Living Shadows
for Living Architecture Environments

Philip Beesley, Kevan Cress & Matt Gorbet
Living Architecture Systems Group

This folio describes the Living Shadows project within the Living Architectures Systems Group's (LASG's) exploration of augmented reality (AR) environments. Living Shadows uses real-time projections to create a virtual world that augments the physical shadows of an LASG testbed. Creatures based on the sculpture's physical components inhabit this virtual world. Set free as "living shadows," they are a way of exploring how these normally static components might behave if they were given the autonomy to move through and interact with the sculpture's environment. The publication forms part of a series of work-in-progress reports and publications by LASG researchers and contributors.

Shadow plays an important role in the immersive environments created by the LASG. A testbed's shadow projects the sculptural shape outward, flattening its forms into compositions of light and darkness. The light sources incorporated into the testbeds allow different intensities of light and shadow to animate the structures, adding mood and nuance to their physical movements. The 2022 workshop Shadows and Whispers: Emerging Forms at the Edges of Nature in Lessac, France, used shadows to explore the boundaries between nature and technology and dreams and waking life.

ISBN 978-1-988366-54-8

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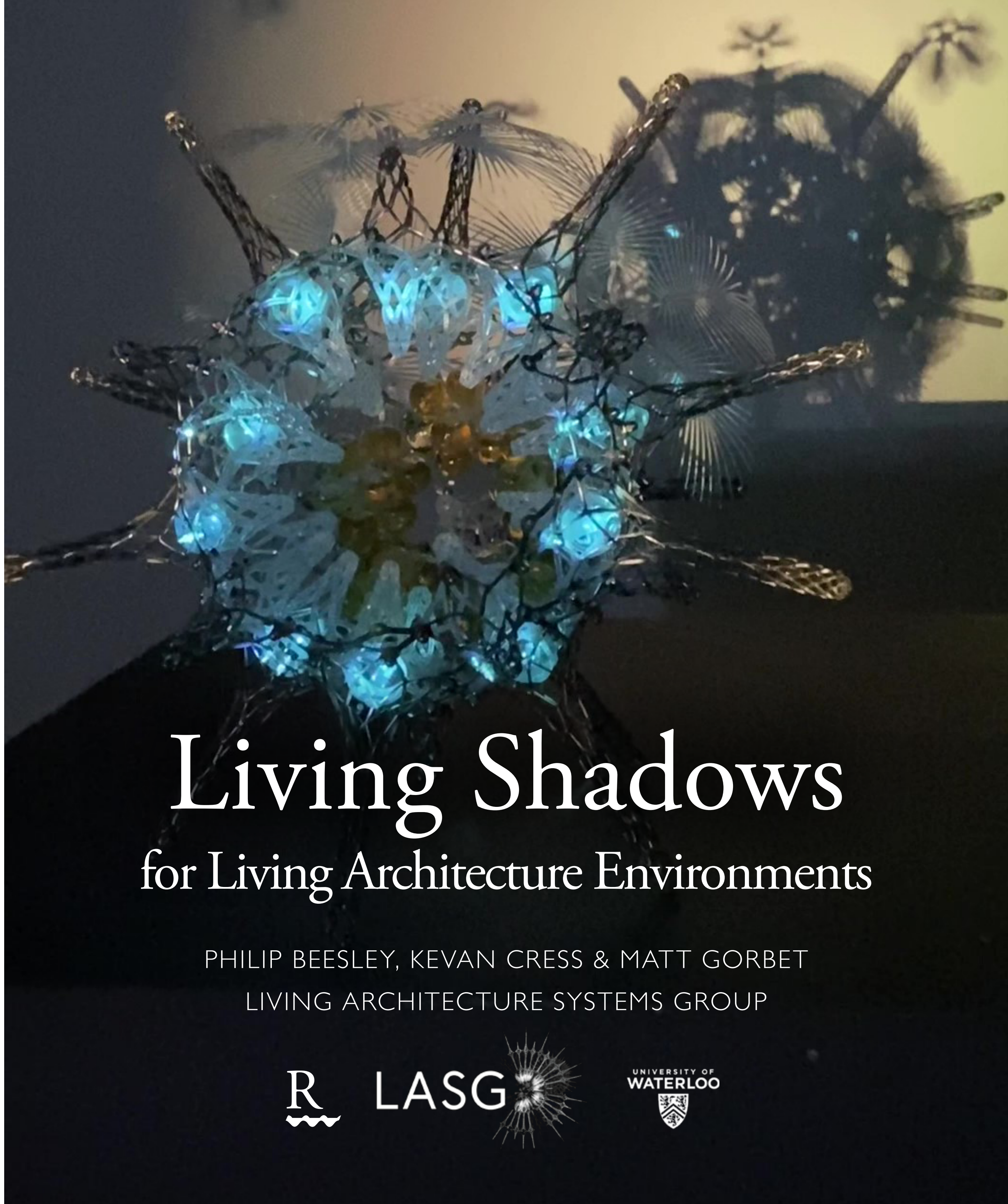
Riverside Architectural Press



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Publisher: Riverside Architectural Press, www.riversidearchitecturalpress.ca

Title: Living Shadows for Living Architecture Environments
Names: Cress, Kevan, 1995-author | Gorbet, Matt, 1973-author. | Beesley, Philip, 1956-author.| Boll, Timothy, 1991-contributor. | Living Architecture Systems Group, issuing body.

Description: Fieldnotes on the work-in-progress design and development of a virtual environment-augmented sculpture-projection environment.

Identifiers: ISBN 978-1-988366-47-0

Design and Production by Living Architecture Systems Group

Publication: December 2022
Riverside Architectural Press
7 Melville Street
Cambridge, Ontario, N1S 2H4
Canada

The individual authors shown herein are solely responsible for their content appearing within this publication.

Errors or omissions would be corrected in subsequent editions.
This book is set in Garamond and Zurich BT.

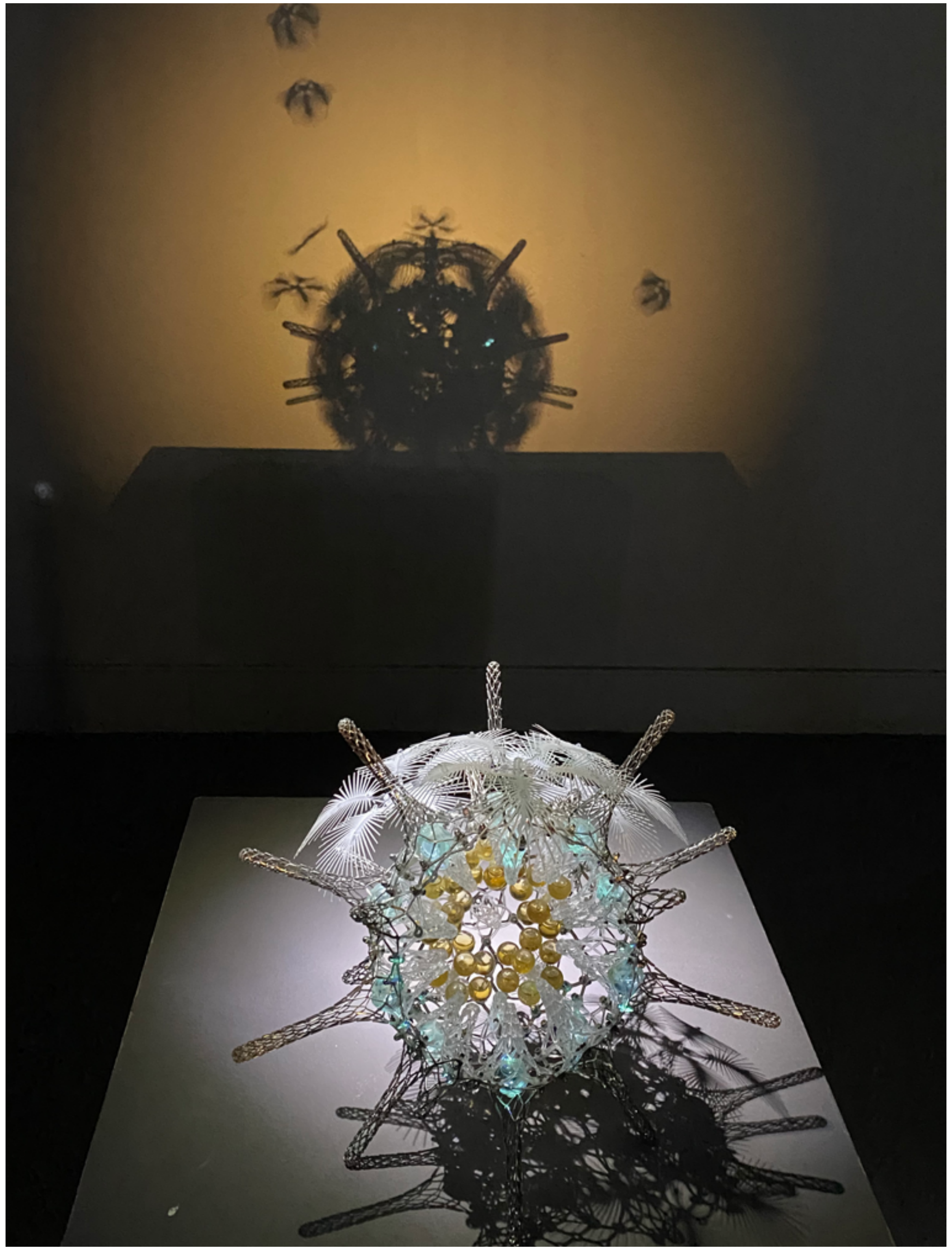
About the Living Architecture Systems Group

This 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. 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 objects6 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, becoming adaptive and empathic toward their inhabitants.

