Living Architecture Testbeds

Philip Beesley and Matt Gorbet
Living Architecture Systems Group

This publication provides background on the development of the LASG's testbeds and the theoretical frameworks that shape their existence in the world. It describes the practical experience of working with the testbeds, including how agreements between the LASG and its testbed partners are developed and managed over time. Finally, it offers some examples of technical, methodological, and philosophical lessons from existing testbeds before concluding by describing what future generations of testbeds might look like. More information about individual testbeds can be found in the folios dedicated to each on the LASG website.

ISBN 978-1-988366-63-0
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Riverside Architectural Press

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LIVING ARCHITECTURE SYSTEMS GROUP

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Published by Riverside Architectural Press
www.riversidearchitecturalpress.ca

Published in February 2023

Title: Living Architecture Testbeds

Names: Beesley, Philip, 1956-author. | Gorbet, Matt, 1973-author. | Chîu, Adrian, 1996-contributor. | Jones, Ruth, Contributor. | Living Architecture Systems Group, issuing body.

Description: Series statement: Living Architecture Systems Group folio series. With Living Architecture Systems Group. Includes Index.

ISBN 978-1-988366-63-0

Design and Production by Living Architecture Systems Group

Riverside Architectural Press
7 Melville Street
Cambridge, Ontario, N1S 2H4
Canada

This book is set in Garamond and Zurich BT.

Contents

Introduction

Living Architecture testbeds are installations of living architecture environments that support research and development while acting as expressive public art. The Living Architecture Systems Group has developed a series of testbeds at architectural scales consisting of immersive-scale interactive environments that integrate distributed physical systems and behavioural software. These testbeds are developed by designers, researchers, artists, and thinkers from the humanities embedded within teams of scientists and engineers in order to develop architectural prototypes of sentient environments, disseminated as public art installations.

This publication provides background on the development of examples of the Living Architecture Systems Group's testbeds and the theoretical frameworks that shape their existence in the world. It describes the practical experience of working with the testbeds, including how agreements between the LASG and its testbed partners are developed and managed over time.It also offers some examples of technology, methods, and philosophy relating to existing testbeds. Concluding comments describe what future generations of testbeds might look like. More information about individual testbeds can be found in the documents that are dedicated to each installation located on the LASG website: lasg.ca

Testbeds are at the centre of the Living Architecture Systems Group's (LASG's) research-creation methods. Part experimental architectural prototype, part assembly of electronic components, and part sculpture, testbeds help to bridge the gap between living architecture designers and the audiences that interact with the environments they create. In scientific research, a testbed is a platform used to test theories, tools, and technologies. In the context of the LASG research and creation commmunity, the term "testbed" connotes ongoing exploration and learning. This may include the implementation of new behaviour algorithms and physical materials by partner researchers focused on technology, and likewise it may include open-ended social and cultural observations by scholars, educators, and theorists from the social sciences. The information gathered by working with existing testbeds influences the development of new generations of living architecture. This development influences the design of new testbeds alongside publications, workshops and new curriculum, pushing techniques, technologies, and theories forward. In turn, testbeds can expose wide audiences to concepts that underlie the LASG's work.

Testbed features depend on the physical surroundings of their sites, and on the social communities that interact with them. Living Architecture testbeds have been developed in collaboration with communities in widely varying locations and cultures. These varying contexts result in differences in design, behaviour, use, and in the accessibility of their underlying components and controls. While some testbeds are installed as short-term temporary installations, others may be designed as long-term and even permanent installations within buildings. Their use can evolve depending on the needs of the institutions, private individuals, or communities that are responsible for them. This use is also influenced by the evolving relationships that develop between testbeds and their hosts. The experience of deploying and maintaining a testbed offers practical learning experience with diverse dimensions.

The technical construction of a typical LASG testbed consists of a suspended cloud-like assembly of multiple electronically active membranes and shells, centred around spatial clearings and surrounded by floating expressive non-electronic scaffolds. Expressive sculptural forms include glass dressing, refractive and reflective materials. Electronically active components may include digital high-power lighting, vibrating and flexing fronds, and high fidelity omni-directional speakers. The control systems of LASG testbeds employ custom Testbed-Control software, supporting behaviour design and dynamic control features. Responsive data is maintained between multiple data sources. Dynamic and responsive visual behaviour is tied to this data stream input. The behaviour systems employ a layered influence engine system that supports rich behaviour responses, as well as adjustable preset 'scenes'.

Background

The current generation of LASG testbeds evolved from earlier living architecture installations that were developed during the past three decades. These installations brought together natural and artificial processes to create a hybrid ecology that invited questions about humans' relationship to the larger living world. By incorporating responsive systems and behaviours into layered, dissipative architecture, recent testbeds are beginning to take on the characteristics of living systems. The constructions are being incorporated as long-term installations within public spaces, beyond the art and architecture exhibitions in which early examples of living architecture were presented.

The LASG now conceives of its testbeds as what the sociologists Susan Leigh Star and James Greisemer have called "boundary objects."[1] For Star and Greisemer, scientific research is an undertaking that requires many different actors and viewpoints. To support this heterogeneity, science needs stable objects that can hold different meanings for the different individuals and communities that contribute to scientific work—objects that are stable enough to survive and be enriched by these multiple views and competing perspectives. As boundary objects, living architecture testbeds become imbued with meanings that are imparted to them by the communities that surround, care for, and experience them. School children visiting a testbed for a day of learning activities interact with it differently than attendees at an evening event or a professor at a university who passes under it on her way to her office, and likewise than the building staff responsible for maintaining it. These different meanings can enrich understanding of what living architecture could be. Because the testbeds are "stable" objects—they are often installed and maintained over a long period of time and continue to be themselves even as meanings and uses are added or subtracted—these different meanings can multiply, grow, and even conflict with and subvert each other.

While long-term testbeds retain the aesthetic qualities of earlier sculpture and living architecture installations, their status as boundary objects and sites of research shifts how they can be understood. In a traditional gallery, the art object and its viewers tend to be kept separate. Even when an audience is invited to interact with an exhibit, a sense of contemplative distance often remains. The mid-20th century German writer Walter Benjamin described this quality as an "aura" in which the experience and art object are bound by the time and space of the gallery and the interaction with the work.[2] However, as host communities spend time with these testbeds, the distance that separates the auratic work of art from viewers and users gradually collapses. The instrumental features of the testbeds create fundamental influences in this relationship. Viewers might still contemplate the testbed—losing themselves in its forms, behaviours, and environment—but they also begin to integrate their perceptions. Alternately, viewers may become concerned with controlling the behaviour of the testbed, interpreting it as a tool, or instrument. This kind of increasingly complex relationship of "instruments" and contemplative "monuments" has been actively debated within twentieth-century discussions concerning architectural design. The experience of a living architecture testbed can become what the English pediatrician Donald Winnicott described as a "transitional experience," a realm in which inner and outer worlds converge and through which we learn to navigate the borders of the self and forge connections with the human (and non-human) communities outside of it.[3]

Above

Ar Frout Reef living testbed installation at the Ar Frout Castle, Carantec, France

1 Susan Leigh Star and James R. Griesemer, "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39," *Social Studies of Science* 19, no. 3 (1989): 387–420, http://www.jstor.org/stable/285080.

