent discussions exemplified by Kolarevic and Malkawi's Performative Architecture[2] offer building performance as a key design principle, adopting new performance-based priorities for the design of cities, buildings, landscape and infrastructures. Following from canonical sources on digital environments such as Negroponte's Aspects of Living in an Architecture Machine[3] and Being Digital[4], McCullough's 1995 work, Digital Ground, explores our technological predispositions in developing a theory of place for interaction design. An interdisciplinary look at current developments in interactive design is offered in publications by specialized Swiss platform MetaWorx's[5] and the 'Hyperbody'[6] research group at Delft in their ongoing 'bookzine' series iA.[7] Immanent, dynamic, and open, the qualities focused on by voices such as Kolarevic[8], McCullough[9], Leach[10], and Spiller[11], are marked by a striking optimism about the expanded powers of performance-based architecture. This positive cast stands in contrast to debates about possibilities for expanded-function architectural systems within immediate past generations. In preceding discussion reaching through the past two decades, the concept of an ‘instrument’ was often negatively associated with functionalism, raising the risk of erosion of individual subjective identity and agency.[12,13,14] Publications and documentation of projects by the LASG have contributed to this discussion in nuanced ways.

A series of monographs authored by the group entitled Hylozoic Ground: Liminal Responsive Architecture [15], Kinetic Architectures and Geotextile Installations [16], Sibyl [17], and Near Living Architecture: Work in Progress from the Hylozoic Ground Collaboration 2011-2013 [18] document this work in detail. Recent work by LASG is based on interaction design methods that integrate high performance standards, contributing practical working methods and complex models of interaction, in particular demonstrating integration of multiple systems that include empathetic kinetics and fluid-based chemical reactions. Previous LASG research has focused on systems design [19-22] affective movement generation [23] and recognition [24], mechanism and structure design [25].

Along with expanded performance and increased complexity, this series of work could also be considered to integrate 'resistance' and degrees of restraint. LASG projects offer design details that feature extremely lightweight, sensitively tuned actuators capable of vibrations and trembling, implying an emotional range that could support vulnerability and fragility in an expanded spectrum alongside robust, highly playful behaviours. Building on the direct, emotional expressions, works by the LASG are characterized by interaction models of open-ended exploration, tending to emphasize the role of each occupant in orienting themselves and in exploring the complex environments. These qualities are discussed by recent publications authored by the group, such as 'Dissipative Models: Notes toward Design Method' in Gerber et al's recent 'Paradigms in Computing: Making, Machines, and Models for Design Agency in Architecture [26]

Possibilities for technical implementation are informed by recent research into kinetic architectural systems design [27], and related tools and design methods currently used for creating interactive architecture are summarized in Fox and Kemp's Interactive Architecture [28]. Past projects in this area have attempted to employ distributed communication and control systems, lightweight actuators and sensors integrated within component-based envelope systems [28]. Accompanying this, considerable research on individual sensor types has been achieved in recent decades. One challenge particularly relevant to the current research is the development of effective tactile sensors, which has received increasing research attention but lags behind development of other sensor types such as audio and visual sensors [29]. A particular focus of the research applies to algorithmic development of intelligent behaviour controlling kinetic, light and sound-based responses embedded within these environments. The Playground Experiment done by Oudeyer, Kaplan, Hafner, and Whyte [30] 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 in sensorimotor ability. One of the research challenges of LASG is to develop a similar learning algorithm and apply it to a distributed system with a large number of sensors and actuators. Furthermore, 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 such as those outlined in a survey done by Peteiro-Barral and Guijarro-Berdiñas [31] are being investigated. Those techniques enable learning from multiple sites while avoiding the need of transferring a large amount of data to be processed centrally in one processor.

2. History of the Hylozoic Series of interactive environments

The work of the Living Architecture Systems Group was publicly launched in 2007 with the presentation of Hylozoic Soil at Montreal's Musée des Beaux Arts. The title of this project relates to the classical philosophy of 'hylozoism', the ancient belief that all matter has life. In contrast to traditional definitions of architecture based on inert, rigid structures, these immersive and interactive spaces explore the implications of constructing dynamic, flexible, highly interactive spaces. The work is situated within the rapidly expanding fields of dynamic and interactive architecture for Next Generation Buildings. Since 2007, the evolving work has been presented in over thirty large-scale installations in seventeen countries, and seen by over 4 million people. Collaborators are organized within the Living Architecture group associated with the University of Waterloo and with numerous international partners. Major presentations include the 2010 Venice Biennale, the 2012 Sydney Biennale and the recent inauguration of the Museum of Modern and Contemporary Art in Seoul Korea, described below. Two permanent installations are currently located at the Leonardo Museum for Art, Science and Technology in Salt Lake City and Simons' Department Store in the West Edmonton Mall. The work has been recognized as an exemplar through VIDA, FEIDAD, Venice Biennale, ACADIA Digital Research, Ars Electronica, Architizer A+, and RAIC Allied Arts distinctions. Since 2007 the work has undergone significant evolutions in form, design, and technology (see www.philipbeesleyarchitect.com/press/index.php for list of distinctions and press).

These environments are composed of many thousands of individual digitally fabricated metal, acrylic, mylar, and glass elements. The massive replication of components is organized within tension-based resilient scaffolds, creating diffusive boundaries between occupants and the surrounding milieu. The environments are based on designs that seek to maximize interchange with the atmosphere and occupants. Design paradigms for this work are guided by a pursuit of qualities lying far from equilibrium. Designs are based on deeply reticulated skins, contrasting to the minimum surface exposures of reductive crystal forms that have tended to organize contemporary building designs. Amplifying physical motions related to interaction with viewers and occupants, the details of many components in these sculpture parts are designed to tremble and resonate, responding to slight shifts in the surrounding environment.

3. Evolution of Physical Systems

3.1. Digitally Fabricated Flexible Scaffolds

Responsive structures need to carry multiple sensory features that can reconfigure and adapt to surroundings and occupants. Optimal responsive geometric structures are a crucial feature of living designs. The ability to adjust the structure to suit locomotion is a function readily apparent in both nature and in robotic technology. Applied to architectural scales, the forces that these structures must carry are substantially compounded. While systems indeterminacy tends to make these systems inherently unstable, a series of measures have been implemented that protect the structures from structural failures. A resilient structural scaffold forms the core of each LASG installation. Techniques for designing these scaffolds combine durable crafts of heavy machining and building with advanced digital visualization, industrial design, and digital prototyping. Components are, in general, designed for force-shedding and dynamic relaxation, avoiding concentrations of force and prioritizing highly distributed, resilient structures. The lightweight digitally-fabricated kinetic meshwork frameworks take the form of experimental tension-integrity 'tensegrity' canopy vaulting systems, developed as prototype laser-cut corrugated meshworks supported by floating struts. Individual mechanisms are designed as interlinking modular component clusters that employ resilient attachments for positioning within this meshwork scaffold. Wiring and electronics are directly integrated within these systems. Industrial design takes into account structural forces carried by electronics hardware and cabling, and structural isolation and strain relief details required to protect individual mechanisms.