Contents



Introduction

Facing Page
The Living Shadows Demo

The Living Shadows project is an augmented reality experience that explores the intersection of physical and virtual worlds through the medium of shadowplay. It investigates how the shadows of a physical object might be augmented with the shadows of animated creatures and field conditions that exist within a virtual world. The aim of the Living Shadows project is to create a virtual world that is closely linked to its physical counterpart. In this virtual world, a digital twin takes on a life of its own, with actions and influences that are projected back out into the physical world and made visible through the interplay of light and shadow on objects and their surroundings.

Overlaid on a physical work, this virtual world of living architecture evokes new dimensions for exploring the lives of virtual beings immersed within environments. The creatures that inhabit this virtual world help develop the identity of a sculpture's static physical components. Action composed within the virtual environment is related to the particular components and organizations of physical fabrications within LASG sculptures. The Living Shadows project explores behaviours that these assemblies might manifest if they were given autonomy and set free within a virtual environment.

This project represents an early step in the Living Architecture Systems Group's exploration of augmented reality environments.

Coupled Physical and Virtual Characters

Left

Virtual creatures swarm around a work of Living Architecture

Imagine a scenario where the physical movement of individuals in the space in and around a Living Architecture testbed triggers reactions in a virtual world. In turn, events within that virtual world can affect the behaviour of mechanical actuators embedded throughout a sculpture. Subtle sounds permeate the environment, suggesting the presence of unseen beings. Shadow-play on the walls reveal not just the intricate structure of the physical environment, but also the occasional movement of otherwise invisible virtual creatures. Sudden movement by a human, picked up by sensors and fed into the parameters of the influence engines, might momentarily quiet the movement of components and/or virtual automata, signaling perception and sensitivity within the ecosystem. The buildup of emergent behaviours from dozens of simple virtual creatures might set off a cascade of sound and light within the physical sculpture synchronised with its virtual twin. Looking closer with an augmented-reality lens, participants could uncover whole communities of virtual creatures. They might also discover weather-like patterns containing shifting, flowing virtual elements, positioned around the physical parts of the environment.

Experiences such as this imagined scenario are proposed by the Living Shadows project. Creating this wealth of virtual biodiversity presents a design challenge: how can we design a host of virtual creatures that inhabit a virtual space coupled to physical environments ?

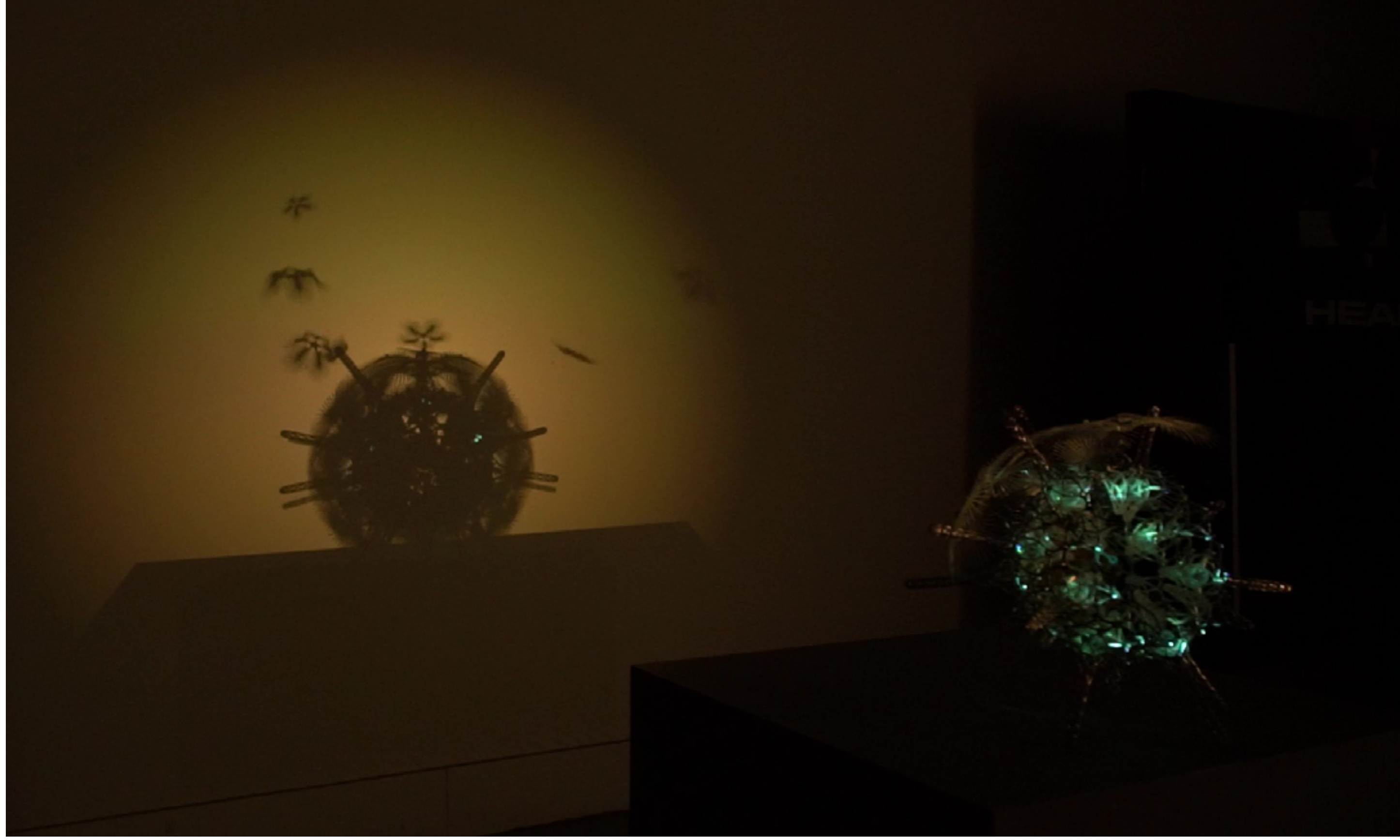
The characters and behaviours generated within the virtual space of the Living Shadows project are linked to physical components in living architecture environments. The conception of the actions and behaviours within the Living Shadows project starts with the development of a conceptual identity that encompasses both a virtual creature and a corresponding physical component. This physical component represents one particular manifestation, or instance, of this conceptual identity.

The physical component expresses this identity in our physical reality. The related virtual creature is not a separately conceived entity that incidentally shares some formal similarities with its physical counterpart, but is rather another instance of that same conceptual identity – one that is manifested in a virtual reality.

This conceptual framework of identities and instances is a useful tool when conceiving of the types of expressive behaviours that might manifest in a virtual space for each of a sculpture's components. To illustrate how this conceptual framework (hereafter called the "identity-instance framework") might be applied, the development of the jellyfish-like "polyp" creatures seen within the Living Shadows Demonstration are described here.

The conception of a component's identity starts with a consideration of the experience it should offer to a human encountering it. The polyps, for example, are inspired by a visually rich mylar material light enough to shiver in response to nearby movement or even in resonance with a loud sound. In the physical world, these behaviours are a direct result of the components' form and materiality, carefully crafted over many iterations of prototyping, testing, and refinement. The identity-instance framework prompts designers to give the same care to a component's virtual behaviours, considering how a component's identity might manifest both in the physical form language and in virtual behaviours that might (currently) be physically impossible. Those behaviours are designed to.resonate with the materiality of the physical object, closely coupled to its environment.

In many LASG physical sculptures, expressive mylar fronds are anchored to expanded metal skeletal components, called "spars". In the virtual world, these spars act not only as anchors, but also as birth points for the polyps. These virtual elements are designed to emulate the delicate mylar petals that can be found within their physical frond counterparts. Given the right conditions in the virtual world, each physical spar has the potential to generate virtual polyps. The spars' relationship to the mylar fronds, as physical anchor point and virtual spawn point, expresses an integral part of the spars' identity. Similarly, the two manifestations of the fronds, as virtual polyps and physical dressing, can be conceived as two instances of a core identity that is ultimately responsible for the viewer's experience. All physical components of testbeds could have similar virtual-world behaviours that manifest when the two worlds are brought together.



Above

Polyps spawning from the augmented shadow of a work of Living Architecture.

