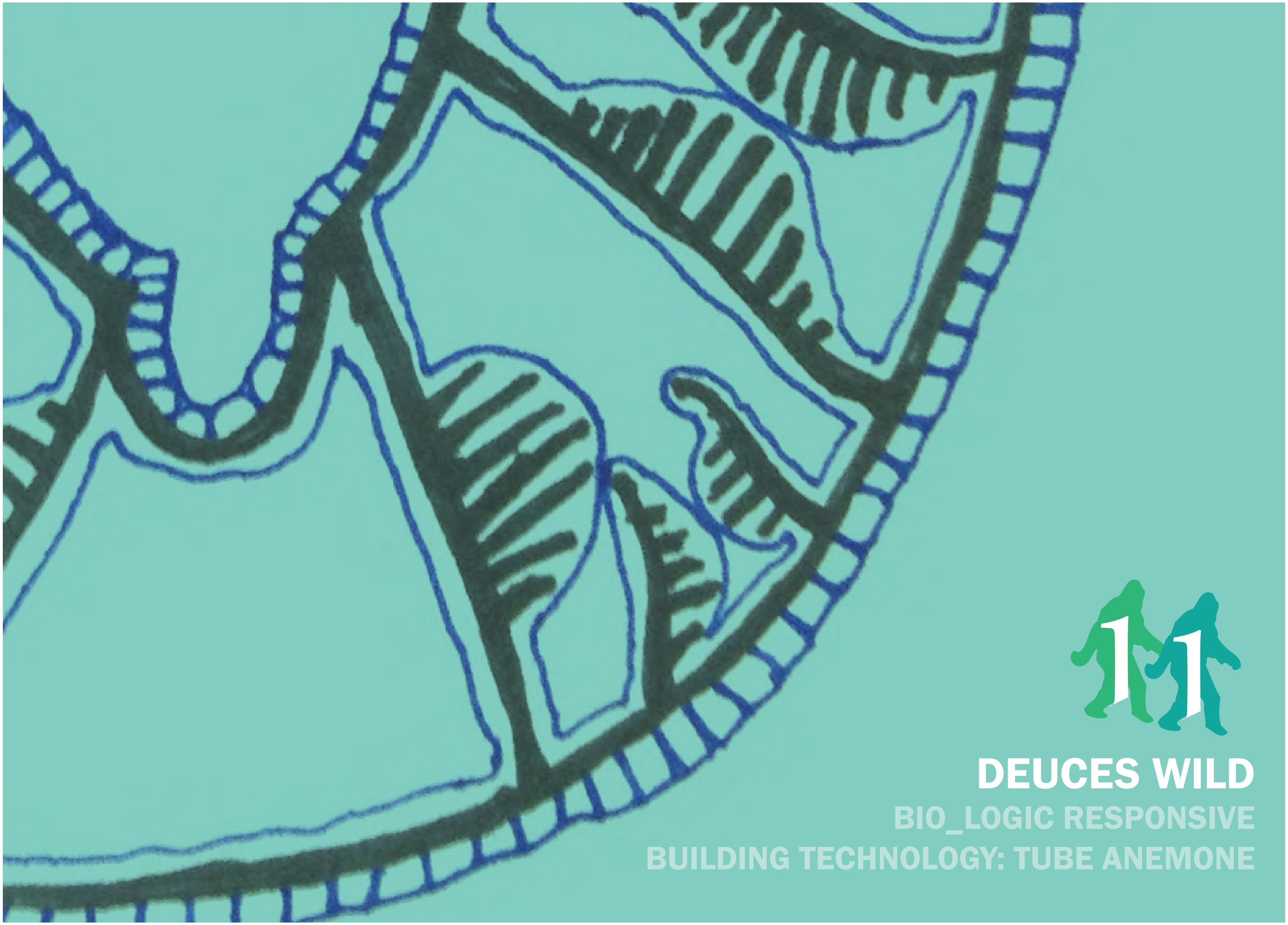

DEUCES WILD

BIO_LOGIC RESPONSIVE
BUILDING TECHNOLOGY: TUBE ANEMONE

Deuces Wild: Team 11

Working Hypothesis

The tube anemone's longitudinal retractor muscles exert a linear force which controls the expansion and contraction of its amorphous membrane through tension and compression. A similar linear force can be applied to a nonlinear flexible membrane, causing it to expand and contract within the framework of a self-regulating system that responds to external stimuli. This system can be activated by passive and active forces in order to create a dynamic massing, ever-changing in response to the surrounding environment.

When integrated with a building's façade this system forms an interstitial space that reduces solar heat gain and light glare into the building's interior, creating a more productive and soothing environment for the building's inhabitants. The temperature differentiation also creates air currents along the façade that provide opportunities for natural ventilation, reducing loads on the building's mechanical systems and removing some of the dividing lines between the climate-controlled interior and the ambient conditions of the exterior.

This system is not limited to the confines of the building's immediate vicinity. It can be extended into the surrounding context in order to create exterior zones for social interaction by diffusing light and providing protection from elements such as rain and snow. The system can also be used for visual communication through the integration of luminescent materials and/or LED lighting.

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DEUCES WILD

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Organism: Tube Anemone

Research Findings

Tube anemones (often referred to by their Order designation, Ceriantharia) are solitary invertebrate water-dwelling predatory animals that create tube-like structures in which they live. They maintain the circular form of their soft, sack-like bodies by regulating internal water pressure. Tube anemones are ammonotelic (excrete nitrogenous waste in the form of amonia). Diffusion across the body and tentacle surface eliminates the ammonia from the body.

Generally tube anemones are nocturnal animals, remaining in their tubes in order to avoid light. They also withdraw into their tubes to seek protection, since they lack the sphincter muscles needed to retract their oral disk or withdraw their tentacles. Their primary predators are organisms that exhibit a resistance to the effects of their stinging cells, such as the dendronotid nudibranchs that latch onto and ingest the tube anemone's tentacles.