2 Walter Benjamin, "The Work of Art in the Age of Mechanical Reproduction," in *Illuminations*, ed. Hannah Arendt, trans. Harry Zohn (New York: Schocken, 2007), 217–52

3 David Winnicott, *Playing and Reality* (New York: Routledge, 1989).

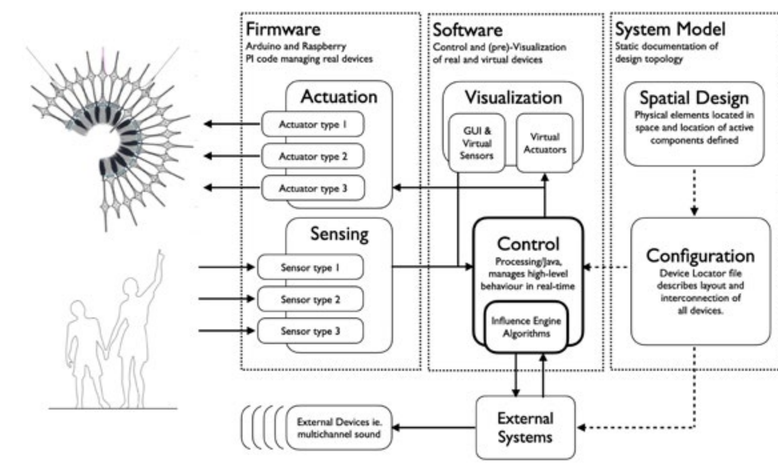
Controls and Behaviour

Behaviour is the collective activity throughout the installation, expressed by the activation and profiles of each electronically controlled actuator within the testbed environment. LASG has developed a software control system that uses a layered behaviour model. The current distributed hardware and software architecture of Living Architecture testbeds accommodates a variety of behaviour algorithms, coded as 'Influence Engines' which impact the behaviour of physical sculpture components according to their internal logic. Influence Engines are parametric and can be added and customized for various sculptures, enabling non-expert artists to shape the behaviour and responses of a given environment by adjusting parameters using a graphical user interface. Example Influence Engines include various particle systems, mathematical models of wavefronts, and systems which pull in data from outside sensors such as environmental sensors. True to their designation, each Influence Engine exerts influence upon the actuators within a sculpture, causing them to respond. The system also simulates the behaviour of the sculpture within a three-dimensional visualization . Within this modular system, new Influence Engines can be created as tools to experiment with new logic or to receive input from new sources of data.

Above

Image of *Amatria*, testbed located at Indiana University School of Informatics. Incorporating a Brain-Computer Interface

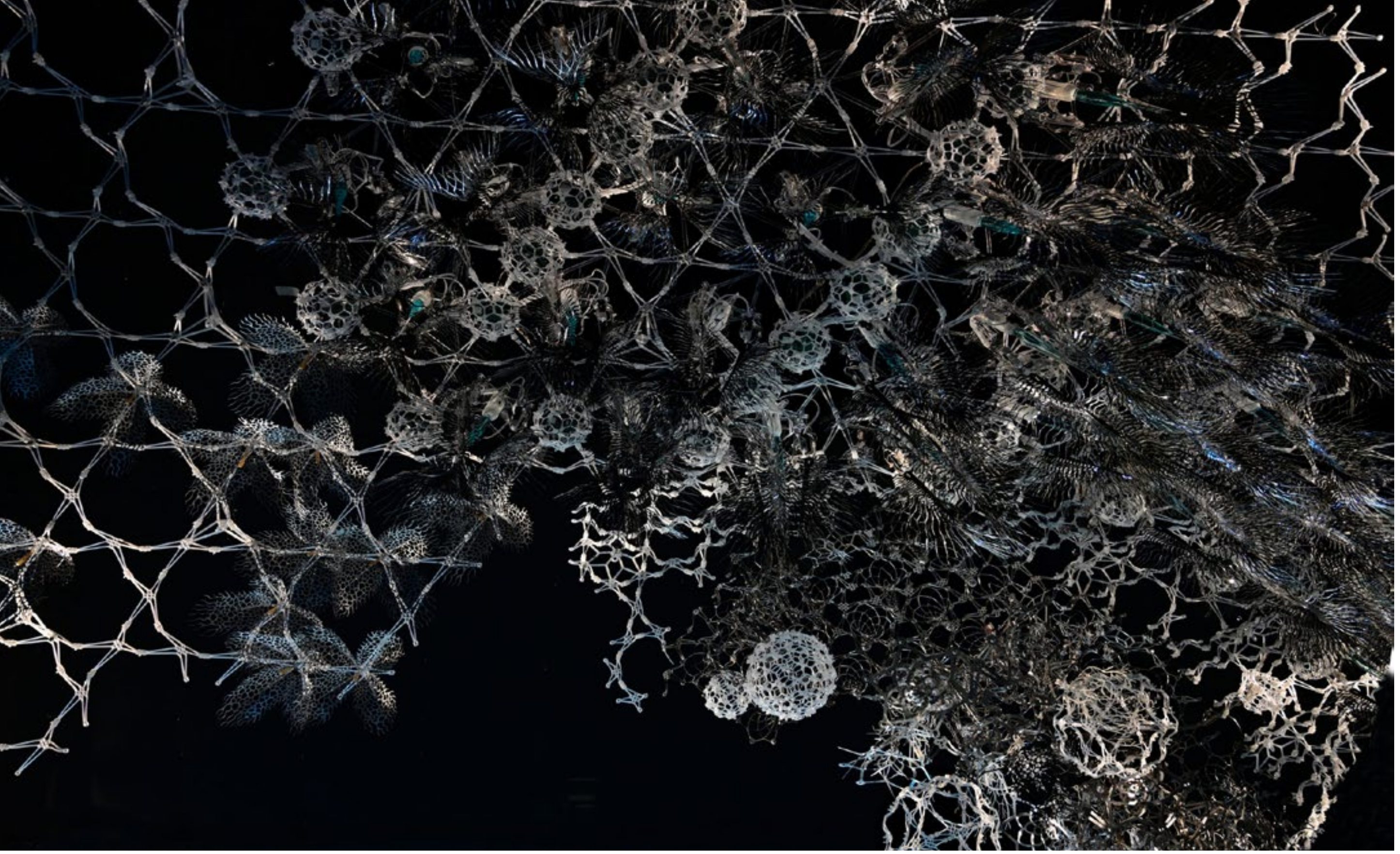
LASG has developed software tools for composing testbed behaviour. Within these tools, actuation "profiles" are stored in embedded firmware on microcontrollers distributed throughout testbed installations. Profiles define how each individual actuator performs, and can be tuned to be long gentle gestures, short bursts, cyclic pulses etc. Each individual actuator can have its own response, allowing for a complex dynamic environment. The group has developed a custom control system that can be accessed with smart phones, tablets and laptops. This can include a range of controls from basic on/off and volume, scheduled periods of dormancy, and "performance" mode buttons.