Considering each component's specific behaviours, both physical and virtual, as part of its identity in the early design phases of a sculpture or testbed helps facilitate the assembly of scalable, distributed active sculptures and environments with many different types of expressive components.

The behaviour in the scenario described at the start of this section can emerge, bottom-up, from the presence of intrinsic behaviours specific to the various physical components within the sculpture. These components may be organized to act in response to each other or in response to changing conditions in the environment. A designer can coordinate top-down effects such as shifting virtual currents or changes to the timing and sensitivity of virtual activity by setting and saving the desired states of parameters. Emerging smart materials and active matter have the potential to translate some of these behaviours into the physical world. Anticipating this future by adding virtual layers to living architecture can support discovery of future expression within existing forms and materials.

From Physical Sculpture to Extended Reality

Above

Grove installed at the Arsenale, Venice Architecture Biennale, 2021

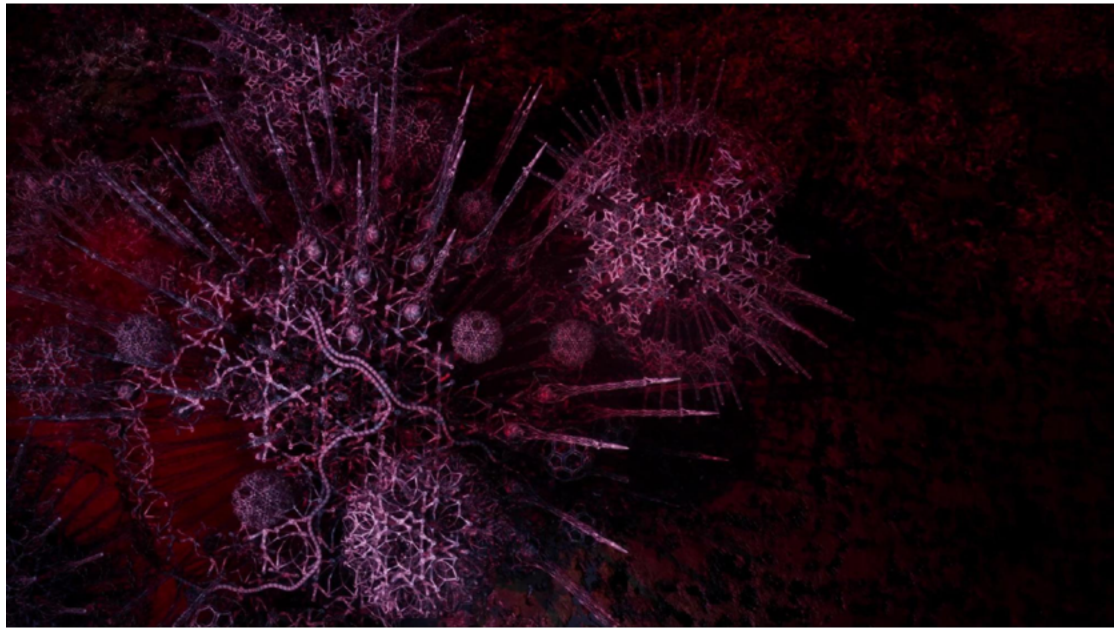
Facing Page

Static Shadows of the *Ar Frout Reef*, Ar Frout Castle Carantec, France, 2021

Shadow has played important roles in the immersive environments created by the Living Architecture Systems Group's (LASG) testbeds. A testbed's shadow projects its sculptural shape outward onto its environment, flattening its forms and making them manifest as crisp compositions of light and darkness.

The Grove installation, created for the 2021 Venice Architecture Biennale, featured some explorations of animated virtual worlds and animated shadow play.

Surrounding Grove's largely static construction of undulating clouds, simple animated shadows provided an illusion of shifting, billowing forms, evoking dream-like worlds of activity just beyond the threshold of the physical. This shadow play was created by alternating the intensities of digitally controlled lighting distributed around the perimeter of the sculpture.

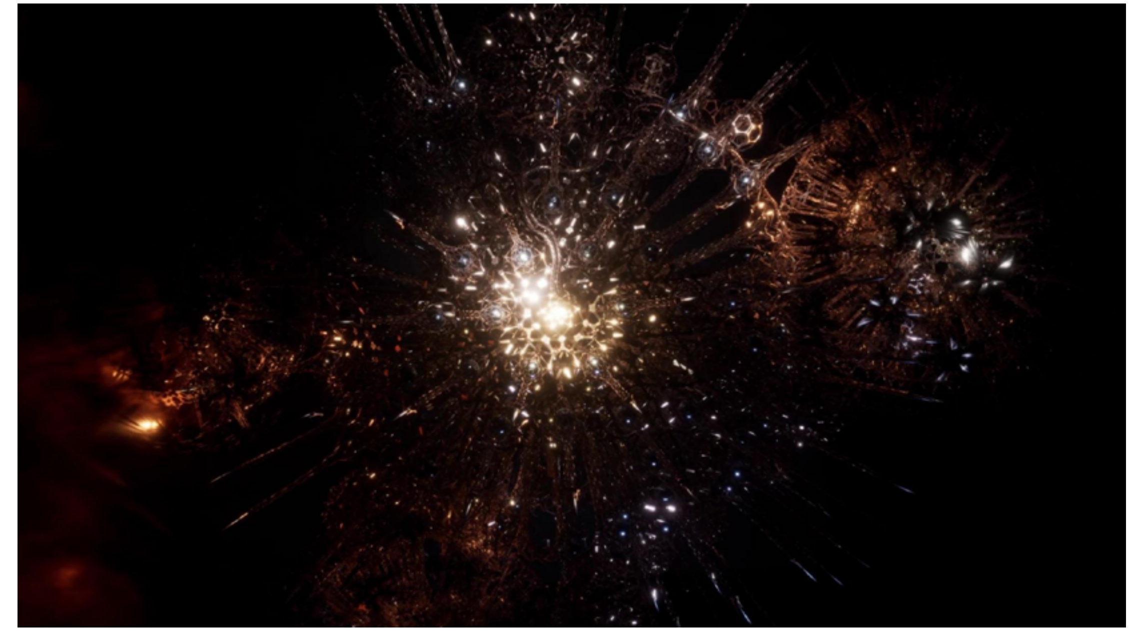


At Grove's core, the short film Cradle was projected onto a pool-like screen on the floor of the installation. Created by Philip Beesley in collaboration with London-based filmmakers Warren du Preez, and Nick Thornton Jones, with sound composition by the Amsterdam artist Salvador Breed, the film showed elements of the LASG's physical testbeds growing, shifting, and influencing one another. These behaviours, as of yet impossible to achieve in the physical world, imagined dynamic future identities for living architecture components. Within Cradle's computer animation these components were witnessed being born, living, and dying in cycles.

Within the physical installation of the Grove project, animated shadows and projected film that augment the physical sculpture remained largely separate. Physical projected shadows originated from the physical form of the sculpture. The locations of real-world lights determined their forms, behaviour, and location on the walls of the Arsenale. The projected film presented a window into a virtual world, bounded by the shimmering pool of projected light at Grove's centre. With the exception of Cradle's sound, which acted as a bridge between the physical and the imagined, movements in one realm remained separate from each other.