The Tube

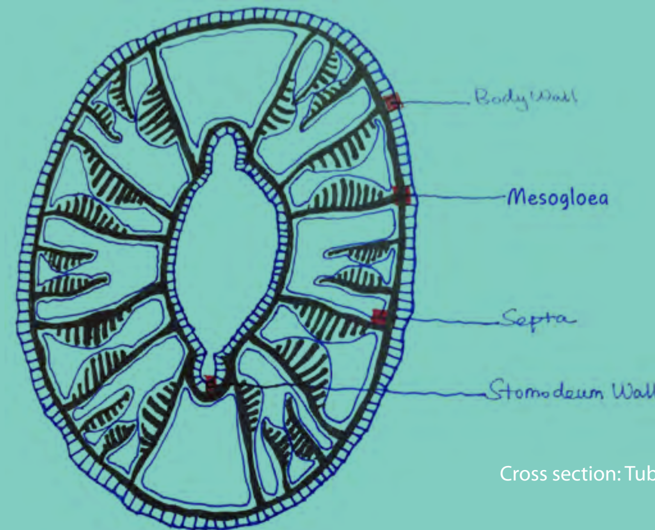
Ceriantharia tubes are composed of a fibrous material which is made from mucus (secreted from gland cells of the column ectoderm) and threads of namatocyst-like organelles known as ptychocysts (specialized cnidae – the stinging cells of all cnidarians). The tube is reinforced by foreign objects (such as grains of sediment). The tube may be as long as 1 meter (3.3 feet), and is longer than the anemone that resides in it.

External Anatomy

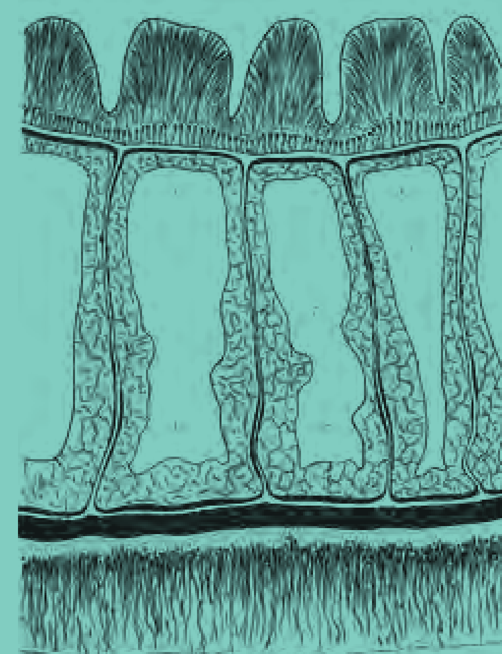
The tube anemone body is basically a tapering cylindrical column (maximum 3 cm diameter and 40 cm length) with a crown of tentacles and oral disc at one end (the oral end) and a "foot" at the other (aboral) end. There is a marked decrease in the thickness of the body-wall and especially of the muscular layer, toward the aboral end. The oral end exhibits greater sensitiveness to tactile and other stimuli, and greater contractility of the muscles of this region when stimulated.

The oral end terminates in an oral disc, which contains a slit-shaped mouth in its center. The aboral end terminates in a blunt point (foot) in which a small hole exists. The hole is used as a means for water to escape the distended animal during retraction into the tube. The column (main body) is hollow and contains the coelenteron (gastrovascular cavity).

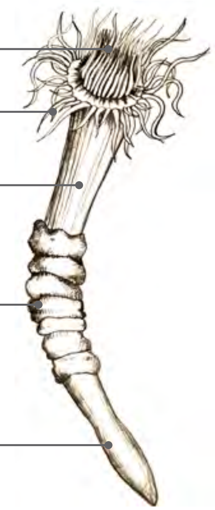
The tentacles are hollow evaginations (out-foldings) of the body wall and contain extensions of the coelenteron. Their epidermis contains cnidocytes used for stinging either prey or predators. Tube anemones have two distinct whorls of tentacles on the oral disc. The outer whorl consists of large tentacles that extend



Cross section: Tube anemone



Detail: Muscle wall structure



outwards. These outer tentacles are used primarily in prey capture and defense. An inner ring or shorter "labial" tentacles surround the mouth and are used primarily for prey manipulation and ingestion. In many species the tentacles can be bioluminescent, which could be a visual "startle" defense against predators that may attack. The outer tentacles can grow up to 20 cm in length and can reach up to one foot in diameter when fully extended.

Internal Anatomy

Tube anemones are diploblastic, having two cellular layers separated by a jelly-like mesogloea in which skeletal elements can occur. The column wall (body wall) of the tube anemone is comprised of three layers of tissue: the ectoderm, the endoderm and the mesogloea.

The ectoderm or epidermis (outer layer) is composed of cells and muscular and nervous elements. The majority of the ectoderm's cells are elongated columnar cells (epithelio-muscular cells), which contain a nucleus and have cilia at their ends. Other types of cells found in the ectoderm include gland cells, sense cells, and cnidoblasts (which produce the "thread cells" or nematocysts).

The endoderm or gastrodermis (inner layer) is also comprised mainly of epithelio-musculer or myo-epithelial cells. It also contains gland cells and nervous elements.

The mesogloea layer (middle layer) is not a cellular layer, but a gelatinous substance secreted by the endoderm and ectoderm. Frequently cells will migrate from the ectoderm and endoderm into the mesoglea.

The mouth is an elongated slit in the center of the oral disc. The mouth is slightly expanded at each end. These expansions are the ends of vertical, ciliated grooves called siphonoglyphs. The cilia of the siphonoglyphs generate a constant flow of water into the coelenteron even when the mouth is closed. This maintains a positive hydrostatic pressure in the cavity and helps keep the column distended. The mouth opens into a short, flattened tube – the pharynx (throat). The pharynx leads into the coelenteron.