Right

The distributed hardware and software architecture of Living Architecture testbeds accommodates a variety of behaviour algorithms, coded as 'Influence Engines' which impact the behaviour of physical sculpture components according to their internal logic

Human-choreographed behaviours within the testbeds employ the pre-visualization and control system as a comprehensive simulation of the components within the system, with visually overlaid invisible influences in 3D-rendered space. The simulation includes depiction of generative ambient influences such as wavefronts that move through the space, or localized influences generated by parametrically controlled particle systems that respond to sensor input and modalities of the sculpture. The parameters of this layered behaviour system can be tuned and shaped by non-specialized operators in order to create expressive responses and dynamic activity within the testbed environment.



Scaffold Structures

LASG testbeds often employ suspended halo-like shells and mechanical veils that are formed like rivers and clouds. The structures use paradigms of dissipative structures and diffusion as guides for their design and fabrication. The structures offer minimal material consumption achieved within automated cutting, thermal and mechanical forming of expanded arrays of filamentary structures. The organization of these components is characterized by punctuated oscillation and *quasiperiodic* geometries.

Clusters of laser-cut translucent polymer elements are arranged by grouping and bundling their angled geometries around close-fitting inner sheath structures. Cantilevered resilient stays are inserted, and arrays of individual impact-resistant polymer chevron links supporting these bundles are chained together with elastic joints to form a diagrid of corrugated mesh Halo-like clouds of hovering material ripple and vibrate in response to shifting forces of the environment.

Above

Lightweight scaffold of *Poietic Veil*, a new LASG testbed in development during 2022-3. The scaffold is designed to be compliant and use minimal materials while maintaining structural integrity. Mounted on the scaffold are devices components including quivering fronds with conductive surfaces that are configured as touch-based sensors.

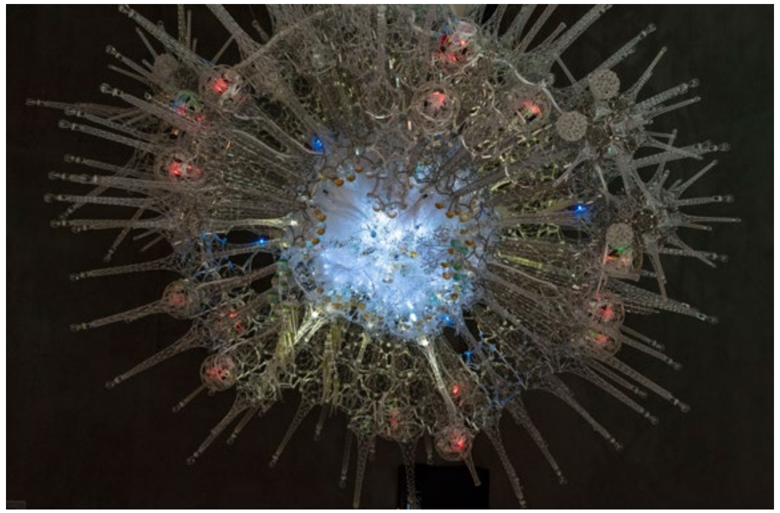
Components

Kinetic functions that offer trembling and vibrating movement are enhanced and amplified by design that brings materials close to their limit of spanning and stability, creating measured precarity. Flexure and elasticity are retained by voiding out large surfaces and volumes, opening the components for deflection and compliance. Mesh works of relatively long tensile filaments are embedded with small compressive struts, creating tension-integrity networks carrying gentle prestressed forces, creating poise.

Scaffolds are designed for resilience and force-shedding. Material is laid down along axial paths by using automated fabrication including fused deposition and digital cutting. By interlinking multiple components, the accumulation of large differences in adjacent assemblies tends to be mitigated. Chains of individual compressive details are linked together into overlapping diagonal arrays containing flexible joints. The thickness and shape of each of those paths is refined in cycles, seeking balances in which all potential forces can be dynamically shared with neighbouring components.

Covering the inner surfaces of these skeletal scaffolds are radial arrays of mechanisms and lighting instruments. The massed lining of hemispherical shells are often designed to respond to feather-light variations of air movement in the surrounding environment, responding with shimmering cyclical motion. Deeply fissured fronds are fitted with spinning miniature motors carrying offset weights that impart vibrating movement to the assemblies. Tapered glass vessels inserted into 3d printed housings carry high-powered LED lights, concentrated by narrow-beam reflectors that concentrate the light into axial beams shining through the central cores of the structural components. Cradling each light and surrounded by frond-clusters are cellular manifolds made from multiple glass vessels. A combination of oil, inorganic chemicals, and aqueous solutions create chemical skins within these prototype cells.

Tile-shaped components used for covering these structures and for stirring and propelling air movements are designed for 'precarious' reactive behaviors. Thin flexible sheets of durable polymer material are shaped into comb-like rows of tapered filaments, creating frond-shaped filters. Rows of filaments are tested in cycles, finding the maximum possible lengths that can maintain their positions without collapse while at the same time maintaining maximum flexibility for reacting to external influence.



Left

Image showing *Noosphere*'s double layer shell, interlinked by a mesh of trumpet shaped spars

Shells

Current LASG testbeds contain the first generations of a new shell and vaulting system made from interlinking expanded-mesh hollow struts. Hexagonal tiles are interlinked at their corners using triangular coupling plates. Arrays of these tiles create flexible membranes. Rings of five face-attached equilateral hexagons create convex clusters surrounding pentagonal cores. Following classical primary polyhedron patterns described by Archimedes, these clusters are assembled into familiar icosahedral spheres each containing twelve pentagon and hexagon ring clusters. The doubly-curved surfaces act with material efficiency. Projection of tile centre points inward and outward create pyramidal units with varying heights that range from shallow spider forms to elongated trumpet-like spines. A series of trumpet-shaped acrylic and stainless steel spars employ thin sheets of mechanically formed stainless steel and thermally formed acrylic and PETG transparent polymer sheet material, formed with polar arrays of concentric overlapping slitting patterns. Forming translates these digitally machined meshwork cutting patterns into hyperbolic curves, providing efficient lightweight branching structures.

Right

Veil of *Meander* made of translucent tines on a compliant scaffold

Veils

Billowing skeletal membranes often extend the outer canopy surfaces of testbed structures intersecting with the edges of the space-grid layers. Skeletal hexagonal frames follow tiled arrangements harmonized with the inner cores. Large sections of the outer membrane show additional chiral organization. In these sections, each tile contains a rotated core encircled by alternating upward and lower-reaching flexible curved arms, creating voided helical rosettes that spiral around their centre. Matching triangular couplers contain similar spiraling arms. Each arm of these curved skeletons carries a curving frond with extended combs of individual tines. The tines are extended close to their cantilever span limit, and react with trembling vibration to slight shifts in the surrounding atmosphere created by mechanical and human-created air movement. Individual tines follow contractions latent within the lower sides of sheet-formed polyester material, creating pronounced concave profiles. Intersecting combs that follow these profiles create a toothed valving structure which tends to close against downward drafts of air while opening and amplifying upward currents. Supporting this turf-like interwoven layer, the linked spring skeletal structure follows a tracery of oscillating filaments whose continuous undulating paths extend throughout the entire canopy. The nested spiral fabric membranes are highly elastic, accommodating large displacements within its hung tentwork placement.