Above

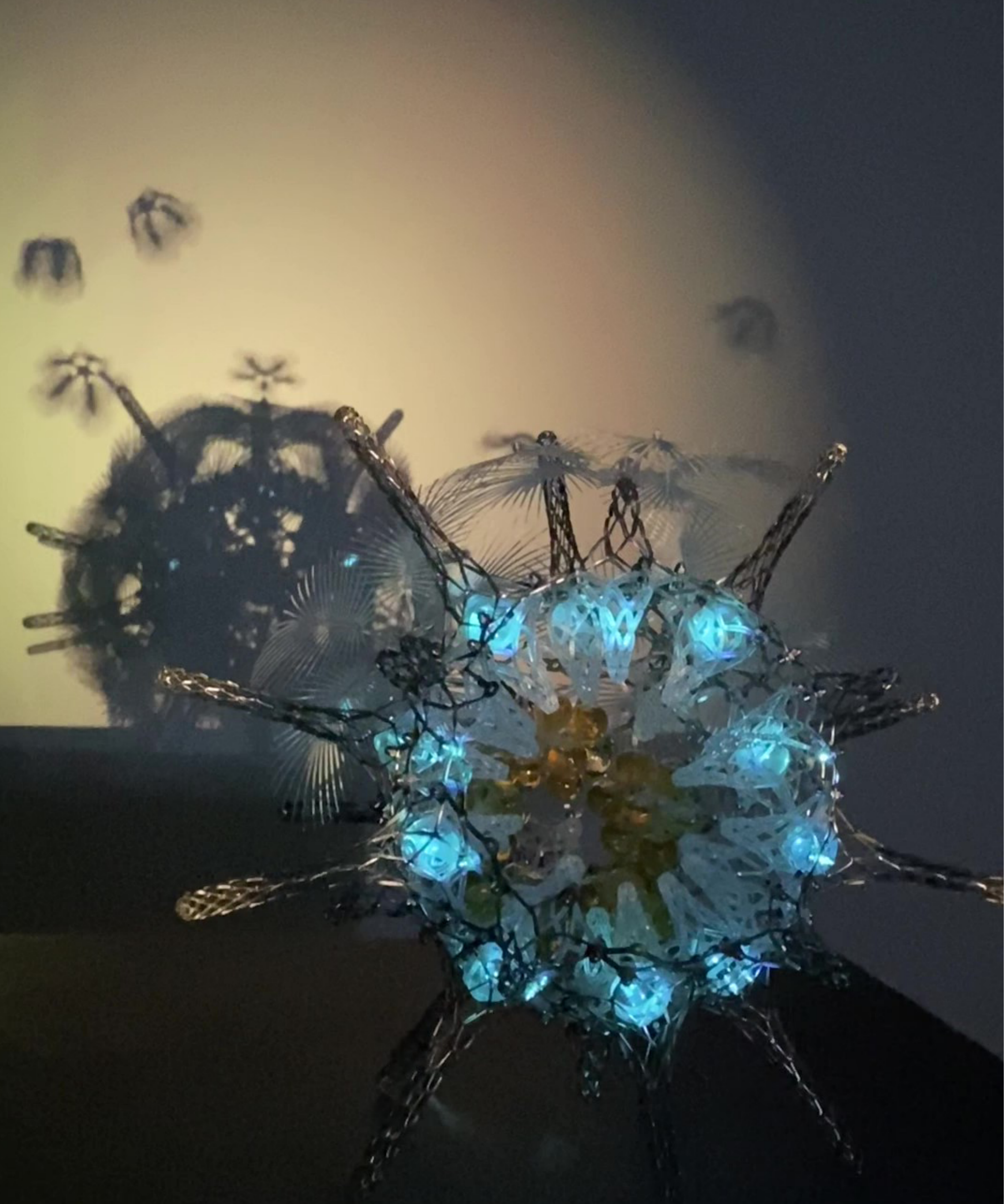
Still from *Cradle,* by Philip Beesley, Warren du Preez & Nick Thornton Jones, showing the imagined life cycle of LASG components. Image depicts a Double Shell Noosphere form in a state of decay.



Above

Still from *Cradle,* by Philip Beesley, Warren du Preez & Nick Thornton Jones, showing the imagined life cycle of LASG components. Image depicts a Double Shell Noosphere form in a state of vibrant life.

The Living Shadows project attempts to dissolve the boundaries between these separate virtual and physical worlds by projecting combinations of real and illusory shadows that blend seamlessly. The composition is designed to express the tangible influence of testbed-born virtual creatures within the physical space and light of the environment.



Living Shadows Demonstration

Facing Page

Close up of the Living Shadows Sphere, glowing with virtually actuated glass vessels.

Following Page

The following pages show a diagram of how the Living Shadows Project is configured in both the physical and virtual worlds. The physical world

Because the projector projects what the camera "sees," by placing the physical projector and the virtual camera and in the same position relative to the physical sculpture and its digital double, it's possible to bring the virtual world into the physical world.

Link

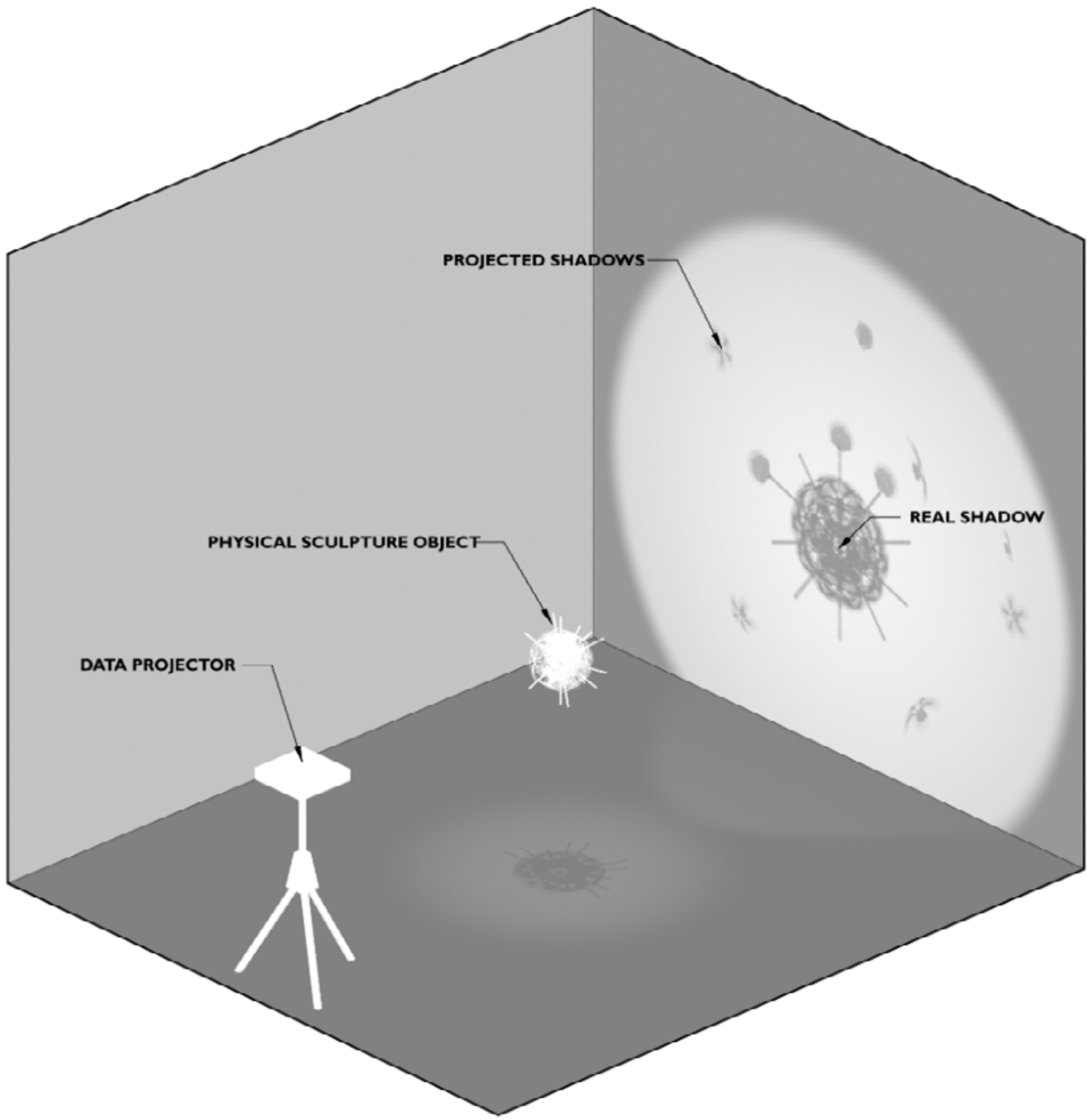
View a video of the Living Shadows smart projection by visiting http://media.lasg.ca/livingshadows/video

The Living Shadows demonstration features first implementations of the systems required to augment a work of Living Architecture through projection. The demonstration illustrated here features a single sphere and single data projector. The projection used for this demonstration employs a real-time simulated virtual environment created in the Godot Game Engine. Godot is a free open-source engine for creating 2D and 3D games.