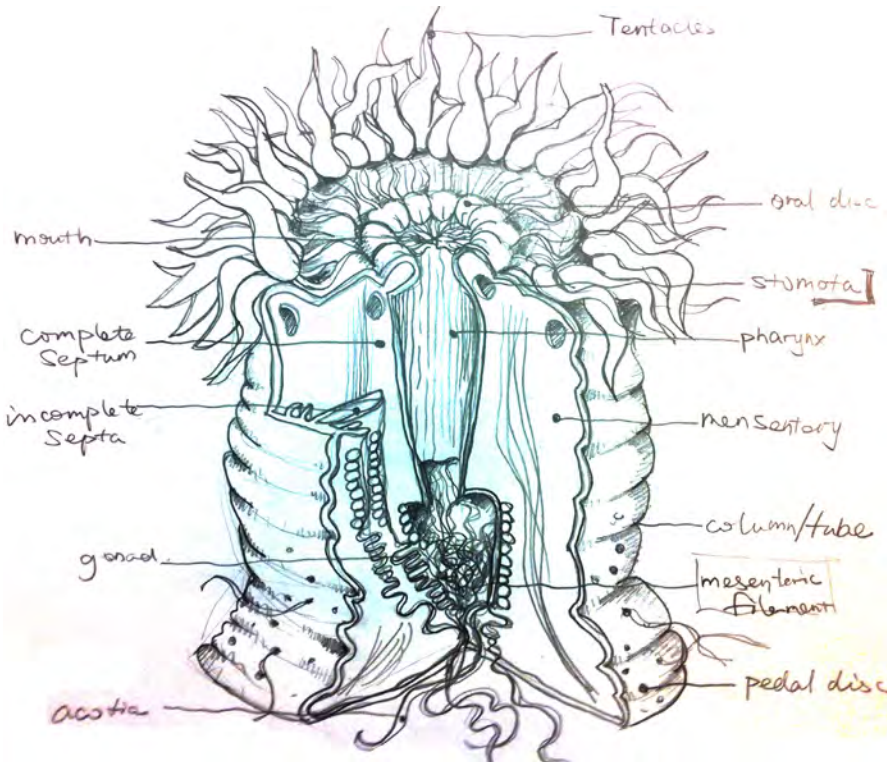
The coelenteron is partitioned by mesenteries that expand the inner absorptive surface. Mesenteries are longitudinal sheets of tissue that extend radially from the column wall to the actinopharynx. These "infoldings" of the endoderm and mesoglea extend from the body-wall into the gastrovascular cavity. The number of mesenteries also decreases toward the aboral end, until only a single pair remains; all new mesenteries appear first at the oral end and extend gradually aborally, thus indicating that growth in circumference begins orally.

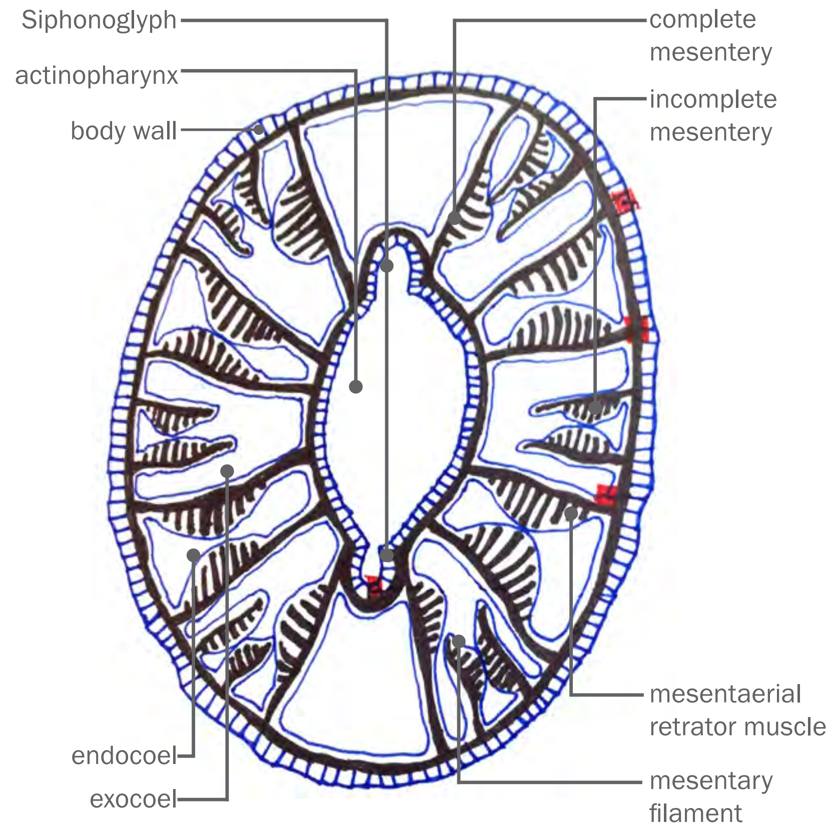
Free edges of the mesenteries bear structures that are termed acontioids (adhesive threads). Covering each surface of a mesentery is a sheet of flagellated epithelio-muscular cells. Between these two endodermal epithelio-muscular layers lies a fibrous mesogloea, similar to the mesogloea layer within the column wall. The function of mesenteries is to increase the surface area for respiration, digestion and uptake of nutrients. They also provide structural support. Attached to one face of each mesentery is a layer of longitudinal retractor muscle.

Expansion, Contraction and Fluid Dynamics

The expansion and contraction of the anemone within its tube is due to the vertical movement of these longitudinal retractor muscles. Even though these muscles react in a vertical direction, they create an inner force or tension within the body of the anemone that stretches the column wall taut and enables the tube anemone to retain its circular form when the digestive cavity is filled with water.

The expansion and contraction is integrated with the hydraulic pressures of the water that flows through the body as it distends and contracts. It uses water pressure to regulate its form in response to environmental and external stimuli. The inability of the animal to extend to its full length without the aid of water-pressure is due to the absence of circular muscles in the body-wall. Extension is passive, not active. The accumulation of water in the column appears to be the result of diffusion through the walls, and especially through the very thin membranes at the oral and aboral ends. When undisturbed, the





Tube Anemone Cross Section

body and tentacles are usually more or less distended with water and the body-wall is always tense – under high amounts of pressure. If the body of a distended anemone is opened quickly by a small cut the water issues with considerable force. When a tube anemone contracts rapidly the water squirts from the aboral foot with great force.

Below are some interesting notes about tube anemone expansion and contraction from C.M. Child's scientific investigations of tube anemones:

When the body is distended the œsophagus, with the exception of the siphonoglyphe and perhaps some grooves and crevices, must be closed.

When contraction occurs the water first issues from the aboral pore; then when the pressure is sufficiently reduced to permit it, the œsophageal walls are separated by muscular action and the remaining water issues from the mouth, often accompanied by mesenterial filaments. Thus the oesophagus is widely open only during extreme contraction.

The cilia on the endodermal surface of the body-wall produce a current flowing orally in each mesenterial chamber. The water passes from each chamber along the aboral face of the marginal tentacle, back on its oral face beneath the disc toward the stoniodaum, probably into and out of the labial tentacles and aborally along the stomodaum. In all probability cilia along the sides or margins of the mesenteries force it further aborally.