In addition to resilience and adaptive functions, simplicity and economy are prevailing qualities that have guided the design of Hylozoic projects. Iterative design is used to propel refinement of each piece in the system, supporting increasing efficiency and material reductions. Material consumption and waste is reduced by using full tessellations of interlinking chevrons (illustrated in Figure 2) and tightly nested cutting patterns for other components, creating valuable economies for massive component repetition mass-manufacturing The tensile forces and textile systems of mesh and shell forms derived from two-dimensional sheets of material also contribute to this material economy.

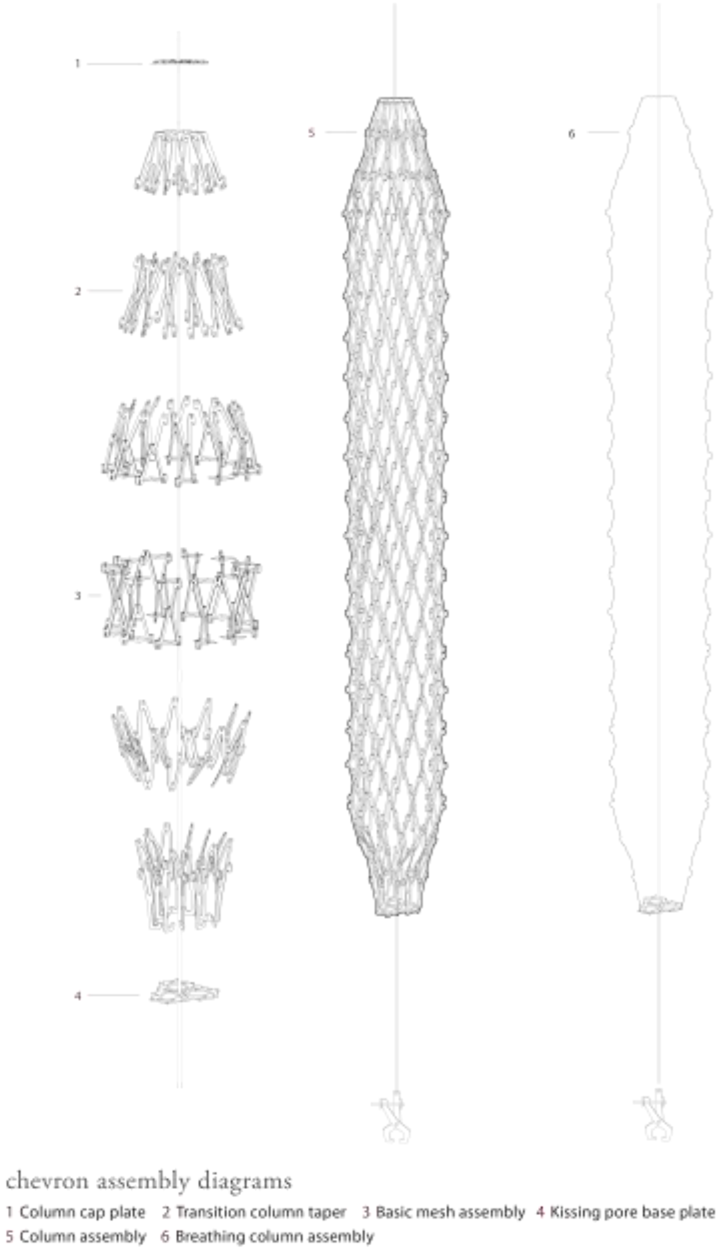
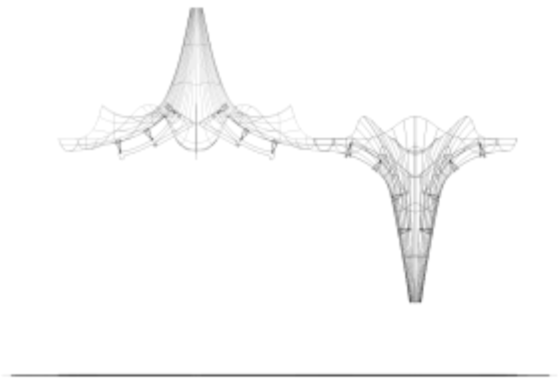


Figure 1 - Individual chevrons are assembled into flexible diagrid scaffolding systems

The structural scaffolding of these projects is designed to act as a self-bracing, diagonally organized space-truss ‘diagrid’. Chevron-shaped components form a primary family of parts within the mesh, akin to individual loops of fibre arranged within the continuous matrix of a knitted fabric, interlinking resilient chevrons are arrayed in opposing pairs and combined in multiple arrays. These primary units act as a basic building block to build a diverse set of structures that include highly efficient geometric waffles and folded tiling systems. Quasiperiodic geometries that integrate variations provide valuable sources of resilience, helping to buffer and augment arrayed structures. The massed, interlinking structures may appear fragile, but they acquire substantial strength and resilience through their textile organizations. These fabric organizations provide force-shedding qualities in which elements under stress are allowed to give way and transfer their forces to neighbouring supports in chained responses.

Early environments were composed of hundreds of interlinking acrylic chevrons that created a flexible, waffle-like canopy arranged in various structures. Lily-shaped transparent ribbed vaults and basket-like columns composed of these chevrons gave dimension to this flexible structure. The work has recently evolved to include new innovations including thermally expanded reticulated structural ‘spars’ that can support significant loading, illustrated in



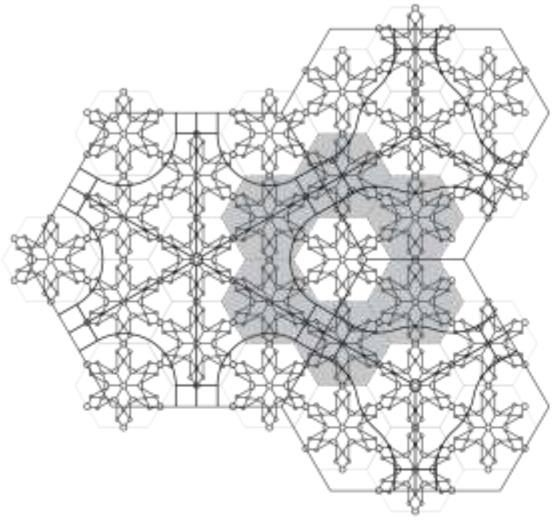


Figure 3. Foam-like waffle structures organized in stratified, cellular groupings organize these new spar arrangements. Originally composed of acrylic, a search for more permanent forms led to the exploration of expanded metal diagonal lattice diagrid

forms. Acrylic and metal diagrid spars are now being used in combinations that provide substantial strength while at the same time retaining flexibility, suggesting that the structures are capable of handling architectural-scale forces (see figure 5). Large passive loads including liquid and glass systems can be carried by these structures in combination with live loads resulting from kinetic functions, for example in the work Protocell Mesh (see Figure 2).