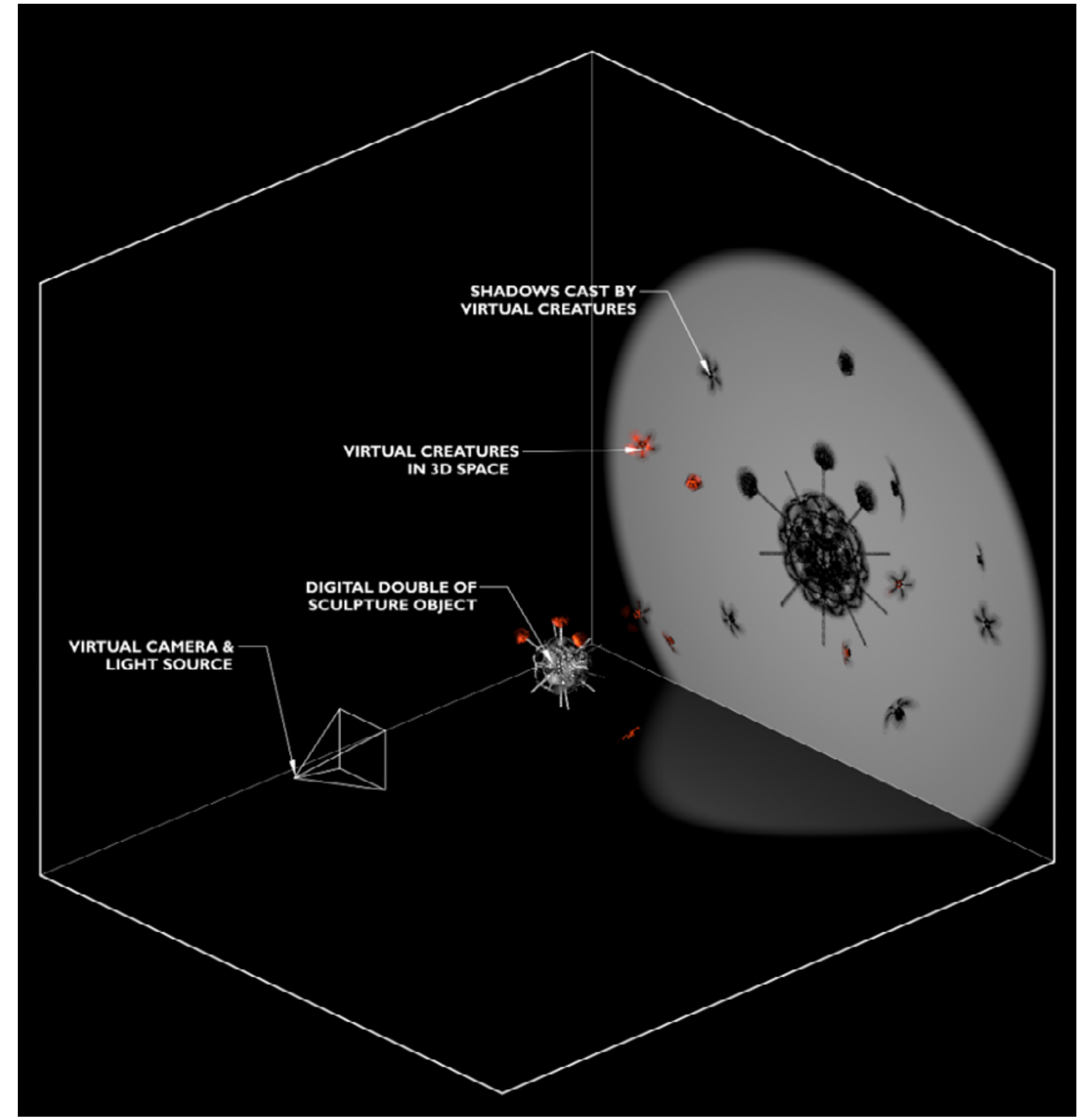
The Living Shadows Demonstration is composed of the following systems:

Physical Sculpture

The physical sculpture in the demonstration consists of a single, static sphere composed of expanded metal and thermally formed laser-cut acrylic skeleton components. Miniature glass vessels are integrated within these forms, filled with aqueous solutions of copper sulphate and potassium ferricyanide. These chemical solutions give distinctive teal and orange transparent colourings. Delicate mylar fronds dress the outer ends of the expanded skeleton forms.



The Physical World of the Living Shadows Demo



The Virtual World of the Living Shadows Demo

Virtual Model

A digital double of the physical sculpture is imported into the Godot Game Engine. This digital twin is based on physical assemblies that were created by the LASG studio. These schematic design models are transferred into the game engine using the Living Architecture Systems Description (LASD) file format and a custom import script written for the Godot engine.[2] This importer automatically configures game-engine suitable materials and attaches behaviour scripts to sculpture elements based on the metadata defined in the LASD file.

2 The use and development of the LASD file format is described in the folio *Living Architecture Systems Description: Extensible Spatial Data System for Responsive Architectural Environments* by the LASG. It is available at https://livingarchitecturesystems.com/publications/

Below

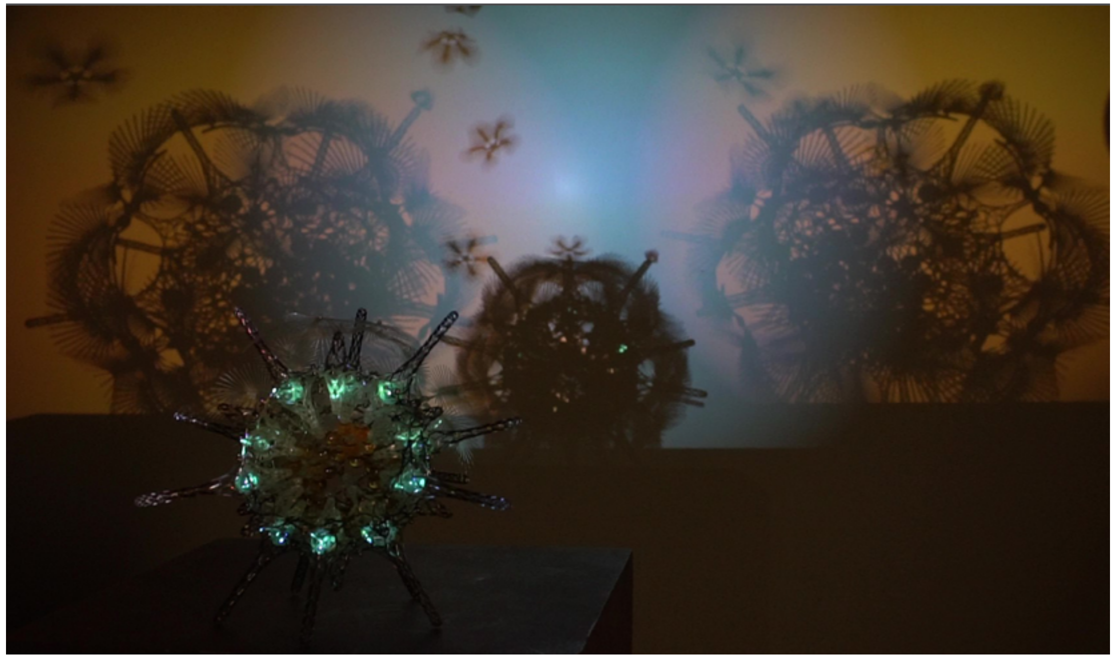
The physical sculpture and its digital twin. Presented next to eachother in an augmented reality viewport.

Link

View digital twin through mobile phone camera augmented reality interface by visiting http://media.lasg.ca/livingshadows/digitaltwin

Digital & Physical Alignment

Within the digital twin, a virtual camera captures creature and component behaviours within a set field of view. In the physical world, a projector mirrors the camera's position and viewpoint in relation to the sculpture. The focal length of the virtual camera is calibrated to match the optical characteristics of the real-world projector. Aligned across the virtual and physical realms, the physical projector and virtual camera form a coordinated pair that allows the virtual world to be projected back out into the physical world. The virtual camera is paired with a virtual light that casts shadows in the virtual world. These shadows are rendered by the virtual camera and projected into the physical world via the projector. The viewer sees a composite of physical-world shadows cast by the light coming from the projector and the projected image of virtual shadows on the wall or screen behind the sculpture.



Above

A Living Shadows setup with three virtual lights.

The center light, (Blue) aligns with the Vritual Camera and Physical Projector.

The second and third light (orange) exist to either side of the virtual camera, and appear to have no discernable source in the physical world.

The effect is most convincing when the virtual light and virtual camera are aligned, creating an illusion of one single integrated set of shadows. However,the virtual light can also move, creating illusory lights that cast shadows in the physical space but have no discernable source. Carefully balancing the intensity of physical lights (both spotlights and ambient lighting) and the virtual light sources being projected creates a compelling merging of the physical and virtual worlds. The illusion is further enhanced when viewers place body parts such as an arm or hand within the beam of the projector, creating their own shadows alongside the shadows of virtual creatures.

Virtual Creatures

Virtual creatures birthed from the digital twin model inhabit the virtual world. Spawn points for virtual creatures can be automatically created (attached to user tagged sculpture components) on import or manually placed in the 3D scene.

Currently only one species of virtual creature is active in the Living Shadows demo. The "polyp" creature is a jellyfish-like manifestation of the delicate mylar fronds that dress the ends of the metal spars in the sphere at the heart of the physical sculpture. The polyps grow curled and bulbous from the spar tips until they reach maturity and are ejected into the fluid-like field of the virtual world. Once ejected, polyps are autonomous, navigating the virtual space and interacting with others of their kind before eventually withering and dying. Upon their death, each of a polyp's fronded arms, now tattered and spindly, breaks free of its body's core, drifting off in the currents of the virtual field.

Left

Shadows of a Virtual Polyp Spawning

Right

Stages of a Polyp's life cycle.