The internal water-pressure plays a large part in form-regulation in Cerianthus. The general pressure affects the rapidity of growth wherever it may be taking place and it is possible that the local pressure exerted on the body-wall by the currents passing orally in each mesenterial chamber is the formative stimulus for the marginal tentacles.

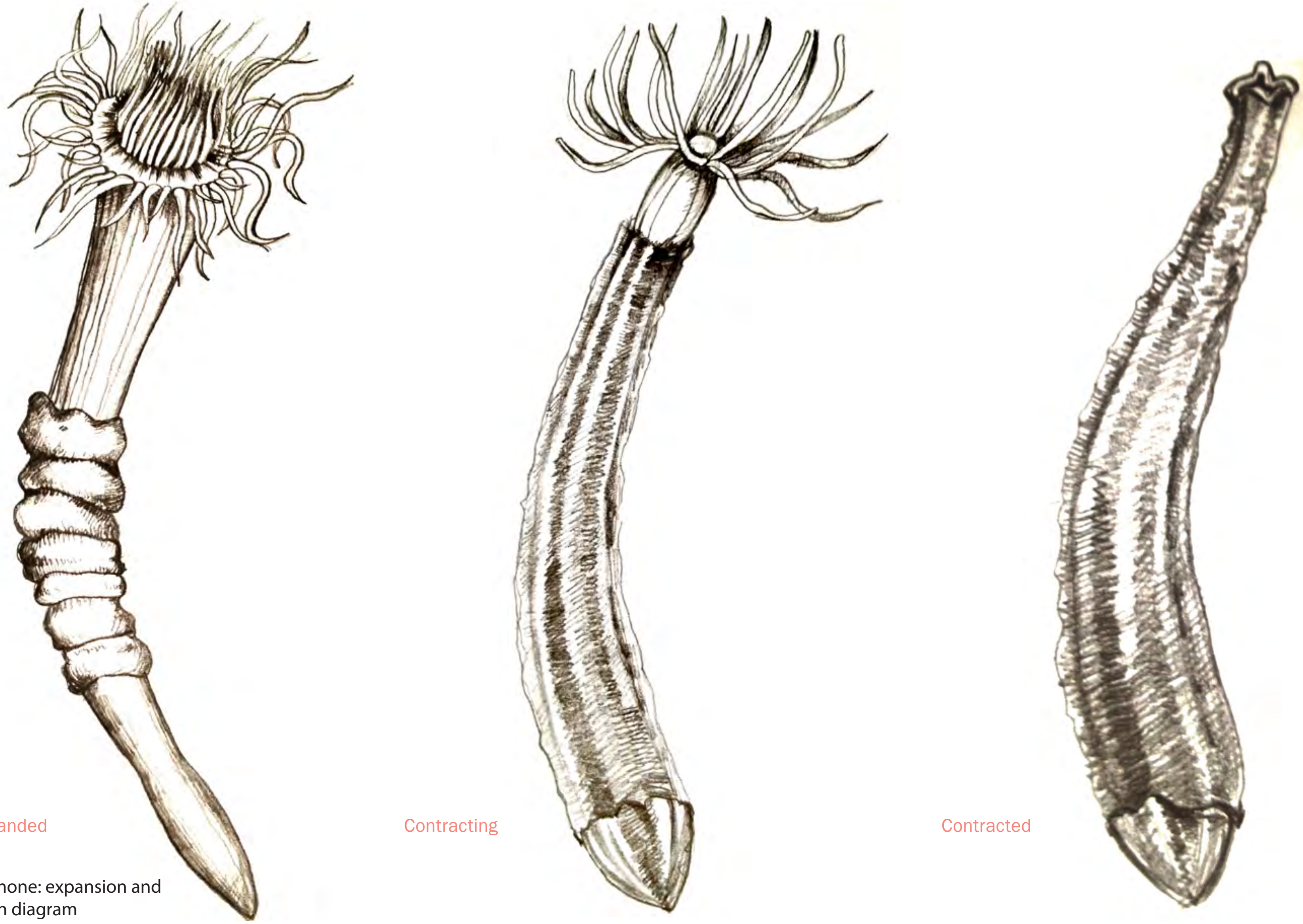
Regeneration of tentacles is impossible unless mesenteries are present. The reason suggested for this is that in the absence of mesenteries there is no localization of the currents corresponding to the intermesenterial chambers, and, moreover, the water being unconfined between mesenteries, exerts less pressure on the inrolled oral end than if mesenteries were present.

Local retardation or inhibition of tentacle-regeneration can be brought about by preventing distension of a part or parts of the oral region.

Items of Additional Interest:

Regeneration: The rapidity of regeneration is dependent on the position which the anemone section occupied in the parent body, a decrease in the rapidity of regeneration occurring with increasing distance from the oral end. The effect of position has a similar impact on rapidity. Not only is there a decrease in the rapidity of regeneration toward the aboral ends, but the total amount of oral or aboral regeneration also decreases in the same manner.

Opacity: The pigmentation of the body is closely connected with the presence and arrangement of the muscular layer. When the muscle layer is thick, or under less tension, it become more opaque. When it is under tension, either from internal water pressure, or due to the regenerative or growth processes, the column wall becomes more translucent.



Tube Anemone: expansion and contraction diagram


Model 1


Model 2


Model 3


Model 4


Model 5


Model 6


Model 7


Model 8

Modeling Process: Memo 1

1 How tentacles react, capture prey:

The tube anemone has two sets of tentacles, an inner and an outer group. The tentacles of the inner group continuously make small spontaneous bending movements which are increased following light mechanical stimulation. The outer tentacles are food grabbers and transfer food to the shorter inner tentacles. The following model attempts to create the mechanism of tentacle movement through the use of sensors and electricity. Tentacles react to stimulation such as touch. In this case electricity conducted through a wire is used as a medium for stimulation. Electrode tips receive the signal and stimulate an alternative current. The spiral starts to spin providing movement to the gears. The connecting rod turns providing a back and forth spinning motion, moving the tentacles.

2 Tentacle Regrowth:

The tube anemone's tentacles are a source of food for certain organisms such as the Nudibranch, and therefore are sometimes substantially damaged by these feeding organisms. However the tube anemone utilizes an interesting mechanism that allows the tentacles to regrow and regenerate. The tentacle is formed through a process called evagination, which is the outward folding of the tube anemone skin. The model idea is to create a double-layered skin. The inner layer extrudes outward as the tentacle grows (or regenerates). This is accomplished with a system of tension vs. compression. The model created uses metal wire and elastic string to hold the system in equilibrium. Heat is applied to release kinetic energy, allowing the tentacle to extend.