Figure 2 - Prototype shown in Nottingham and London of Protocell Mesh, containing massed flasks with carbon-capturing Leduc protocells integrated into a flexible meshwork scaffold. Photograph: Philip Beesley

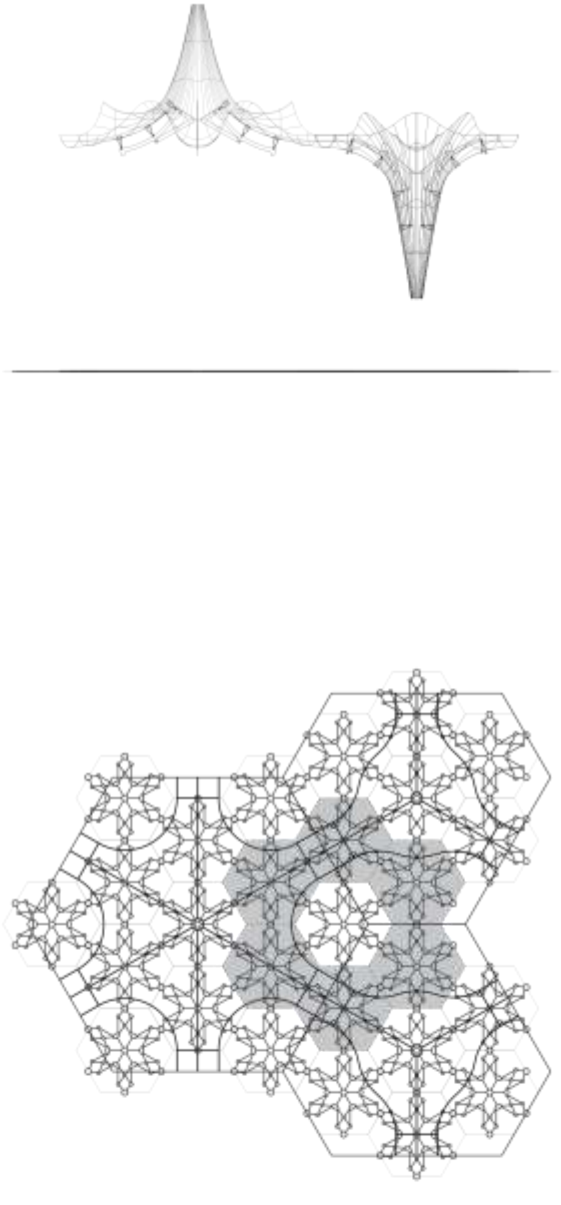


Figure 3 – Digital model of Hylozoic Series 1 corrugated diagrid meshwork following tulip-like hexagonal waffle geometry. The meshwork is composed of interlinking snap-fit stainless steel and impact-resistant acrylic chevrons, supported by radiating compression stays. The system can accommodate substantial dynamic forces. (Image: PBAI)

Figure 5 - Thermally-expanded ‘spars’ allow for significantly higher loading than previous chevron-based meshwork systems. Thermal expansion of laser-cut impact-resistant sheet material creates a diagrid meshwork structural system, following doubly curved surfaces and optimized for structural performance. Shown here are spars used to support new proprioreceptive Series 3 mechanisms. (Image: PBAI)

3.2 Resilient Materials and Junction Designs

Components such as arms, tongues, fronds, and lashes form mechanical assemblies that incorporate sensors, kinetic ‘actuator’ elements that create controlled movement, and fluid-filled glands and bladders. Resilient, flexible materials—acrylic, copolyester, and silicone- are used to manufacture components in the environments, alongside high-temper metal sheet stocks selected for spring and elasticity. Impact-resistant modified acrylic is used for the Hylozoic diagrid meshwork and for skeletons of most Hylozoic assemblies and devices. Snap-fit joints, crack-stop corners, and gussets have been developed, permitting integration of integrated fastening details that tends to almost entirely avoid the use of fastening hardware. Cartilage-like layers of silicone and polyvinyl chloride polymer appear throughout Hylozoic environments. Laser-cut resilient plates and pre-manufactured tubes of silicone are used within flexible joints and vibration dampeners these details are employed in areas receiving additional stress, including force-relieving gussets for meshwork canopies.

Specialized snap-fit acrylic joints are predominantly used for joining mechanisms required by the Hylozoic meshwork, assemblies, and devices. Novel snap-fit junctions expand the efficiency of sheet goods by employing inherent material elasticity. Junction slots within mating components are each given pairs of tapered wedge insert protrusions, matched to corresponding locking holes positioned to receive the tapering forms. The dimensions of these slots and protrusions are precisely gauged to support flexing under assembly load. The part opens, creating a spring tension that in turn impels a ‘snap’ return locating the wedging insert securely within its locking hole. This detail permits almost complete integration of attachments, avoiding the requirement for additional attachment hardware. Additional forces are inherent in this design, requiring precise c*rack-stop* detailing in which slots and interior corners are rounded off, distributing stress over large areas. These individual precisions work in concert with the general configuration of dynamic relaxation, giving these structures substantial resilience and durability.

3.3Kinetics and Actuated Devices

The Hylozoic series includes a large number of actuated, kinetic components that have evolved over the past decade. A mechanism that has appeared throughout this evolving process is a ‘breathing pore’, powered by a NiTi shape-memory alloy wire actuator and configured with frond-like polymer sheet extensions supported by a leaf spring-like tongue. The breathing pore is illustrated in Figure . The mechanism [21] provides two fundamental actions, tending to occur simultaneously. The fissured, frond-like surface that extends the mechanism tongue is detailed for air stirring, encouraging slow-moving currents that help to exchange stale and fresh air within the space of the installation. In parallel with this environmental function, the pore responds directly to human stimulus, imparting curling and stroking motions when its infrared proximity sensor is stimulated. These dual functions tend to impart a strikingly lively version of human-machine interaction.

In preceding testbed installations, breathing pores have been positioned in combinations including double helix columnar arrays, horizontal centrifugal clusters, and distributed fields of repeating triangular nodes. Preceding breathing mechanisms have followed relatively simple revolute motion paths which have been extended by secondary flexing and fluttering motions seen within the lightweight component extensions. These preceding mechanisms have each employed single actuators. The limited contractions offered by individual shape-memory alloy wire actuators are expanded by several layered kinetic amplifications, each building upon the preceding motion. These include primary levers, driving secondary leaf-spring tongues and tertiary thin sheets of fissured polymer that yield substantial visible movement, compounding the original limited contractions. The core assembly of these devices is