Facing

Construction of *Meander* at Tapestry Hall, Cambridge, Ontario

Working with the Testbeds

Living Architecture Systems Group (LASG) testbeds are hosted by public and private institutions such as museums, educational institutions, and commercial developments in locations around the world. The testbeds are presented within these institutions as unique exhibits and original artworks. The LASG remains in close contact with testbed hosts and works with them to develop approaches for use, presentation, maintenance, and activities.

While LASG members are closely involved, other individuals can also take responsibility for research-creation activities facilitated by these testbeds. Outside researchers may develop unique experiences, performances, or activities, or conduct academic research using the testbeds.

Examples of LASG testbeds are:

- *Amatria*, installed in Luddy Hall, an informatics research building at Indiana University in Bloomington, since 2018.
- *Futurium Noosphere*, installed in Futurium gGmbH, a hands-on museum in Berlin, Germany, from 2019 through 2023.
- *Meander*, installed in Tapestry Hall, an historic warehouse building that has been converted into an event space at the heart of a residential high-rise development in Cambridge, Ontario, since 2020.
- *Ar Frout Reef*, installed in Ar Frout Castle, a 16th century chateau in Carantec, France, owned by a private collector, since 2021.
- *Poietic Veil*, a new LASG testbed in development during 2022-3 and was exhibited at the TU Delft Science Centre in 2023 as part of Highlight Delft.

Each testbed is adapted to the needs and context of its host. Professors at Indiana University have integrated *Amatria* into their curriculums, and *Noosphere* has formed a core of public programming at Futurium. *Meander* and *Ar Frout Reef*, meanwhile, act as background to the events that take place in their respective contexts. As interactions accumulate, the relationship between the testbed and its context changes. Like a garden, each testbed requires ongoing care. The integration of Living Architecture with the human systems of an institution and community are crucial.

Accompanying the proof-of-concept demonstration installations described here, the organization of multiple partners working across disciplines has involved conception of a set of guidelines designed to support successful research collaboration.

For the purpose of furthering living architecture research-creation, testbeds may be made accessible to individuals or groups (Researchers) seeking to develop unique experiences, performances, or activities, and to conduct specific academic research using the Testbed. This access is subject to the voluntary authorization, joint oversight, and cooperation of the Host and the Artist.

These locations are hosted by public and private institutions such as museums, educational institutions, and commercial developments. The Testbeds are presented within these institutions as unique exhibits or original artworks as conceived by their principal creator and/or collaborators (Artists). Specific arrangements for hosting, presentation, long-term maintenance, and associated activities are unique to each hosting institution (Host), and the Host maintains day-to-day oversight and maintenance of their Testbed.

These guidelines are formalized in a Testbed Hosting Agreement to help conserve the functions and ensure consistency throughout multi-year collaborations. The form of this Agreement is in its early stages of development. The current form of this evolving document has been drafted in order to set out general principles and guidelines for Hosts and Third Parties seeking to conduct experimental activities using LASG Testbeds, as well as to outline operational requirements that must be met by a Host.

Right

Installation of *Futurium Noosphere* at Futurium gGmbH, Berlin, Germany

Guidelines for Working with LASG Testbeds include:

1. Maintain Integrity of Artwork: Hosts, Artists, and Third Party co-creators (composers, etc.) will establish guidelines for maintaining the integrity of the Testbed as an artwork.

2. Respect Context of Host: Third Party projects will respect the Host's physical and social context including the physical environment surrounding the Testbed, institutional protocols, and relationships with communities as articulated by the Host.

3. Clearly Delineate Contributions: Credit all contributors including funding parties and sponsors

4. Contribute to Research Infrastructure: Features, functionality, and capabilities of the installation should be made accessible to researchers.

5. Support Knowledge Mobilization: Testbeds should be positioned to support knowledge dissemination including academic dissemination, skill-sharing, and industrialization & commercialization.