3 Form Regulation:

This model focuses on the form regulation of the tube anemone and its ability to expand and retract due to internal water pressure. The enteric cavity is distended with water which in turn expands the body of the tube anemone. When the anemone contracts the water is expelled through the aboral pore and through the stomodeum and mouth. In this model air is used as the energy source to create the inflation mechanism. Air inflates a balloon which is placed inside a flexible vinyl tube. As air inflates the balloon the tube expands to a regulated state. The energy of heat is then used to puncture the balloon causing a release of air pressure deflating the balloon and causing the tube to collapse.

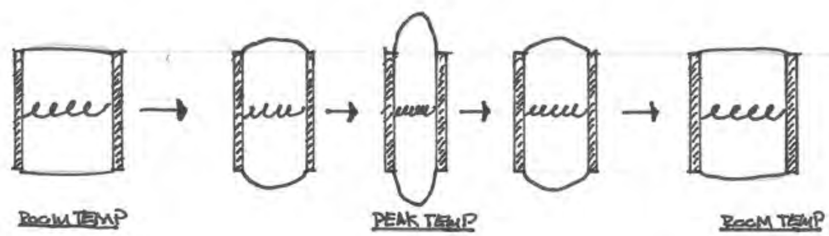
4 Tube Retraction via touch or sensory:
The model demonstrates tube retraction via touch through the concept of strings in tension and compression. When tension is increased the spring retracts and the strings compress causing the tentacles to retract within the tube.

5 Tube Retraction via touch:
The purpose of the models is to reflect the ability and process of the animal to retract into its protective tube. The spring-loaded model includes a coiled spring held by a trigger that is released by movement of the tentacles, which are represented by flexible plastic tubes. When the tentacles are disturbed, the spring snaps into standard position, thus pulling the tentacles into the protective tube – the PVC pipe.

6 Tube creation:
The tube is a product of the tube anemone. The anemone creates the tube from cells capable of discharging mucus saturated fibrous threads which forms with sand and sediment from the tube anemones natural environment. This sand and sediment behaves as an aggregate in the formation of the tube. By constructing a tube made of loosely woven fabric doused in fiber glass resin the basic idea of an anemone without a tube is created. Next the tube is pulled from a sandy bed; what can be seen is how sand adheres to the tube during the creation.

7 Bioluminescent Tentacles:
The tentacle of the tube anemones are smooth cylindrical tubes. They taper from the oral end and the proximal end is perforated by a pore. There are two sets of translucent tubes within the oral disk of the tube anemone. These translucent tubes carry strands of ptychocyst held together by mucus. These ptychocysts are stinging cells discharged from the bioluminescent tentacles that scare off prey. The tentacles also have the ability to change color with sunlight. The model shows a flexible tube with strands of fiber stringing throughout. The fiber strings puncture the tube at different stages to allow for the light to filter through. The blue LED has a light sensor attached. When no light is present the LED glows bright and the light streams through the fiber strand which is then transferred through the tube. The tentacles light source is derived from one end therefore, the intent was for the fiber strands to transfer the light to the opposite end.

8 Tube expansion:
Focusing on the Tube Anemone's ability to extend itself out of the tube led to the use of potential energy. To facilitate this action a rubber band was used as the potential energy. The theory behind this was to turn the horizontal force of the rubber band into vertical movement. This was achieved by using the outward movement of the top of the wires to climb up the cylinder. This demonstration used heat as a trigger by severing the anchoring element. Further research would be to explore a "rubber band" that had inherited expansion and contraction properties.



Modeling Process: Memo 2, Study Model 1

This model explores the activities of the organism's body wall during expansion and contraction. Three separate phenomena are investigated:

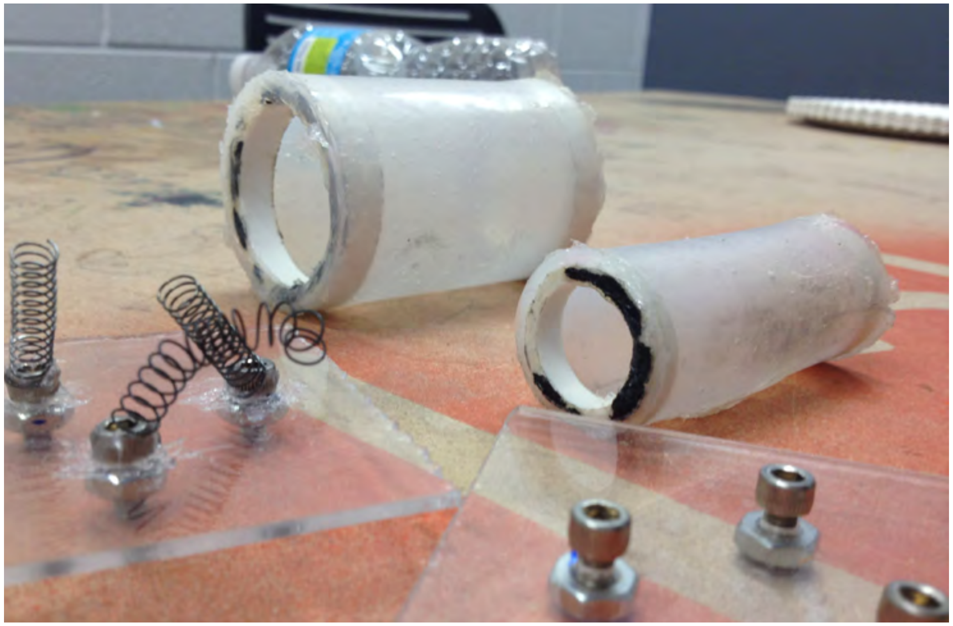
1. The movement of the longitudinal (mesenterial) retractor muscles
2. The water pressure of the body wall
3. The opacity of the body wall

When the longitudinal retractor muscles constrict a chain reaction ensues. The result is a release of the internal water pressure on the body wall. As the body wall compresses, the tension on its surface decreases and the membrane increases in opacity. As the water pressure within the body cavity builds back up during the expansion process, the tension on the surface of the body wall increases, making it more translucent.