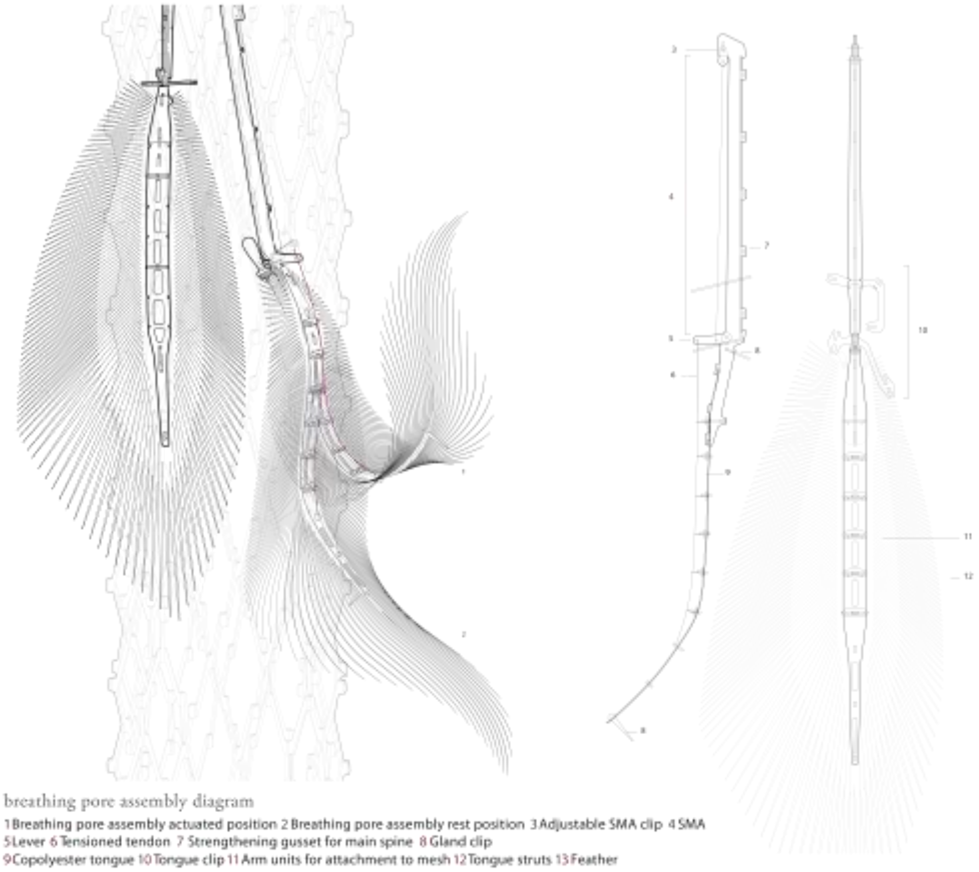


Figure 6 – The Breathing Pore provides human-computer interaction within the interactive environments.

a flexible acrylic and copolyester tongue. A nylon filament is used to pull on the tip of the tongue. The tendon is then attached to the tongue using low-friction ring bearings at intervals, translating the movement of the tendon into curling motion of the tongue. Silcone lashes fitted to the narrow tip at the end of the tongue, and outward-reaching laser-cut mylar frond forms extend the dimensions of the mechanism, providing a human interface encouraging touch and gesture-based interaction, and at the same time configuring a fissured surface capable of stirring air. Complex composite motions have been achieved by combining large numbers of these mechanisms in overlapping layered arrangements, and by orchestrating chains of responses in waves.

A new kind of ‘tentacle’ breathing pore is currently being developed for current Sentient Canopy testbeds, achieved by a hybrid design that combines pairs of preceding breathing pore component designs into a unified composite capable of expanded kinetics and responsive functions. The tentacle is illustrated in Figure . Each tentacle is designed to cover approximately one third of a hemisphere in range of motion. By combining nodal sets of three tentacles in radial groupings, a full perimeter of directional response is achieved within each node. These nodes are in turn organized within a modular triangular array that can be extended into a continuous three-dimensional canopy field. Individual nodes are grouped at vertices of spaces designed to support individual and small-group human occupation. The intersections of inward-facing tentacle fronds from adjacent nodes creates a distinct ‘cupola’ form, providing a basic spatial unit supporting this occupation. Multiplication of the cupola yields a self-bracing structural waffle that imparts strength to the canopy structure and that shelters an extensive occupiable field of space beneath it.

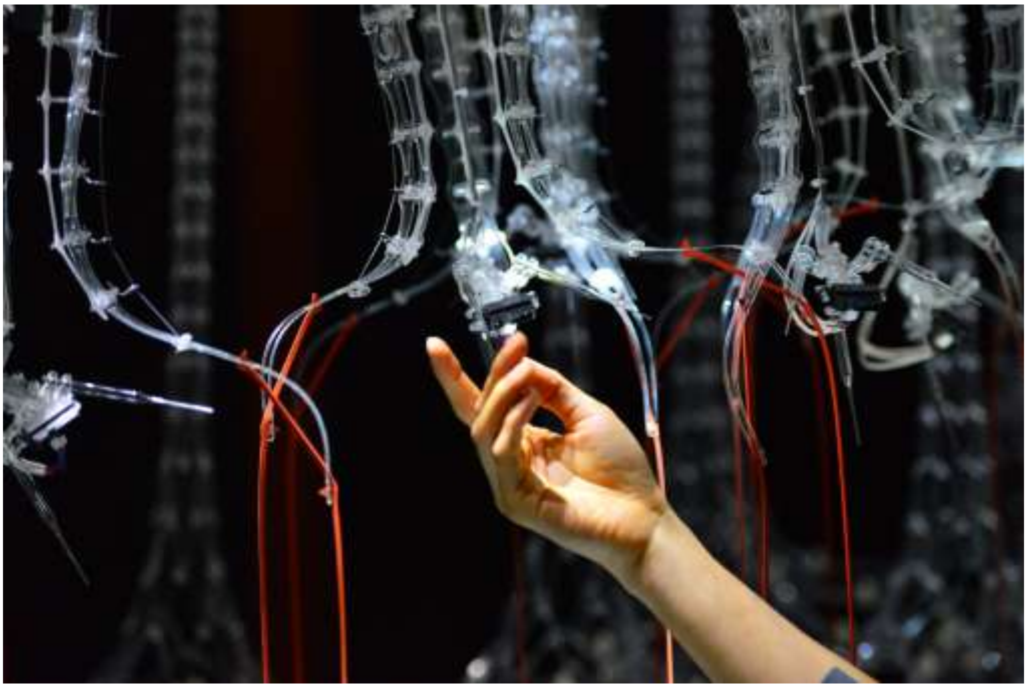


Figure 7 – Interactive tentacle integrated into a LASG environment. Epiphyte Chamber, MMCA, Seoul, Korea [2013-14] Photograph: Philip Beesley

Two shape-memory actuators coupled to silicone spring tensors are configured within each of these tentacle mechanisms, organized to work in concert and providing controlled twisting and directional movement. This device carries new electronics hardware associated with the curiosity-based learning algorithm being developed to control the new responsive structure. Mobile proximity sensors are positioned on each tentacle face, with feedback controls that permit motion that follows the locations of stimulus received from each moving sensor. The arrayed mechanisms offer continuous, active responses that can work individually and that can also be chained together for large-group dynamics. 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. Details of the curiosity-based algorithm control systems that can support this emergent dynamic behaviour are described below.

4. Evolution Of Electronics Hardware, Software, & System Behaviours

Three series of control systems have organized the evolution of the series. In the first series, early LASG implementations included distributed embedded sensing and actuation nodes, each responsible for infrared (IR) proximity sensors and kinetic mechanisms activated by shape memory alloy wire actuators. A typical installation might contain dozens of these nodes, which react to individual IR sensor triggers with a pre-programmed local response followed by behaviours that feature “rippling out” from the activated node, achieved through communication with, and corresponding response by, neighbouring nodes.