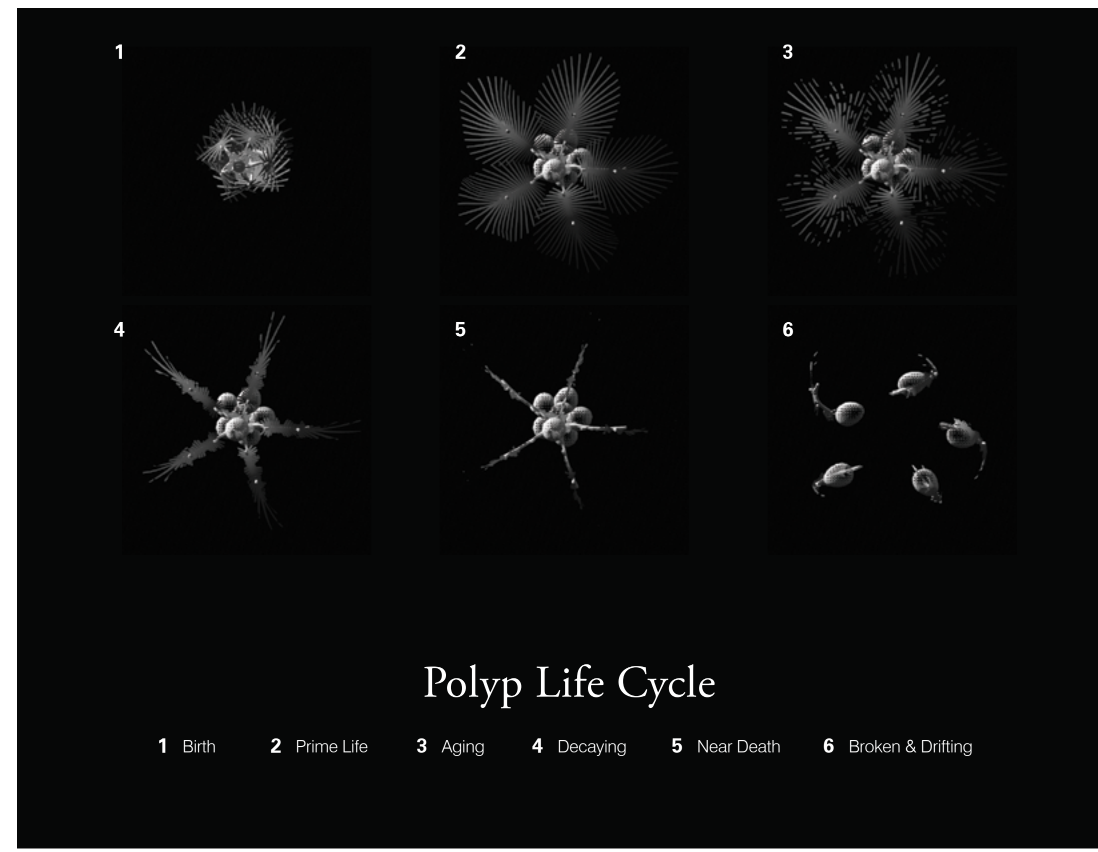
The polyps are finite state automata. Originally presented by Warren McCulloch and Walter Pitts in their 1943 paper "A Logical Calculus Immanent in Nervous Activity,"[3] popularized by the American computer scientist Edward F. Moore in 1956,[4] and refined and revised by many others in the decades since,[5] a finite state automaton is a simple model of artificial intelligence in which the automaton's behaviour corresponds to a particular state of being, with defined conditions that control the transition from one state to the next. For the polyps, each phase of their life cycle corresponds to a particular state, and a preset timer governs the transition from one state to the next.

Once a polyp has been ejected and is free to wander the virtual world, an additional behaviour model is used to guide its movement. The wandering and coordination of the polyps is driven by a "boids" model. Developed by

3 Warren McCulloch and Walter Pitts, "A Logical Calculus Immanent in Nervous Activity," *Bulletin of Mathematical Biophysics* 5 (1943): 115–133.

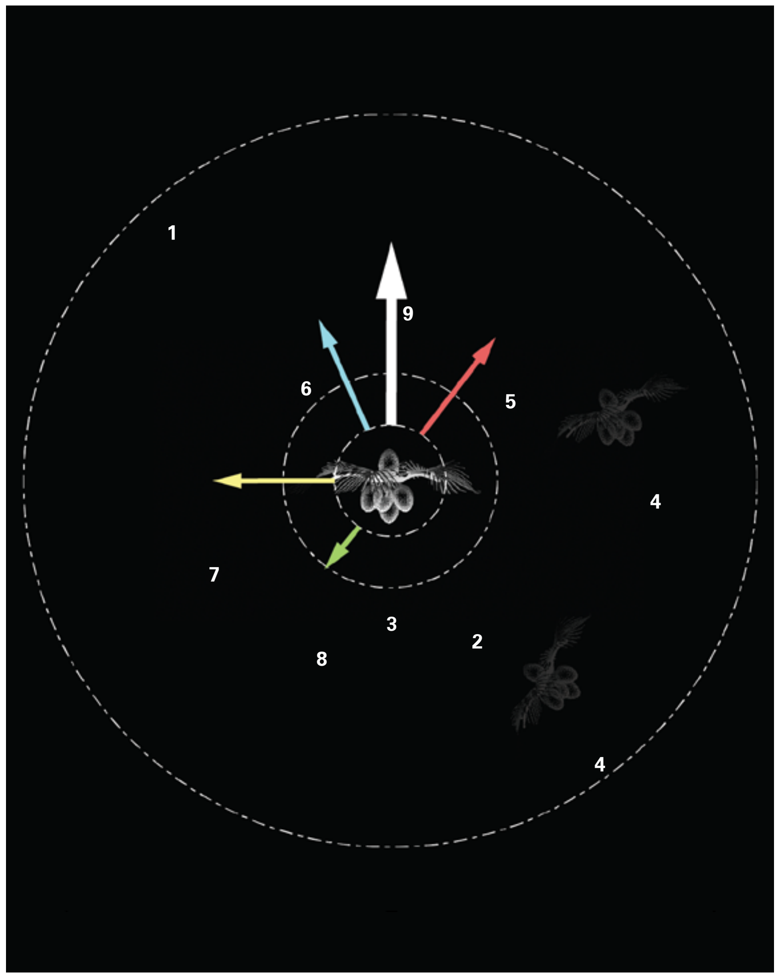
4 Edward F. Moore, "Gedanken-experiments on Sequential Machines," Automata Studies, *Annals of Mathematical Studies* 34 (1956): 129–153.

5 See, for example, John H. Conway, *Regular Algebra and Finite Machines* (London: Chapman and Hall, 1971).



Craig Reynolds in his 1986 paper "Flocks, Herds, and Schools: A Distributed Behavioral Model," the boids model results in emergent life-like flocking behaviour for groups of creatures, driven by simple rule sets.[6] Each polyp determines its travel direction based on a weighted average of its goal position and its fear of, or desire to be near, others of its species, a variable that is set when it is released by its spawn point.[7] By altering the weight of these three parameters for each polyp, individual behaviour can be created within the flock.

6 Craig W. Reynolds, "Flocks, Herds, and Schools: A Distributed Behavioral Model," *Computer Graphics* 2, no.14 (1987): 25–34. The rules in a boids model dictate steering behaviours, governing separation (how close one individual will get to another before moving away), alignment (individuals steer in the average direction of the flock), and cohesion (individuals steer towards the average position of their flockmates, bringing the flock together).



A polyp's fear level determines how close it must get to other polyps before moving away; a polyp that gets quite close to its fellows before changing direction will join the flock and appear to demonstrate less fear than a polyp that changes direction at distances that prevent them from joining flocks.

Each spar that spawns a polyp in the digital twin has a set fear range, and each polyp is assigned a specific fear level within the range of its spawning spar when it is released. A spar's fear range may be more or less wide and inclined towards lower or higher degrees of fear, allowing for a broad range of fear levels in the individual polyps.

Left

Polyp Flocking Behaviour:

1) Neighbour detection radius

2) Direct Interaction radius

3) Colision radius

4) Neihbouring Polyps

5) Target Vector

6) Conformity Vector: The average path of travel of Neighbouring Polyps.

7) Fear Vector: The path of travel that maximizes distance to neighbours

8) Field Vector: The influence of the Curl Noise vector field that permeates the virtual space. This has minimal influence on living Polyps.

9) Resulting Travel Vector: the weighted sum of the 5,6,7 with weights based on the Polyp's age and behaviour characteristics.