Exploring the movement of the retractor muscles involves placing helical Nitinol wires between two acrylic planes, representing the inner and outer body wall. The acrylic planes are cut to the desired shape using a 3-axis CNC Machine. The inspiration for using the CNC Machine is derived from similar equipment used at Quality Metal Craft. As the helical wire is heated it contracts, pulling the acrylic planes closer together.

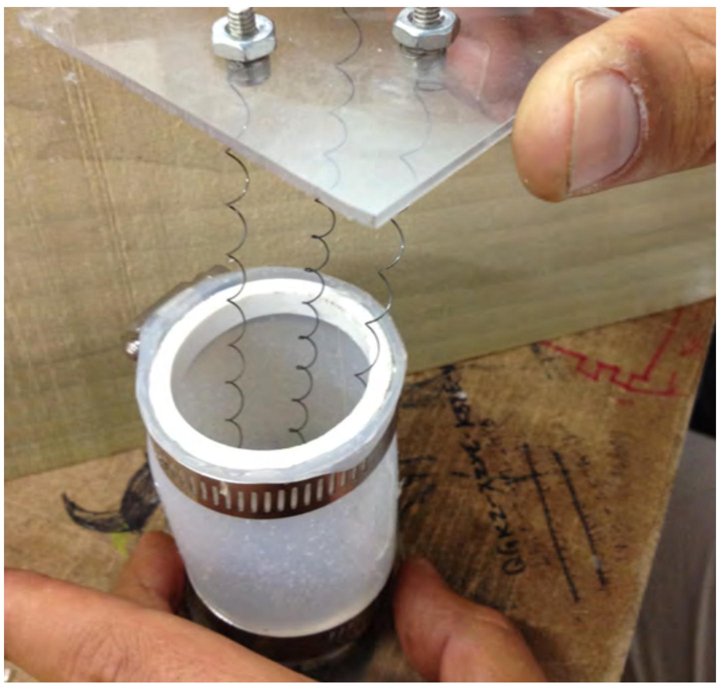
The planes and wire are surrounded by a silicone sleeve which is cast in a form, much the same way Ransom and Randolph and Quality Metal Craft use casts to form jewelry and dies respectively. The silicone is flexible to allow for the movement of the acrylic planes. The air now enclosed by the silicone sleeve and acrylic planes can be replaced by fluid. Once heated the acrylic planes move closer together, increasing the fluid pressure inside. This increased tension on the membrane surface reduces its opacity. Once the helical wire has cooled the internal pressure causes the planes to reset back to their original positions.

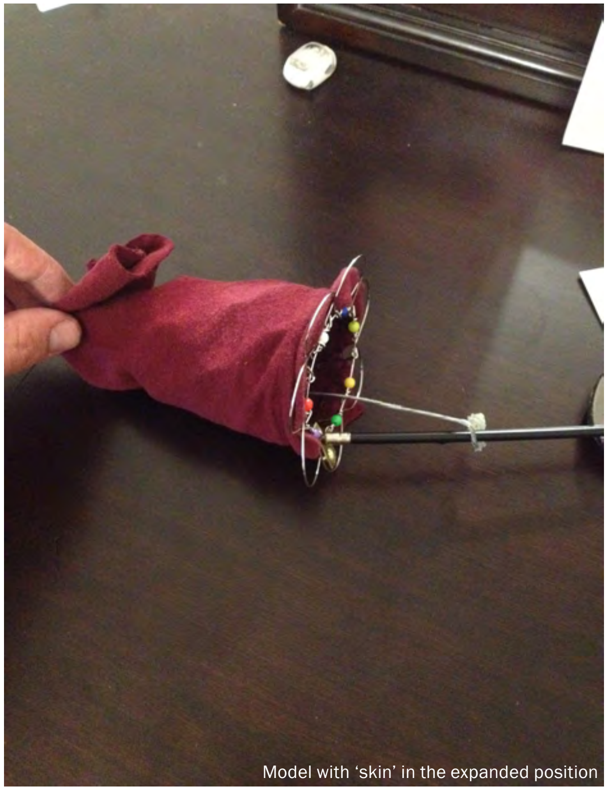
This model allows for exploration of material properties and fabrication processes, providing a better understanding of the actions of the tube anemone during the process of expansion and contraction.



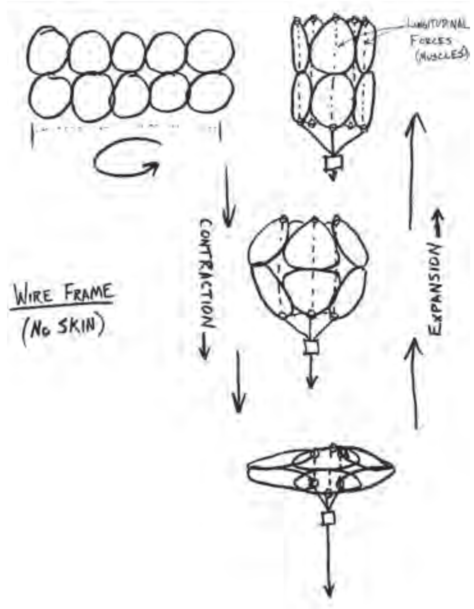
left: construction process of model

right: complete model

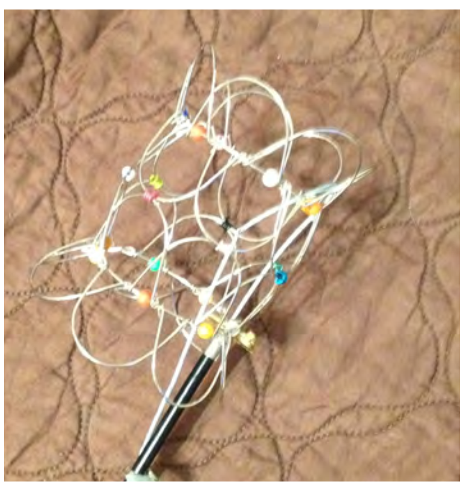




Model with ‘skin’ in the expanded position



model development sketches



Model in the expanded position

Model in the contracted position

Modeling Process: Memo 2, Study Model 2

The tube anemone contracts sharply when sensing danger by using longitudinal muscles to pull downward, releasing stored water through the aboral “foot”. This allows the body to compress. The expansion is a much longer process. The organism must replenish its membrane with water through diffusion, which usually takes days.