A second series of projects were designed from 2011 through 2014. These projects featured expanded functions including increased density of sensor and actuator arrays, organized within chains, individually controlled by nested sets of microprocessors communicating with a central computer. A fixed set of behaviours was pre-programmed within this series of environments, requiring the designer to specify the sensor and actuator relationship for each behaviour. This model required a programmer to anticipate what gestures the guests would use to attempt to engage with the sculpture, and what programmed responses would induce a positive reaction. While the distributed structure of the controllers, together with their interconnectivity and variety of human responses created some emergence, the elementary interactions do not change over time, leading to a potential for habituation and predictability during long-term interaction. In addition, designers needed to predict behaviours that could induce positive user reactions, which is very subjective.

To address the challenge of long-term, adaptive engagement, a new third series has recently been developed. Two new Living Architecture Systems Group test-beds based on this new control framework are currently installed in the Waterloo and Toronto studios, and are slated for public dissemination in 2015. In these prototypes, the pre-programmed behaviours seen in the preceding series 2 have been replaced with supervisory adaptive behavioural algorithms based on the work of Oudeyer et al [32]. The aim is to improve the behavioural and perceptual capabilities of the interactive sculpture systems through developing learning algorithms that could acquire novel and engaging behaviours through their interactions with the users. By developing learning algorithms using motivations such as novelty and users’ engagement, the behaviours of the sculptures can evolve and improve over time, without requiring detailed programming.

The evolution of the Hylozoic Series hardware platform was motivated by the introduction of the curiosity-based learning algorithm (CBLA) as the control software, based on Oudeyer et al.’s [32] intrinsic motivation system approach. The CBLA functions by exploiting the system’s inherent curiosity to learn about itself, much like an infant might learn by exercising groups of muscles and observing the response. In its simplest form, the algorithm chooses an action from its action repertoire to perform, and measures the response. At the same time, it generates a prediction of what it thinks should happen. If the prediction matches the measured response, it has learned that part of its sensorimotor space and that space becomes less interesting for future actions. If the prediction fails to match the measured response, it remains curious about that part of its “self,” as it obviously still has more to learn. It will create a new prediction and try again. This learning architecture allows the system to learn both about itself, and also about interactions with occupants, whose movements and actions create new and “surprising” responses, activating the system’s curiosity.

To accommodate this algorithm requires the system to be able to sense the consequences of its actions, similar to the human capability for proprioception. Similar to human proprioceptors, these sensors allow the sculpture to both detect its own actions, and the actions of occupants on its embodiment. For example, an accelerometer on a tentacle senses both when the tentacle actuator is activated, and also when the tentacle is touched by a visitor during interaction. Without proprioceptors, the sculpture can only estimate its own dynamics based on a feed-forward model. For a human being, this capability is implemented through a neural mechanism known as efferent copy [33]. For example, human eyes are constantly moving while a stable image is reconstructed using the efferent copy. However, the efferent copy can be deceiving when the external environment is disturbed to conflict with the predicted model. For instance, a stationary image will appear to be moving when the eye is pressed (Bridgeman, 2007). However, if the disturbance is permanent, over time the efferent copy will be updated to reflect the new conditions, and an accurate model is once again available for prediction. Hence, not only is an accurate model of an agent’s own dynamics difficult to obtain; such a model might change over the life of the installation due to wear and tear and interaction with its surrounding environments. Proprioceptors play an important role in giving the sculpture information about its own state to enable model learning and adaptation.

Compared to previous generations of control hardware and software, this requires greatly increased sensing capabilities, and a corresponding radical increase in the amount of data transferred in each control cycle. To maintain a responsive control cycle time, a drastic increase in communication rates was required. Thus, the Hylozoic Series 3 interactive system enables the control and sampling of a large number of actuators and sensors at relatively high frequencies. While this evolution was primarily driven by interest in implementing the CBLA, the enhanced capability will benefit future development as well, allowing the implementation of other complex behaviours.

4.1. Hardware Components

Figure 8 illustrates a high level diagram of the electronic hardware system for a tentacle group in the Hylozoic Series 3. The electronic system consists of the following module types: actuators, sensors, Teensy control board, peripheral boards, and high current power source. The module types are depicted in yellow/orange, green, blue, brown, and gray respectively. Each module type is explained separately below.

The current design of the tentacle group includes three main types of actuators, including high power LEDs, Shape-Memory Alloy (SMA) mechanisms, and custom-made speakers. They are controlled by pulse width modulated (PWM) signals in order to provide the ability to dim their brightness levels and control the current. Audio output is enabled through the use of MP3 Trigger audio boards, with sound samples triggered by the embedded controllers.

Each actuator in the tentacle group is paired with a proprioceptor in order to provide feedback on their actuation behaviour for the CBLA algorithm. In order to obtain feedback from the SMA actuator, the tentacle group is equipped with an accelerometer sensor which provides feedback on its movement caused by the SMAs or environmental interactions. This sensor provides acceleration data in all three dimensions of space. It communicates through I2C digital communication. The LED actuator is paired with a phototransistor that provides feedback on its brightness level. This sensor provides analog information. The sound modules have vibration sensors associated with the speaker cones, allowing the detection of speaker actuation while distinguishing from ambient noise. 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.

The Teensy control board is responsible for collecting sensor information and providing actuator control signals. The information collected from the sensors can be used locally, and can also be transmitted to a master computer as raw data or in an interpreted format. The control signal for the actuators can also be determined locally or be received from the master computer. The control board communicates with the sensors and actuators located on peripheral boards. Up to 6 peripheral boards can be supported by each Teensy control board. Each peripheral port is equipped with 4 PWM signal lines for actuator control, one I2C bus for digital sensor communication, and two analog input lines for reading analog sensors. The board is powered by the Teensy 3.1 microcontroller, which coupled with I2C multiplexers and PWM drivers, allows the system to support the peripheral boards.

Peripheral boards are responsible for transferring the data from the sensors to the control board and communicating commands from the control board to the actuators. In the current design of the electronic system of the tentacle group, there are two types of peripheral boards: the tentacle modules and the LED module. The tentacle module supports up to 4 actuators and each individual actuator can either be an SMA or an LED. The module also supports two IR sensors and an accelerometer. Due to the location of the accelerometer and one of the IR sensors, which is at the tip of the tentacle, a special board, called the tentacle tip board, was designed to combine these two sensors into one unit. The current setup of the tentacle group is equipped with three fully populated tentacle modules. The LED module supports one actuator that can only be an LED. The LED module also supports a phototransistor.

In the current design of the system, a high efficiency switching power supply is chosen as the power source, which is capable of producing 25A at 12VDC. Each circuit board reduces the voltage to provide 3.3VDC, 5VDC, and high current 5VDC for their supported sensors and actuators as necessary.