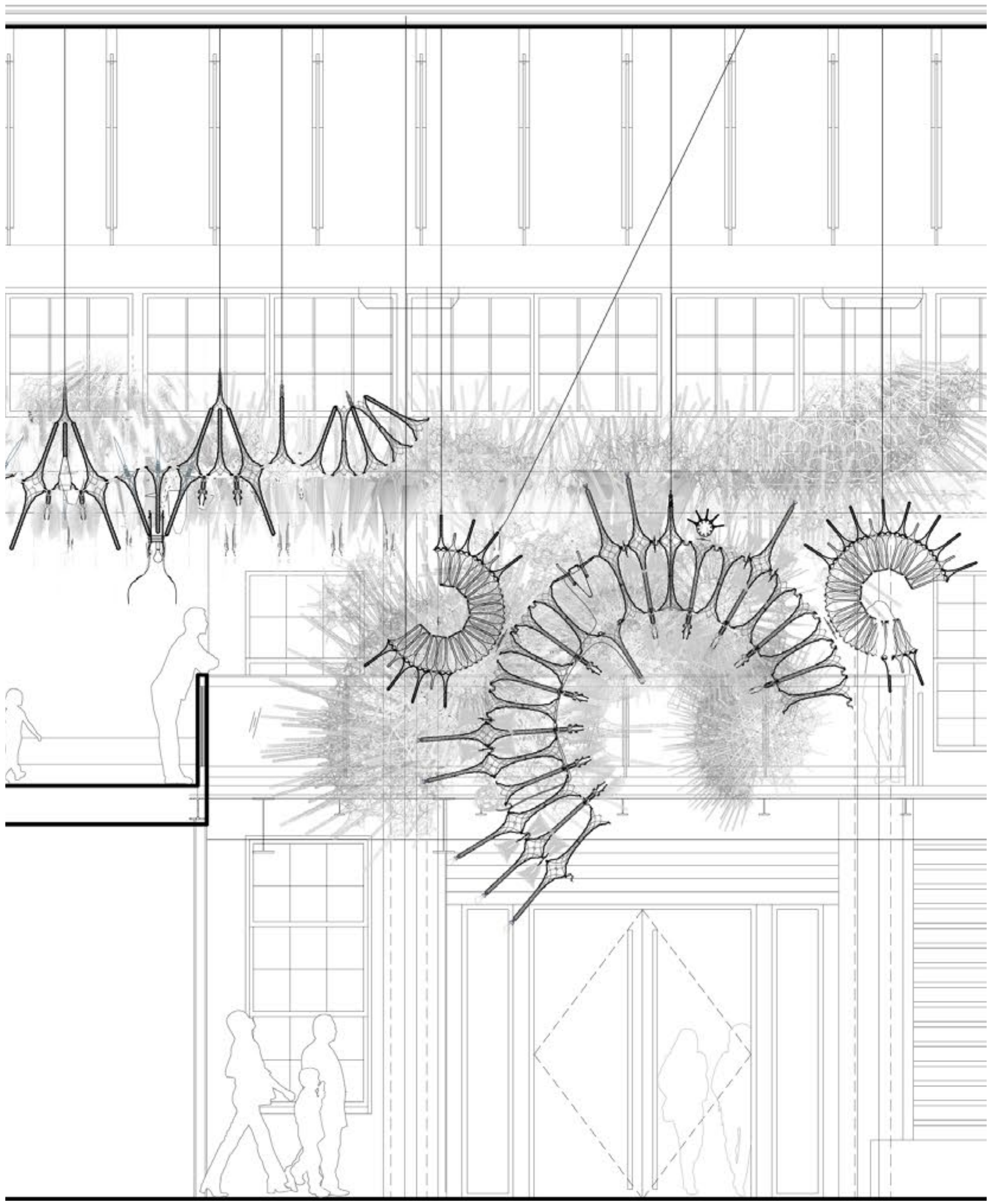
Testbed Examples

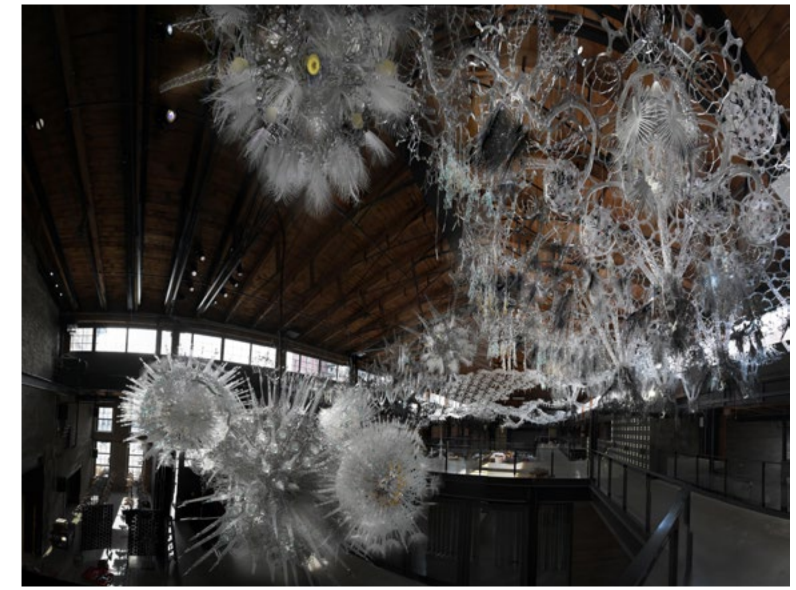
Facing

Amatria in the atrium of Indiana University at Bloomington's Luddy Hall

The installation of LASG testbeds in museums, private venues, and universities has led to discoveries about the relationship between living architecture and different human communities. The following three case studies include examples of lessons that can be gleaned from this research creation. In these examples, experiences that accumulated around the testbed in question revealed aspects of its nature—sometimes technical, sometimes emotional, or philosophical—which deeply informed and sometimes surprised the researchers and designers responsible for creating it.

Meander, Tapestry Hall, Cambridge, Ontario (2020)





Meander

Right

Meander at Tapestry Hall, Cambridge, Ontario

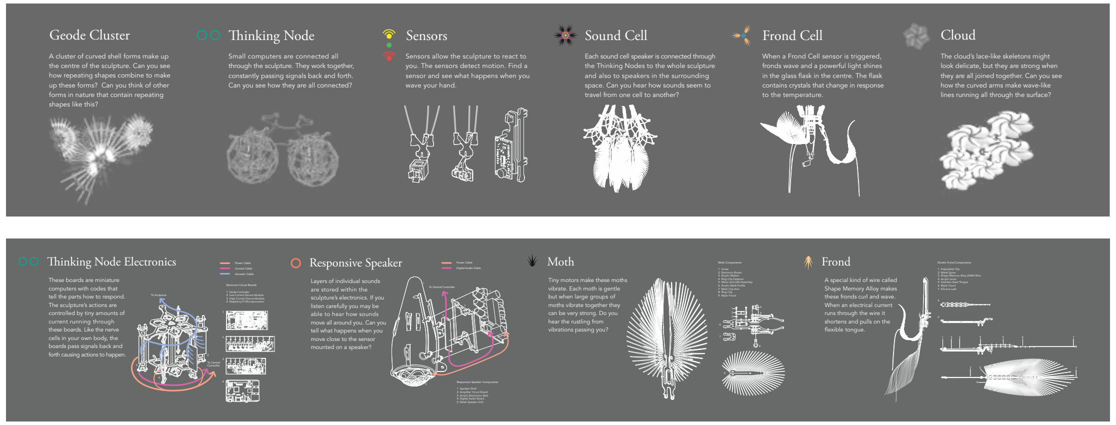
Facing

Section through the main spheres of *Meander* showing how visitors can interact with responsive actuators of the testbed on the mezzanine level

The *Meander* testbed, installed in Cambridge, Ontario, in 2022, deploys a design which integrates a central cluster of spherical structures combined with dense river-like secondary layers and a billowing cloud that reaches over an adjacent event space.

The geometric structures seen in *Meander* use interlinking, flexible lattices that behave like textiles and natural shell structures. Overlapping strands of materials balance each other within doubly-curved conical stem-shaped forms. The skeletal forms create inner and outer shells. The interwoven structures are developed to handle shifting, unstable environments and are capable of absorbing strong forces. Instead of the heavy masses of material used in traditional building, this kind of process uses extremely light, thin sheets of material, reducing material use and saving energy.

Sensors embedded within the environment signal the presence of occupants, and send ripples of light, motion and sound through the system in response. Software is organized in clusters of interconnected groups that can communicate with neighboring groups resulting in global behavior connections throughout the system.



Above

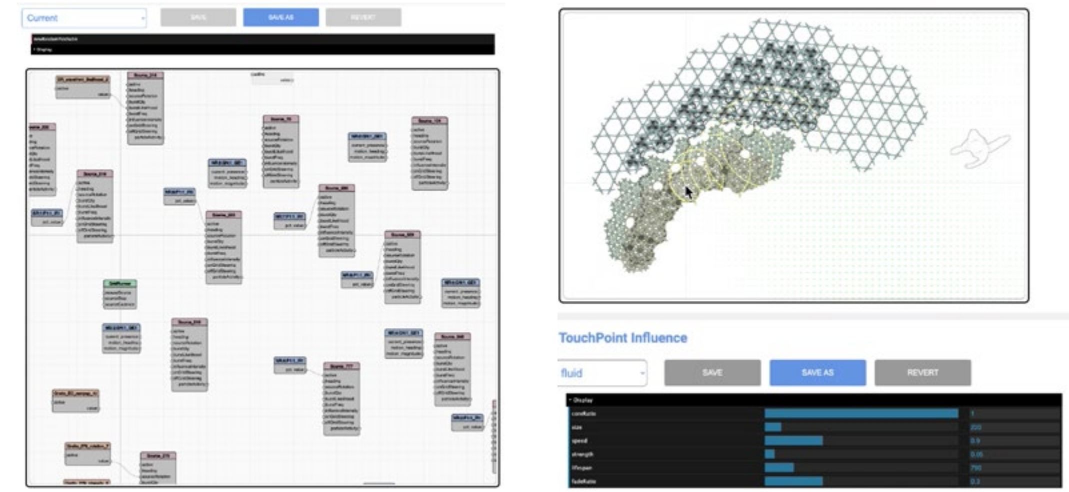
Meander Interpretive display showing various components of the sculpture

The project includes an immersive distributed soundscape developed in collaboration with the Netherlands-based group 4DSOUND. The composition is carried within arrays of custom speakers embedded throughout the environment, making constantly-shifting sound that responds to visitors.