In this model, the break wire that is connected to the top and bottom of the frame represents the longitudinal muscles that cause the organism to contract rapidly. The body of the tube is made up of a series of connected wire rings that move in synchronization with each other. The skin is a flexible cotton/spandex material that conforms to the shape of the tube in all positions.

Direct coordination of the materials working with and against each other to create simultaneous movement is comparable to the stamp press used at Quality Metal Craft. Once metal is stamped into a mold at QMC it has a tendency to slightly return back to its original position or shape. With this model the cotton/spandex material can be held in resistance or freely allowed to return back to its original form.

As the break force is applied, the tube model contracts rapidly, flattening almost completely. The longitudinal forces contract vertically, causing horizontal expansion around the middle of the tube. Once settled, the expanded center of the tube then starts the slow process of returning back to erected form by means of soft springs and bands that pull together.

This model provides detailed exploration in the way hinge connections interact, and the transferal of lateral and longitudinal forces. The cause and reaction is more than simply a domino effect— it is instantaneous. One portion of the body cannot move without another. All parts work together as one.

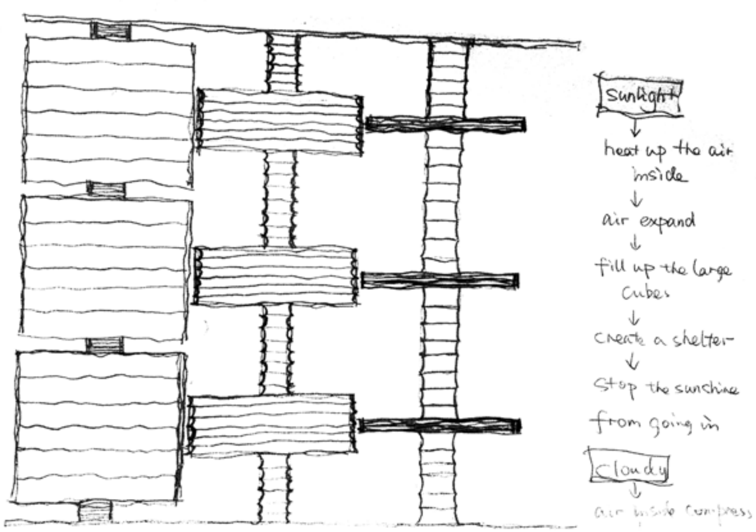
Modeling Process: Memo 2, Study Model 3

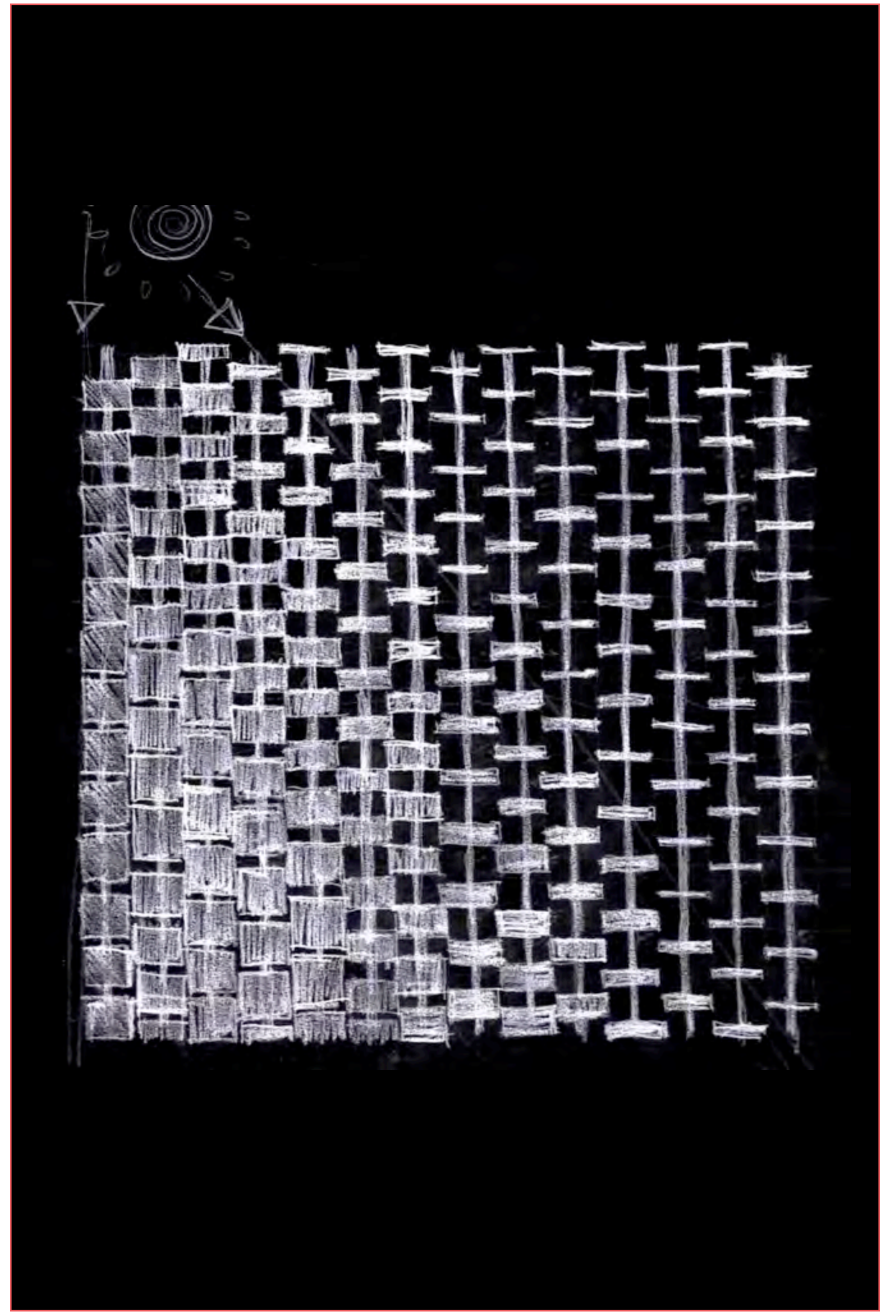
This model applies the tube anemone's expansion and contraction as a potential shading device. The main part of this model consists of two thin square boards placed parallel to each other. Their corners are connected with four springs to form the frame of a cube. This frame is sheathed with super elastic plastic. Each board has a hole in the middle which is connected to a tube made of temperature-sensitive material.