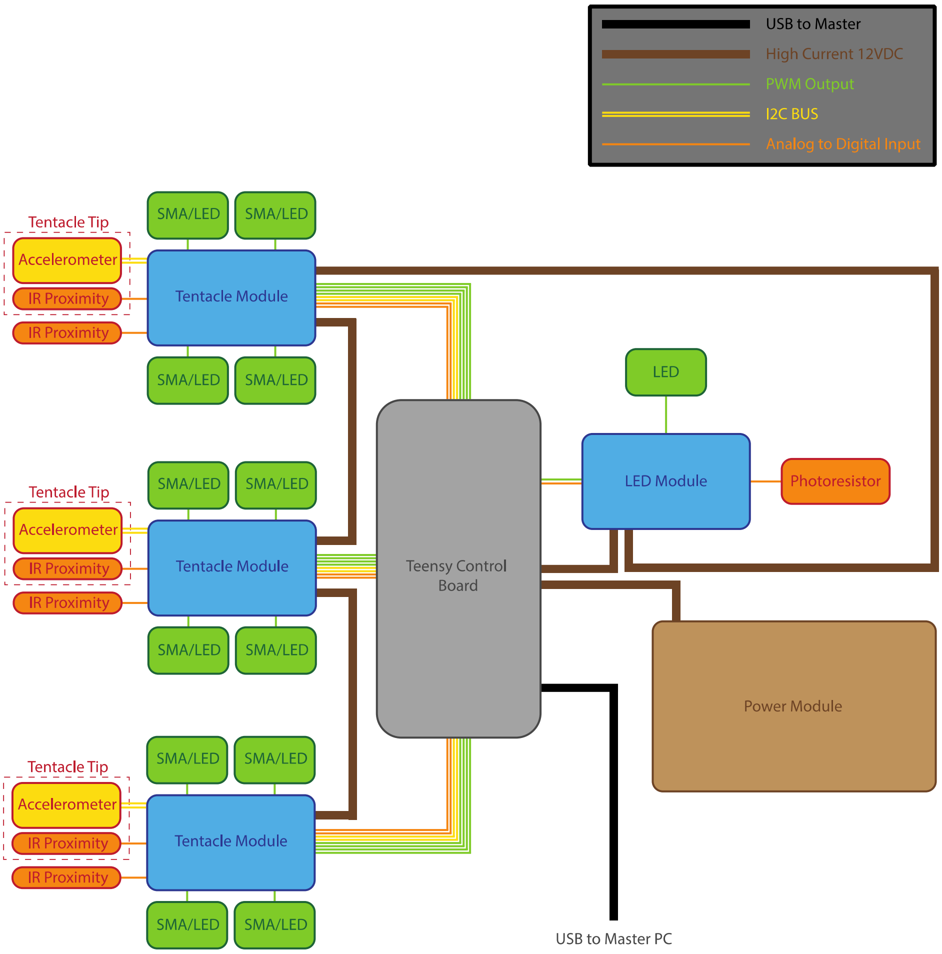


Figure 8: Overview of the Series 3 hardware systems

4.2. 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 USB-based development boards which interface with the peripherals that connect with the actuators and sensors. High-level software written in Python is referred to as applications, and 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. Code that is necessary for communicating with the low-level layer is packed into a Python Package named interactive-system. Developers can then develop applications that control and retrieve information from the sculptural system firmware using the software utilities provided by the Python Package. Each application can run on its own thread. While care should be exercised to avoid conflicts among threads, this should permit multiple applications to execute simultaneously,

The CBLA is an example of an application that communicates with the low level using the interactive-system Python package. A further example of an application is an occupancy map that uses the sensors on the sculpture to interpret the locations of the occupants. Those two applications can run alongside each other independently, taking advantage of the multi-threading properties of the high-level platform.

4.3. Communication Network

Figure 9 illustrates the relationship between the software components. The high-level and the low-level layers share a set of output parameters that govern the behaviours and input parameters that represent the states of the sculptural system. The values of those parameters are synchronized across the two layers. Figure 10 illustrates how an application communicates with the Teensy devices. At the high-level layer, the Teensy Interface module in the interactive-system package is used to create a thread for each Teensy device. The thread looks for changes in those parameters and performs synchronization. Each Teensy device on the low-level layer is represented by a Teensy Interface thread on the high-level layer. An InteractiveCmd thread or other applications derived from it can modify a Teensy's output parameters and retrieve its input parameters through its Teensy Interface.