Interactions with its hosts and local students and educators involved in the testbed's STEAM curriculum inform the LASG's understanding of the relationships between testbeds and wider communities, especially outside of cultural environments like museums. Alongside the sculpture, a *Meander* STEAM curriculum foregrounds a space where young learners can engage in a collaborative web of science, technology, engineering, arts and math to playfully form new solutions for sustainable technology and design. The interpretive exhibit invites visitors to view detailed visualizations of the interactive systems within the sculpture and includes prototype samples and videography documenting the development of the work.

Behaviour and Controls

Meander and its controls need to accommodate many different types of users. The host requested a simple way to "turn it on" for educational programs or building protocols, while event staff might need to set the system to a certain behaviour mode. Because the testbed is an active research creation site for the LASG, it also has features for troubleshooting and designing new behaviour. These use cases led to the development of a lightweight browser-based control panel system. The initial implementation was a simple system of hard-coded buttons and sliders, with different



Above

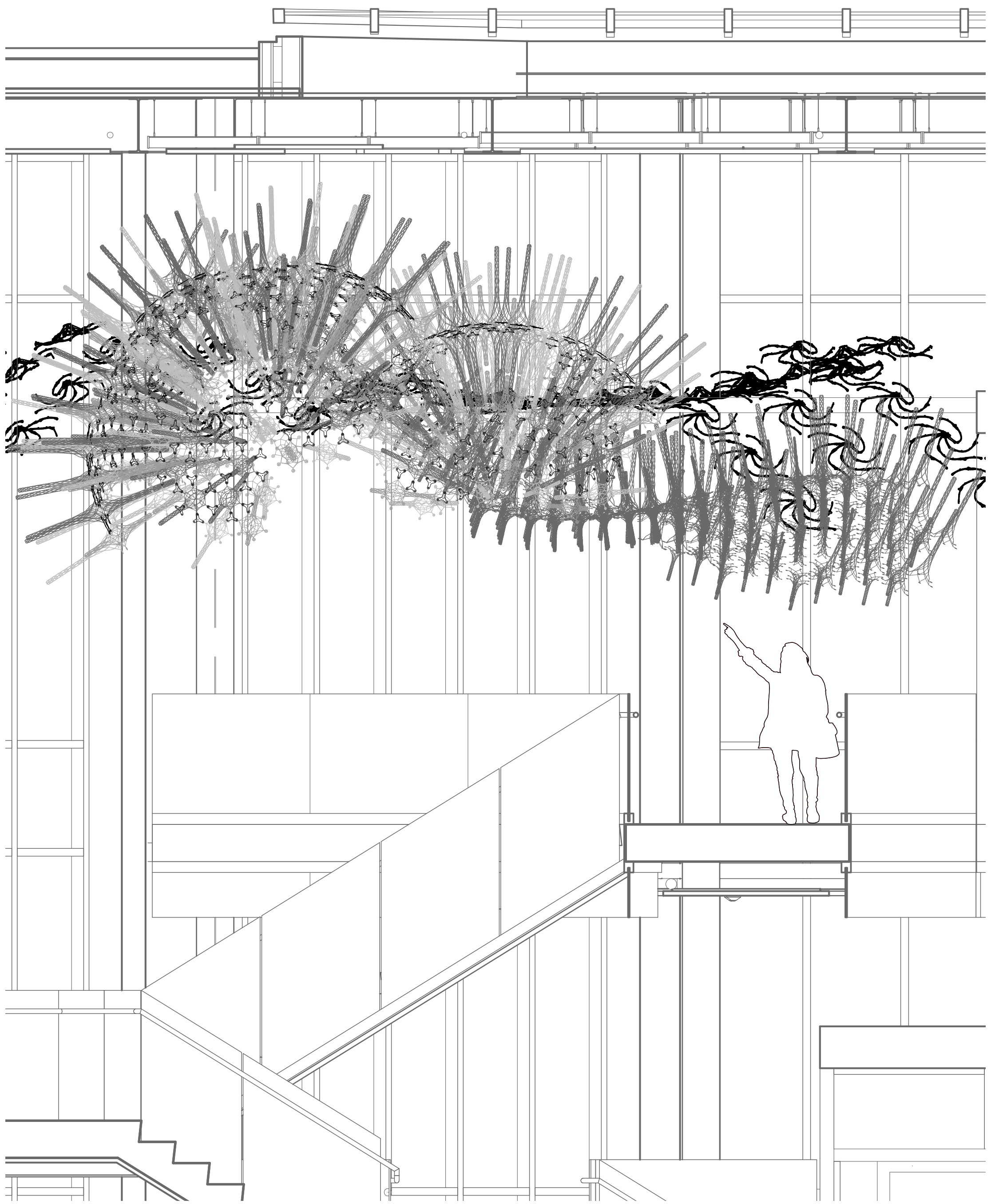
Browser-based interfaces initially developed for simple control of testbed functions have evolved to include sophisticated behaviour authoring tools.

"pages" for each type of user, enabling a flexible set of features. Using web infrastructure also meant that users could log in and control aspects of the environment from their own phones.

Beyond simple buttons and sliders, the browser-based controls soon opened a world of possibilities for further exploration. Once the software infrastructure was in place for browser-based control, it became possible to distribute more and more functionality to lightweight software scripts that powered the control surfaces. What had been merely interfaces quickly became composition and design tools in their own right. Layers of experimental interfaces were created for various tasks, setting up tools to design scene changes, parametric behaviour control, and real-time interaction with the testbed, all accessed from users' web browsers. In many ways, the centre of the system began to dissolve across its many devices.

Meander's (now) distributed control panels led to a redesign of its internal messaging system to ensure that information displayed using these tools was always reflecting the current state of the system, and a host of other technical improvements. Building on this distributed system, later testbeds like *Ar Frout* and *Poietic Veil* further distributed the control system to the point that, between more powerful microcontrollers and lighter-weight control scripts, *Meander*'s original centralized, resource-intensive Testbed-Control and simulator software were no longer necessary for those testbeds to produce expressive behaviour.