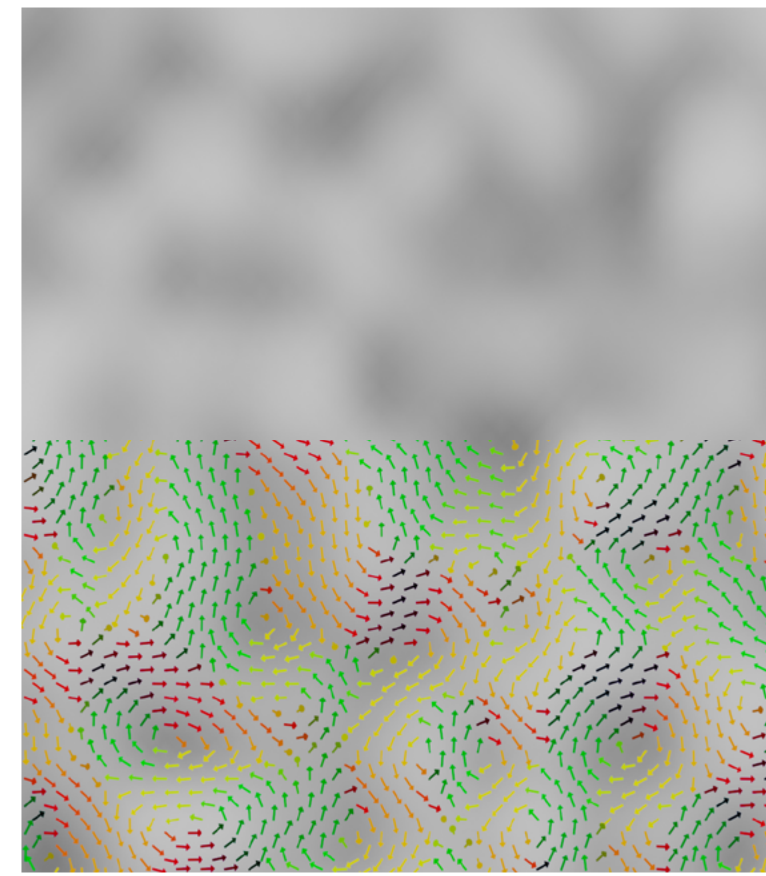
Field conditions:

In order to create the illusion of a viscous, fluid-like environment, the virtual field is configured to exert forces on the active polyps and polyp-debris that exist within it. While early Living Shadows explorations attempted to use real-time fluid simulation techniques, requirements for performance and simple art-directable control of fluid flow characteristics led us to settle on the use of curl noise to drive the fluid forces present in the virtual field.[8] Curl noise produces a motion vector that is tangent to the derivative of a 3D simplex noise field, producing motion that appears similar to the vortices and eddy currents that emerge in turbulent fluid flow.

8 Robert Bridson, Jim Hourihan, and Marcus Nordenstam, "Curl-Noise for Procedural Fluid Flow," *ACM Trans*. Graph. 26, no. 3 (July 2007): 46–es. https://doi.org/10.1145/1276377.1276435

Right

A 2D Simplex Noise Field, and its associated Curl Noise Vectors.



Virtual Actuation

In physical testbeds, devices are distributed throughout the sculpture, forming a networked topology of sensors and actuators that exchange influences and exhibit behaviour through illumination, mechanical movement, and sound. The arrangement of these sensors and actuators is documented in a three-dimensional digital model whose components are classified and organized using Living Architecture Systems Description (LASD). The LASD classification provides a systematic organization that permits efficient configuration of components, compatible with kinetic animation and behaviour scripting. The LASD framework is described within a 2023 publication within the same series as the current Living Shadows publication. In the physical testbeds, control software is configured to uses this data in order to manage and simulate communication between devices. Open Sound Control (OSC) messaging protocol is used for this communication.

By using this data organization, device data can be read and emulated by the Living Shadows system. The configuration allows objects to be tagged as virtual actuators. These actuators can be given behaviours inherent to the virtual world, or alternately may be triggered externally from outside the Godot game engine by using externally generated OSC messages. The current Living Shadows demonstration has two types of virtual actuators. These elements are titled virtual lit vessels and virtual moths. Descriptions of these elements follow here.

Virtual Lit Vessels

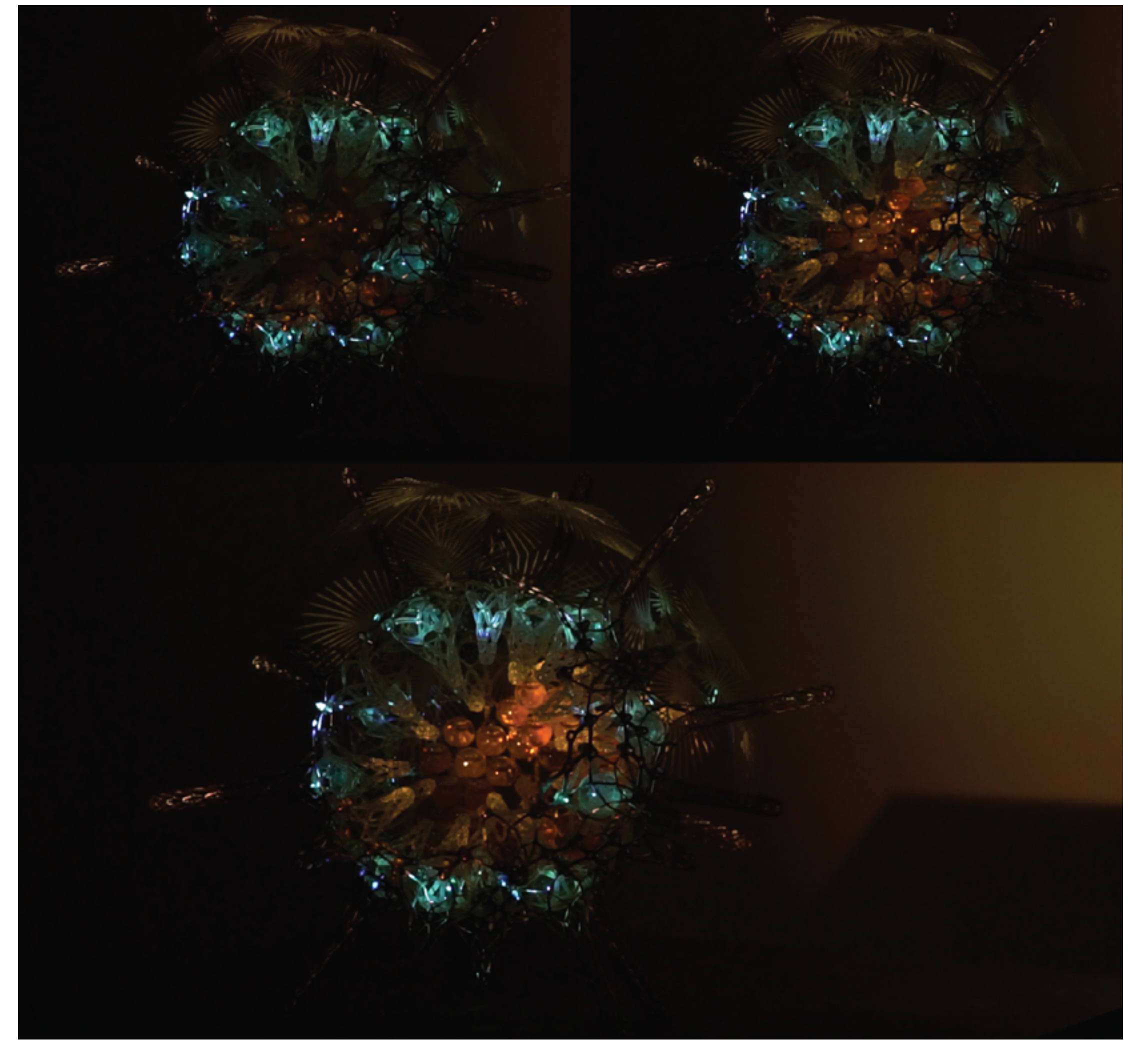
In physical testbeds LED lights illuminate glass vessels embedded within the sculpture. Virtual lit vessels allow for these embedded glass vessels to be illuminated through projection instead of embedded LEDs. Virtual lit vessels are imported into the game engine with a virtual emissive material that emits light across its surface. When activated (via OSC or through interaction with a virtual creature), virtual lit vessels create bright spots in the virtual camera's view, which are projected back out onto physical glass vessels, causing them to glow.

Virtual Moths

Virtual moths are the digital doubles of the static mylar dressing found at the ends of sphere spars. When triggered, virtual moths undulate with a shifting movement driven by a vertex displacement shader. The movement of the digital twin fronds creates a shifting shadow in the physical world that gives the illusion of subtle movement on the mylar fronds and their projected shadow.

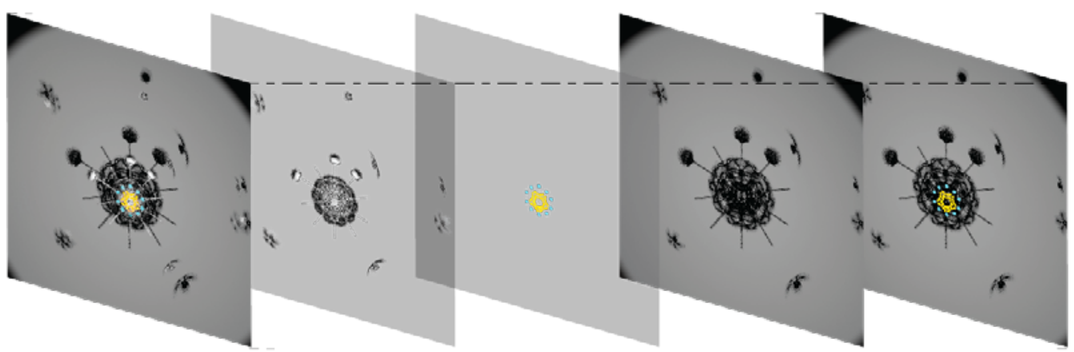
Below

A wave of virtually actuated Light passes through the core of the sphere.