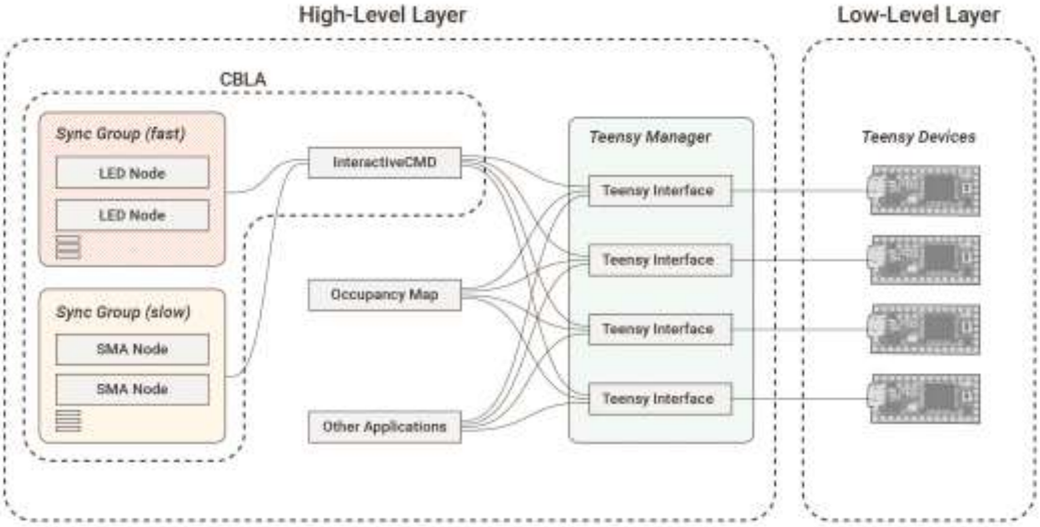


Figure 9: Communication between the high-level and low-level software layers

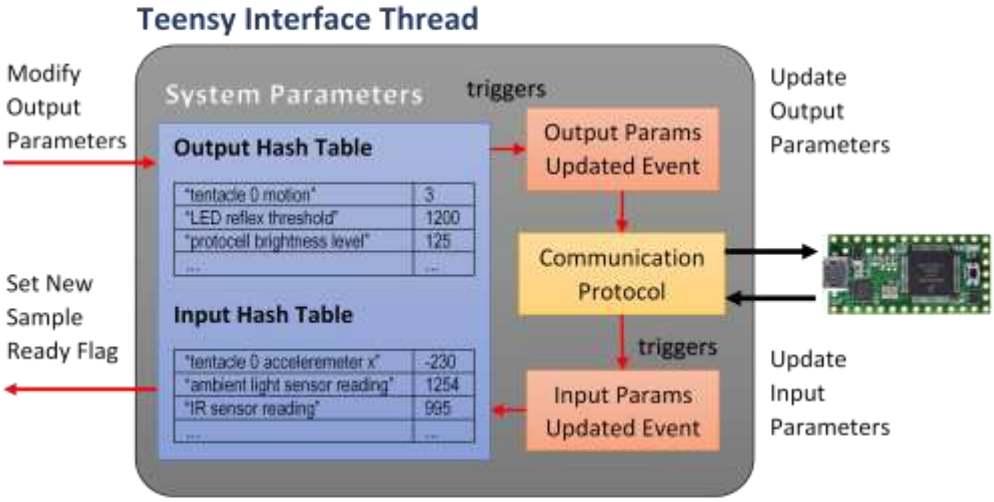


Figure 10: Teensy interface

4.4. Control Software

In previous installations, the interactive behaviours of the sculptures have been pre-scripted. Each node responds 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. These can be implemented either directly at the low-level, distributed throughout the sculpture directly on the Teensy hardware, or at the high-level controlled by a computer which passes messages to each of the Teensy low-level controllers. Figure 11 shows a sample graphical definition of several such pre-programmed responses for devices from the current configuration of the sculpture.

Even though the previous versions' behaviours in each node are pre-scripted, because of the physical complexity and proximal coupling, non-deterministic patterns can emerge through the interactions between pre-programmed nodes. One motivation for introducing the Curiosity-Based Learning Algorithm (CBLA) is to take the

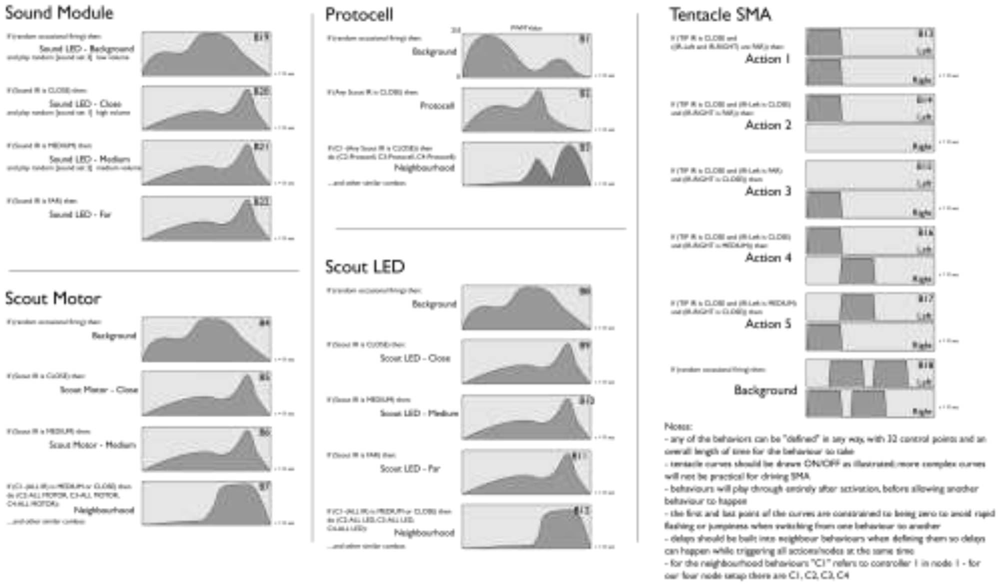


Figure 11: Pre-programmed response envelopes for different actuator behaviours

emergence of new behaviours to the next level. In the CBLA framework, there are no longer any pre-scripted behaviours. Instead, the algorithm is presented with a list of input and output channels that it can observe and control. Driven by an intrinsic desire to learn, it will try to understand itself, its surrounding environment, and the occupants, through active mobilization and interaction. It is hypothesized that occupants will find the behaviours produced by the CBLA more interesting, more life-like, and less robotic.

The CBLA is a type of reinforcement learning algorithm, where the reduction of prediction error is the reward. During the learning process, it will explore regions of the state-space that are neither too predictable nor too random; it wants to focus on areas that have the highest potential for new knowledge. To structure the learning process and identify interesting regions of the state-space, the CBLA automatically segments the state-space into regions; an expert in each region makes predictions about the effects of an action and adjusts its prediction model based on the actual resultant state. The value of each expert is determined by its record of error reduction. This value will then determine the execution likelihood of the action associated with this expert.

All of these software components make it possible to fully connect the numerous local controllers and realize a coherent entity that responds to occupants and adapts to changes in the surrounding environment.

5. Epiphyte Chamber, MMCA Seoul (2013)

The project Epiphyte Chamber, presented in Seoul in 2014 is an example of a test bed integrating new resilient structures from Series Two environments, leading to the most recent work in Series 3. Emerging out of the ongoing Hylozoic Series, Epiphyte Chamber was an interactive environment composed of hundreds of thousands of individual laser cut acrylic, mylar, glass and aluminium elements (Figure 12-14). The suspended structural scaffold was composed of vertically aligned hollow diagrid acrylic and stainless steel structural components, employing novel laser-cutting and thermal and mechanical forming processes that made tulip-shaped diagrid spar forms with attachment points permitting assembly into a dense, foam-like aggregate matrix. This densely repeating system created a hovering building system full of interlinking voids, akin to the spaces of sinuses or termite mounds.

Figure 4 - Epiphyte Chamber, an immersive environment erected for the inauguration of the Museum of Contemporary and Modern Art, Seoul, 2014, demonstrates key organizations employed by LASG constructions including lightweight resilient scaffolds, distributed interactive computational controls, and integrated protocell chemical metabolism. *Epiphyte Chamber*, MMCA, Seoul, Korea [2013-14]. Photograph: Philip Beesley

Figure 5 - The forms of the installation turn away from the minimum surface exposures of reductive crystal forms as they seek to increase their exposure and interchange with the atmosphere. *Epiphyte Chamber*, MMCA, Seoul, Korea [2013-14]. Photograph: Philip Beesley