Amatria, Indiana University’s Luddy Hall, Bloomington, Indiana (2018)



Above

Amatria at Indiana University's Luddy Hall, Bloomington, Indiana

Facing

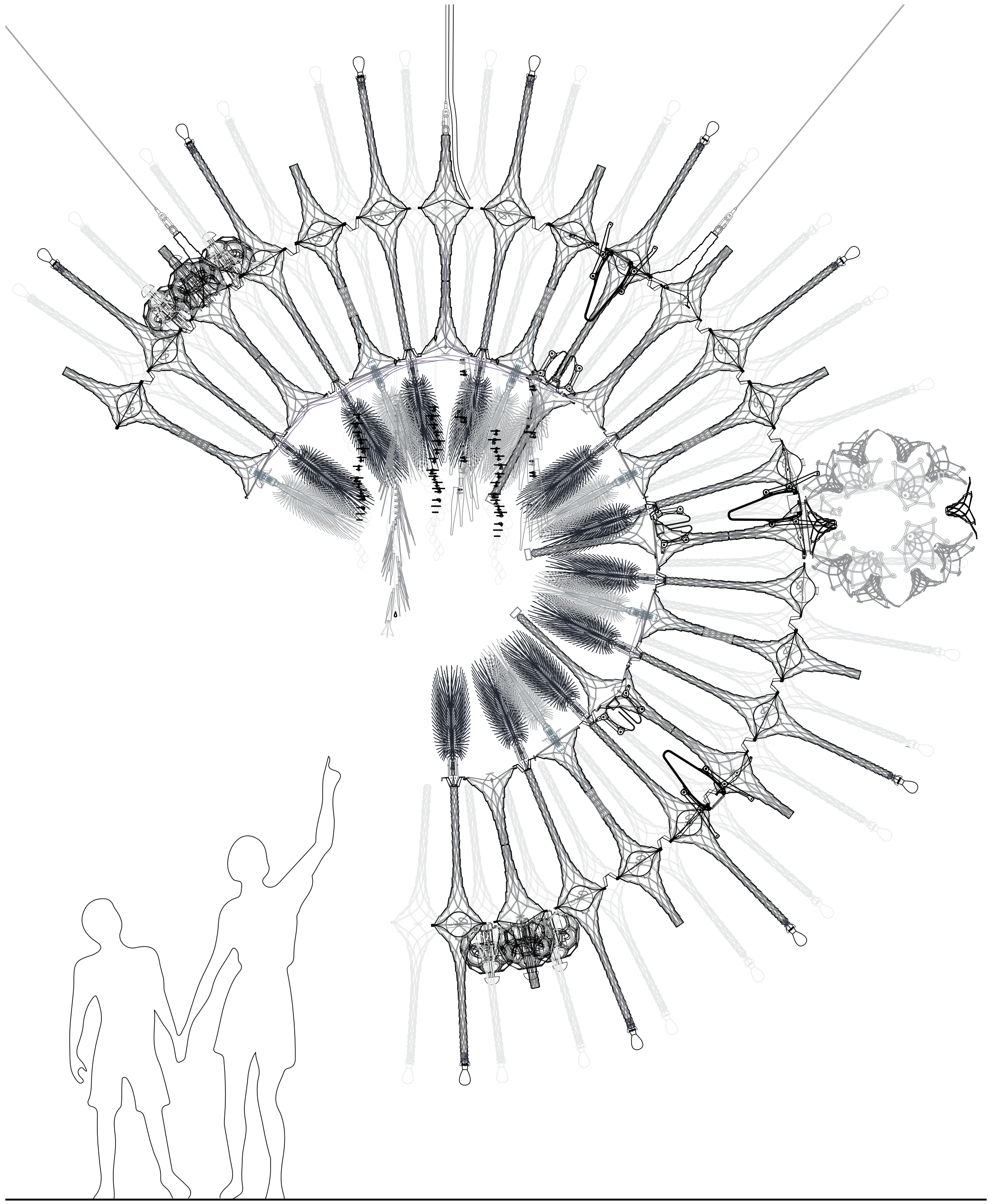
Section through *Amatria* hanging in the main atrium of Luddy Hall

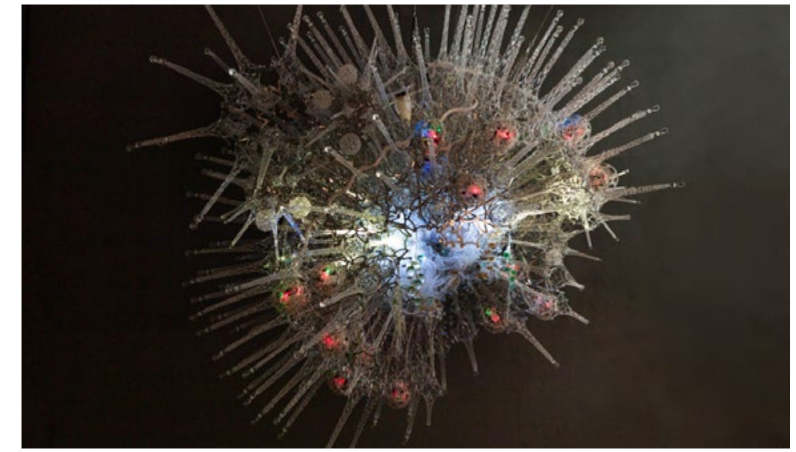
Amatria

The *Amatria* testbed, installed at the School of Informatics building ("Luddy Hall") on Indiana University's campus in Bloomington, Indiana, has shown the power of a living architecture installation to inspire and draw together the local community. The piece itself has become a destination for wedding and tourism selfies, but beyond this, its caretakers exhibit a sense of pride in its presence. Composers from the nearby Jacobs School of Music have composed multi-channel performances using *Amatria*'s ten channels of embedded speakers. It has been used as an output for brain-computer-interface experiments. It has inspired the university's maker community to produce a kinetic toy kit based on its form language, and it has been used in data visualization curricula within the School of Informatics. The IU community even hosts a birthday party for *Amatria* every April, coming together to share related research and celebrate this unique cultural and technical artifact.

In addition to technical development, *Amatria* is also serving as a testbed for agreements and policies regarding the scope and stewardship of a living architecture system. Important lessons have been learned and are still being formalized on many levels, from technical, logistical and maintenance needs to intellectual property, collaboration, and authorship considerations for something that exists between a building, an artwork, and a practical instrument.

Futurium Noosphere, Futurium gGmbH, Berlin, Germany (2019)





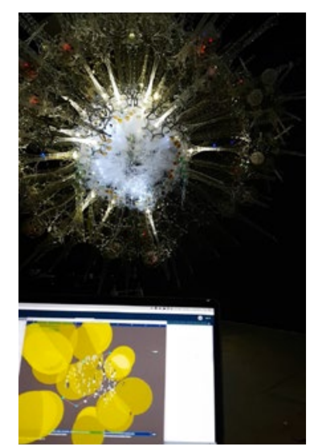
Right

Visitors interacting with *Futurium Noosphere*

Facing

Section through main sphere of *Futurium Noosphere*

4 Pierre Teilhard de Chardin, "The Formation of the Noosphere," in *The Future of Man* (New York: Image Books Doubleday, 1959), 149–78.