Render Pipeline

Render layers are automatically configured on import to ensure that the virtual camera only renders shadows cast and light emitted by virtual objects. The virtual objects themselves are omitted from the virtual camera's rendering.



Above

Render Layers used in the Living Shadows Demo.

From Left to Right:

1) A typical render of the full 3D Scene.

2) The Virtual Objects in the 3D scene, used only by the virtual lights for shadow casting.

3) Emissive material used for Virtual Lit Vessels.

4) Shadows cast on the environment.

5) The composite render used for projection. A combination of Layers 3 & 4.

Scalability and Distribution

The Living Shadows demonstration is currently composed of a single projector and sculpture object.Full-scale installation will involve several distributed projectors, rendering multiple coordinated views in real time from a central simulated virtual environment.

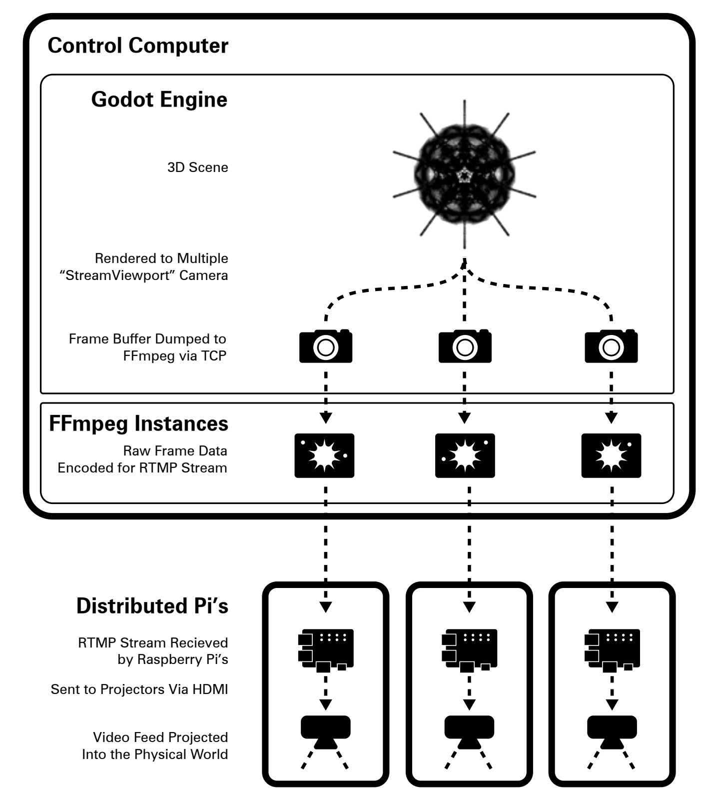
To support a distributed set of projectors, a system for real-time streaming of multiple virtual cameras was developed in Godot Engine. Godot Engine's render pipeline is designed to render from a single camera to a single root viewport for display on a single screen. However, Godot also supports the creation of sub viewports which can each render from a unique camera with unique render settings. These sub viewports are typically displayed as a user interface element on the same screen. Alternately they may be used for split-screen multiplayer games. The Living Shadows project extends Godot's native Viewport class to create a StreamViewport that can be configured with its own render settings, as well as a real time messaging protocol (' "RTMP" stream address.

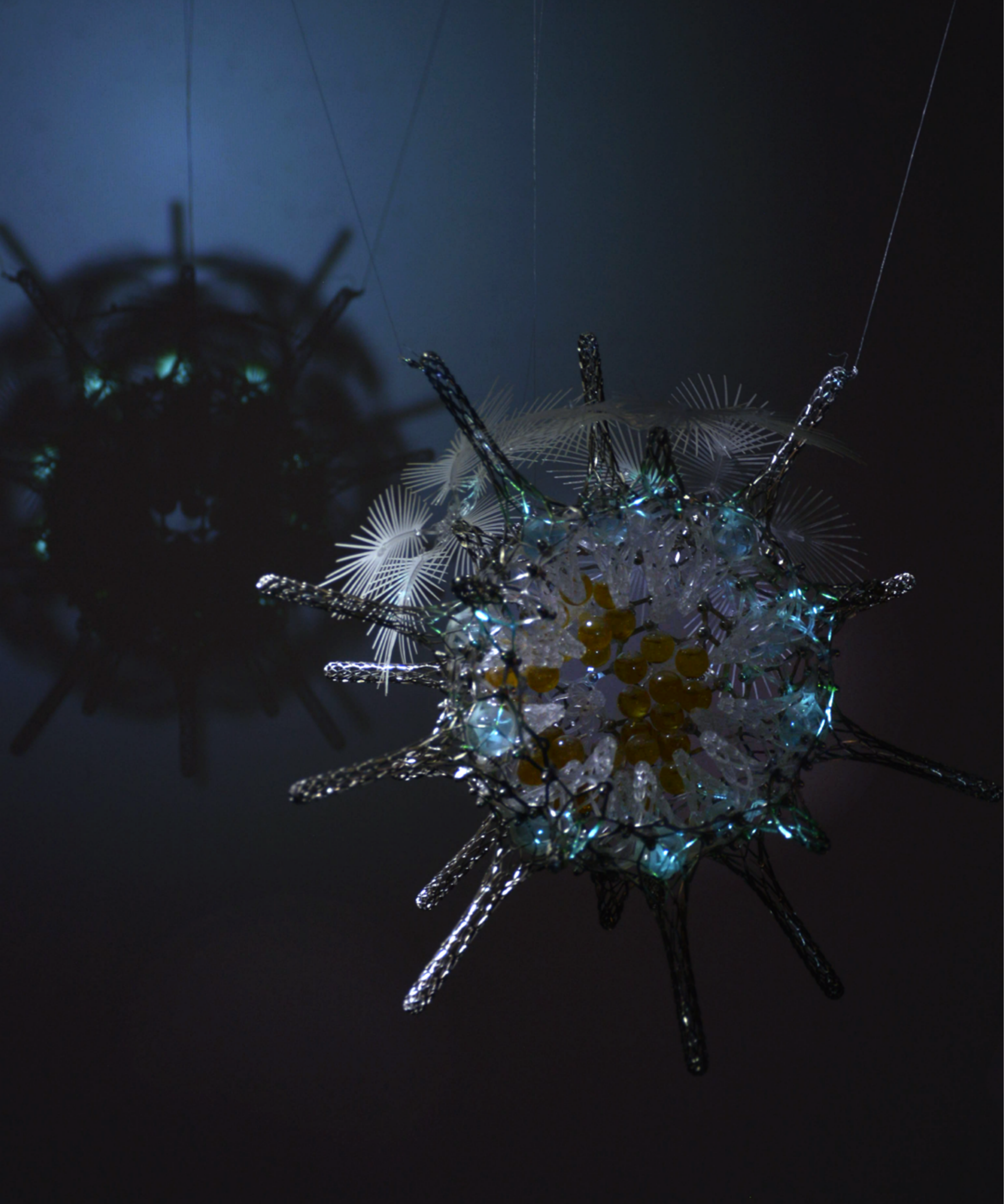
When the virtual scene is run, each stream viewport creates an instance of the open-source audio and video encoding platform FFmpeg, configured with the user-defined RTMP stream address. Rather than rendering its camera view to the screen, each StreamViewport instead renders to its frame buffer, which is dumped directly to the FFmpeg instance over Transmission Control Protocol ("TCP"). The FFmpeg instance then encodes and broadcasts the frame data as a real-time video stream to the address specified.

A Raspberry Pi single-board computer, connected to a projector and configured to receive the same stream address, can then pick up and display the rendered StreamViewport over the local WiFi network. This allows for multiple distributed projectors to receive rendered video feeds from a central simulated virtual environment.

Right

Stream Configuration Diagram





Next Steps for the Living Shadows Project

The Living Shadows project provides a new path for exploration within the realm of living architecture. The lights and shadows of its virtual world create a new realm where the lives of virtual beings and their influence on physical space can be investigated. The example of polyps described within this publication provide an example of dynamic cycles and life-like emergent behaviours that can arise from simple systems of artificial intelligence. The identity-instance model described here provides a framework to guide the creation of new creatures and new behaviours, drawn from a wide library of components used in testbeds created by the Living Architecture Systems Group. This demonstration of the concept of Living Shadows briefly describes the creation of tools and workflows that can support the creation of large, complex distributed Living Shadows installations.

Future versions of the Living Shadows project can increase the integration of virtual and physical worlds. By incorporating real-world sensor data as a driver for virtual actuation and creature behaviour, this project series can create cycles of interaction across the virtual and physical realms, allowing each to influence the other.

As the Living Shadows project continues to develop in tandem with the development of the LASG's physical testbeds it will grow into a diverse virtual world. An ecosystem of virtual creatures interacting with their physical counterparts can emerge. The digital realm of this project evokes vibrant emergent behaviour that enlivens the physical world with light, shadow, and sound, dissolving boundaries between natural and artificial life.

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