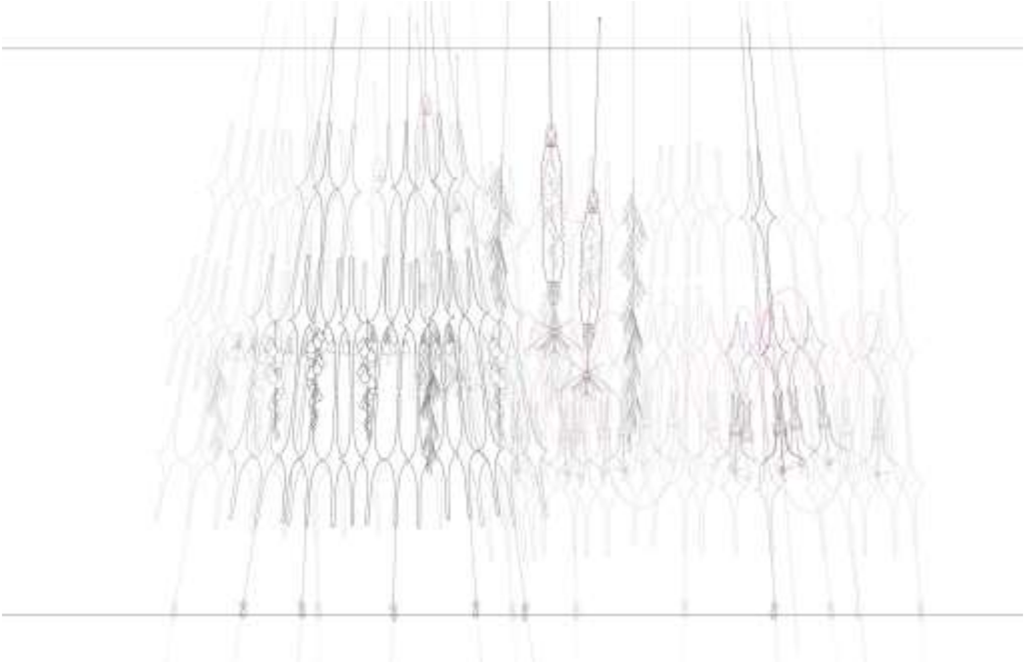


Figure 14 – Elevation of Epiphyte Chamber illustrating distribution of different scaffolding, interactive and chemical systems.

Lining one side of the structure were arrays of tentacle-like lashes, organized in triple sets that extended the lower tips of the structural spars. These tentacles were derived from the ‘breathing pore’ shape-memory alloy mechanisms described earlier within this paper. Infrared proximity sensors were mounted on each tentacle, configured to provide reflex-like curling reactions. Reacting to the stimulus of viewers, composite chained reactions from adjacent mechanisms created motions that ripple out in peristaltic waves. Secondary reactions were configured to follow these primary reflexes, including the operation of high-power LED lights inserted within liquid-filled glass flasks positioned immediately above each tentacle cluster.

In parallel, separate chains of LED lights within glass vessels were positioned high around a central grotto-like space, each with their own IR proximity sensor configured to respond to the movement of viewers providing local reflex reactions and related ripples of responsive light. This separate grouping used shift-register microprocessor controls, permitting control of massive numbers of individual LED lights, and employing pulse-width modulation envelopes for smooth transitions in rising and fading levels of illumination. Softly rolling clouds of delicate light were emitted around these centrally located chains.

Lashes extending from shape-memory alloy actuated mechanisms intermittently brushed against adjacent IR proximity sensors, creating cycles of self-triggered signaling and motion that propagated in turbulent cycles. When occupant activity heightened, the structures of this space became saturated with turbulence combining both physical triggers and behaviour caused by software-based communication. In a second series of liquid cells also located within the central area of the environment, organic batteries made of glass flasks holding vinegar with copper and aluminum electrodes generated tiny amounts of electricity. The trace currents generated by this battery system functioned as triggers for acoustic modules that produce subtle, drifting whispers of sound emitted from cycles of MP3 samples.

The organization produced deeply interwoven fields of reaction that combined complex combinations of human interaction and emergent machine-based cycling. approaching 'subsumption' in which nested reflexes are built within the system, Alongside the mechanized component systems, a wet system was introduced into the environment that supported simple chemical exchanges in the same way renewing functions of the human lymphatic system operate. Thousands of primitive glands containing synthetic digestive liquids and salts were clustered throughout the system. The adaptive chemistries within the wet system captured traces of carbon from the vaporous surroundings, translating this into inert carbonate precipitates located within the fluid cells suspended within the system. Engineered protocells – liquid-supported artificial cells that share some of the characteristics of natural living cells – were arranged in a series of embedded incubator flasks. Bursts of light and vibration triggered by viewer movements influenced the growth of the protocells, catalyzing the formation of vesicles. The growth of skin-like layers growing within the flasks suggests the possibility of architectural environments clothing structures in generative skins.

In related models such as Patrick Blanc's widely published Vertical Gardens [34], architectural envelopes have been renewed by directly integrating biological matter, including soil and irrigation systems. 'Green' walls have, in the past decade, become a familiar and popular model for interior applications to public space and these have been extended by certain applications to external environments such as Jean Nouvel's Quai Branly [35]. The Epiphyte Chamber project, and its preceding Hylozoic Series environments, extends this emerging tradition. In contrast to the stable instrumental focus of integrating natural and artificial systems exemplified by Le Blanc's designs, the Hylozoic Series tends to emphasize wide hybrid relationships that encourage the reconception of spatial systems. Dr. Rachel Armstrong's 'After Machines: An Ecological Age of Space Exploration' [36] offers an expanded conception of an architectural system that envisions future architecture as if an aerial 'soil', activated by chemical metabolisms and kinetic exchanges. The Hylozoic Series is closely tied to Armstrong's description. By integrating dissipative, extremely lightweight kinetic component systems accompanied by open-ended models of exploration and chemical exchanges, this experimental work offers a distinct model for creating self-regulating architectural layers for future building.

6. Conclusion

In contrast to the long traditions of vehicular movement and mechanism design, public architectural spaces integrating automated kinetic functions are at early stages of development. The orchestration of massively repeating interactive robotic mechanisms and the related densely arrayed electronics and software-based control systems applied to the scale of full-architecture introduces significant challenges and obstacles. New technology and new design working methods are needed to work effectively within this emerging field. Technical systems require re-conception and redesign when applied to interlinked arrayed network organizations and architectural scales. An environment that can effectively function within the public sphere of architecture requires specialized expertise that draws from multiple disciplines including professional architecture, systems design engineering, electrical and computer engineering, mechanical engineering and industrial design.

LASG projects offer design details that feature extremely lightweight, sensitively tuned actuators capable of vibrations and trembling, implying an emotional range that could support vulnerability and fragility in an expanded spectrum alongside robust, highly playful behaviours. The architectural craft that is in development to support this work involves designing with materials conceived as filters that can expand human influence while at the same time expanding the influence of the surrounding environment upon human occupants, emphasizing oscillating functions of catching, harvesting, pulling and pushing. Building on these direct, emotional expressions, works by the LASG are characterized by models of open-ended exploration, tending to emphasize the role of each occupant in orienting themselves and interacting with the complex environments. In these environments, occupants and build up a deeply layered, deeply fissure set of relationships in which there are multiple sensitive boundaries. The pursuit of these spaces could be considered as a synthetic new kind of expanded ‘soil’. The projects of the LASG have moved through several stages of focus from scaffolding and structure, through integration of mechanisms and interactive controls, to chemical metabolisms integrated within densely interwoven tissues of kinetic mechanisms. Structures have employed lattice geometries, integrating resilience from textile matrices, and in turn moving toward quasiperiodic systems in which things shift and multiply and effloresce. A further stage of development has involved construction of diffusive metabolisms in which protocell chemistries show material flux, raising the possibility of construction of renewing skins of material.

The combination of conceptual and applied work described in this paper spans a range from hypothesis-making and humanities-based discussions to precise engineering, with verification by field testing and implementation in large-scale public buildings. The integrated projects of the LASG offers a valuable model of multidisciplinary research-creation that examines interconnectedness within the built environment.

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