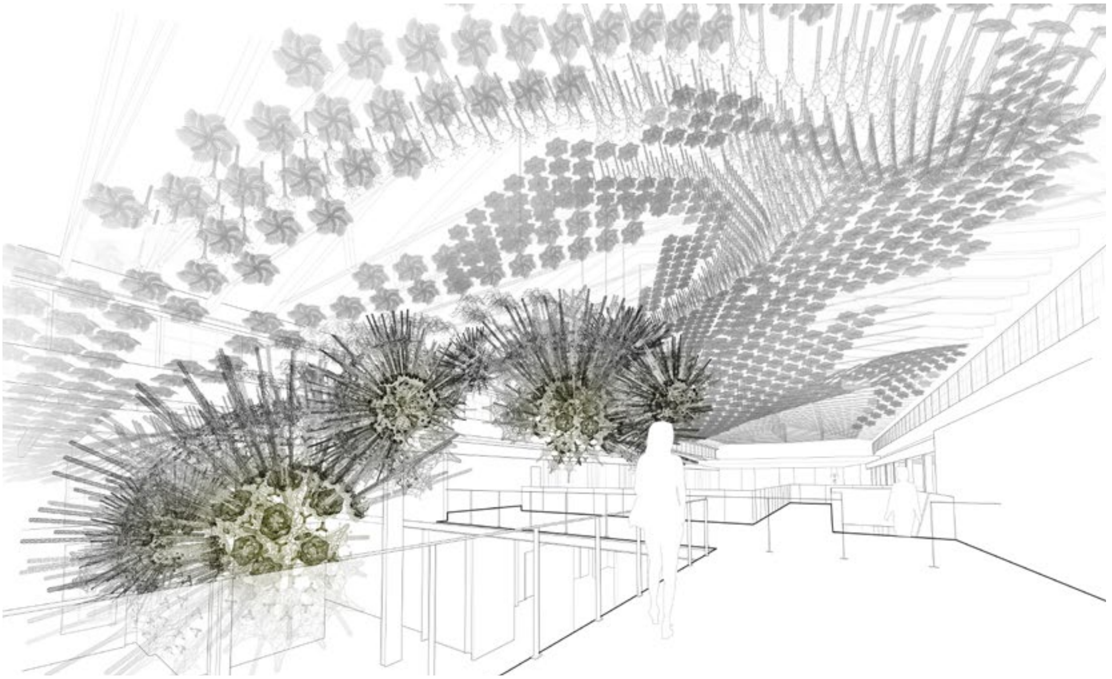
Above

Visualisation of excitors with in the *Noosphere*

Futurium Noosphere

Futurium Noosphere was the second iteration of an installation originally presented at the Royal Ontario Museum in Toronto in 2018. It was installed in Futurium gGmbH, a cultural hub for science and technology in Berlin's city centre in 2019. *Noosphere* is a spherical structure incorporating light, sound, and vibrating and, shivering movement. The name *Noosphere* comes from the Greek word *noos*, which means knowing or perceiving; the term *noosphere* was first coined by the French theologian and geologist Teilhard de Chardin. In seeing the Earth as a whole organism, de Chardin imagined the possibility of a collective Earth consciousness in which living and non-living beings were connected by mutual sympathy and empathy.[4]

It was the first LASG testbed to feature "excitors", a behaviour actuation concept that uses virtual objects moving through the same space as the sculpture according to an embedded physics model. As these excitors overlap with the physical positions of components of the sculpture, they exert influence on the actuators within it. The principle was developed through close collaboration with 4DSOUND and grew out of techniques employed for the dynamic spatialization of sound within environments. *Noosphere*'s integrated multi-channel speaker system served as a testbed for integrating 4DSOUND's technology with the sculpture's light-emitting and kinetic components into a single expressive system of behaviour. Excitors were further developed and refined in subsequent LASG testbeds such as *Meander*.



Conclusions and Future Directions

The LASG's testbeds are the primary sites of research creation for living architecture. As such, their forms and capabilities are constantly changing, incorporating new materials, algorithms, behaviours, and characteristics, as well as fueling evolutions in the LASG's working methods and design tools. Their existence within their host communities, as boundary objects and transitional environments, amplifies the scope of the LASG's work. It fuels adaptation in logistics, software, and control mechanisms, generates surprising philosophical and emotional shifts in the testbeds' identity, and grounds the development of new forms of living architecture in more open interactions with human beings. As the relationships between testbeds, the LASG, and hosts continue to multiply and deepen, these rich interactions will have key implications for the definitions of life, community, and living systems that inform the creation of living architecture.

About the Living Architecture Systems Group

The publication forms part of a series of work-in-progress reports and publications by Living Architecture researchers and contributors. The Living Architecture Systems Group is an international partnership of researchers, artists, and industrial collaborators studying how we can build living architectural systems— sustainable, adaptive environments that can move, respond, and learn, and that are inclusive and empathic toward their inhabitants. "Smart" responsive architecture is rapidly transforming our built environments, but it is fraught with problems including sustainability, data privacy, and privatized infrastructure. These concerns need conceptual and technical analysis so that designers, urban developers and architects can work positively within this deeply influential new field.[5] The Living Architecture Systems Group is developing tools and conceptual frameworks for examining materials, forms, and topologies, seeking sustainable, flexible, and durable working models of living architecture.

Living Architecture Systems Group research is anchored by a series of prototype *testbeds*: accessible, immersive architectural sites containing experiments and proof-of-concept models that support living architecture as a practical model for our future built environment. These testbeds act as *boundary objects*[6] that help researchers answer ethical, philosophical and practical questions about what living architecture means and who it is for within our societies and environments, creating sites of collaborative exchange that act both as research ventures and as public cultural expressions.

A series of far-reaching critical questions can be explored by using the tools and frameworks that are described within this specialized publication series: can the buildings that we live in come alive? Could living buildings create a sustainable future with adaptive structures while empathizing and inspiring us? These questions can help redefine architecture with new, lightweight physical structures, embedded sentient and responsive systems, and mutual relationships for occupant that provide tools and frameworks to support the emerging field of living architecture. The objective of this integrated work envisions embodied environments that can provide tangible examples in order to shift architecture away from static and inflexible forms towards spaces that can move, respond, learn, and exchange,[7] becoming adaptive and empathic toward their inhabitants.[8]

5 Kas Oosterhuis and Xin Xia, *iA #1, Interactive Architecture* (Rotterdam: Episode Publishers, 2007)

Nicholas Negroponte, *Soft Architecture Machines* (Cambridge, Mass.: MIT Press, 1975).

Lucy Bullivant, *4dsocial: Interactive Design Environments* (London: AD/John Wiley & Sons, 2007).

Neil Spiller, *Digital Architecture Now: A Global Survey of Emerging Talent* (London: Thames & Hudson, 2009).

Michael Fox and Miles Kemp, *Interactive Architecture* (Princeton: Princeton Architectural Press, 2009).

6 LASG uses Bowker and Star's terms *boundary object* and *boundary concept* to frame the design and analysis of the multiple physical armatures and architectural constructions that make up LASG testbeds. In order to act effectively, a boundary object needs to be both concrete and abstract, both precisely defined and fluid, offering an "object that is part of multiple social worlds and facilitates communication between them; it has a different identity in each social world that it inhabits": Geoffrey C. Bowker and Susan Leigh Star, *Sorting Things Out: Classification and Its Consequences* (Cambridge, Mass: MIT Press, 1999): pp. 409.

7 For example the Living Architecture (LIAR) next-generation, selectively programmable bioreactor developed by LASG Metabolism Stream Lead Rachel Armstrong, Newcastle, uses microbial processes to generate electricity, oxygen, fertiliser, and other life-sustaining outputs from waste (carbon dioxide, grey water) that would otherwise be ejected from a building: "Living Architecture LIAR," accessed February 2, 2022, https://livingarchitecture-h2020.eu/.

8 Bullivant, *4dsocial.*

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