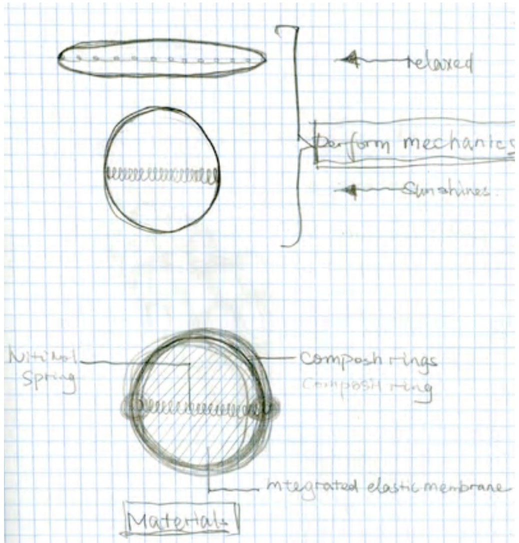
During the tour to the Glass Pavilion, two different kinds of fire were discussed: practical fire and phenomenal fire. Practical fire is used in a basic sense – to heat, provide light, etc. Phenomenal fire creates an experience with the user – it goes beyond the necessities and can also continue, start, or stop another process.

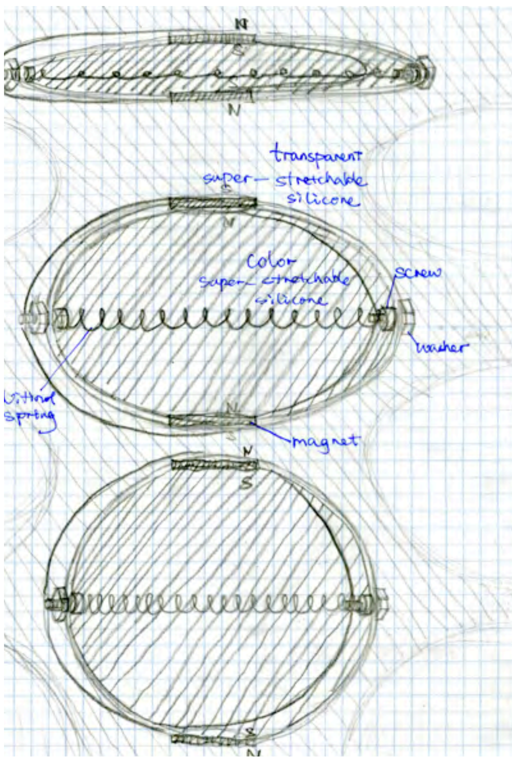
In this instance, the sun serves as both practical and phenomenal fire. It is practical fire because it offers heat and light. It is phenomenal fire because it activates the model. When the sun shines directly on the model, the tubes warm up, causing expansion of the cube. As the sunlight fades, the device cools down, contracting to its original position.

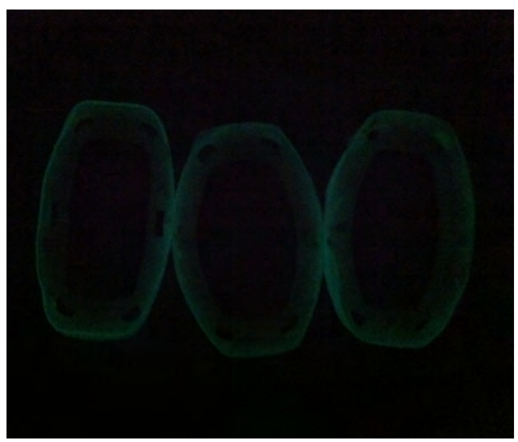
This device can provide shade when solar heat is strong and close when the temperature lowers, allowing more light and heat into the building. It is possible to carry this further to form a system. Several tubes and cubes connected to each other can create a second building skin over the glazing and act as a spontaneous organism to protect the building's interior from excessive solar heat gain.











luminescent material in 'brick' from daylight to evening

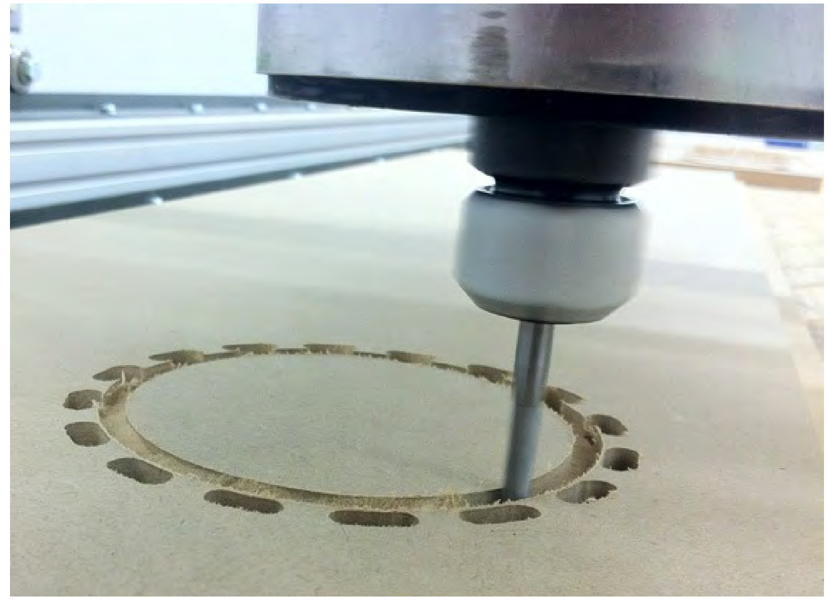
Modeling Process: Memo 3 Initial Prototype, Expansion/Contraction

The model is based on the tube anemone's self-regulating process of expansion and contraction, and is a continuation of ideas developed during the Memo 2 assignment. The tube anemone uses the contraction of its longitudinal retractor muscles to release hydrostatic pressure within its body cavity, allowing it to withdraw into its protective tube. The organism then uses diffusion through its body wall in order to distend back to its resting position, placing its body wall in a natural state of tension.

The model uses Nitinol wire in a manner comparable to the longitudinal retractor muscles. The device is self-regulating because it has the ability to be activated by an external trigger (in this case heat) and returns to its original position without mechanical assistance. In order to accomplish this, a composite membrane is developed, whose physical properties cause it to return to its natural elliptical form when not activated by the Nitinol wire.

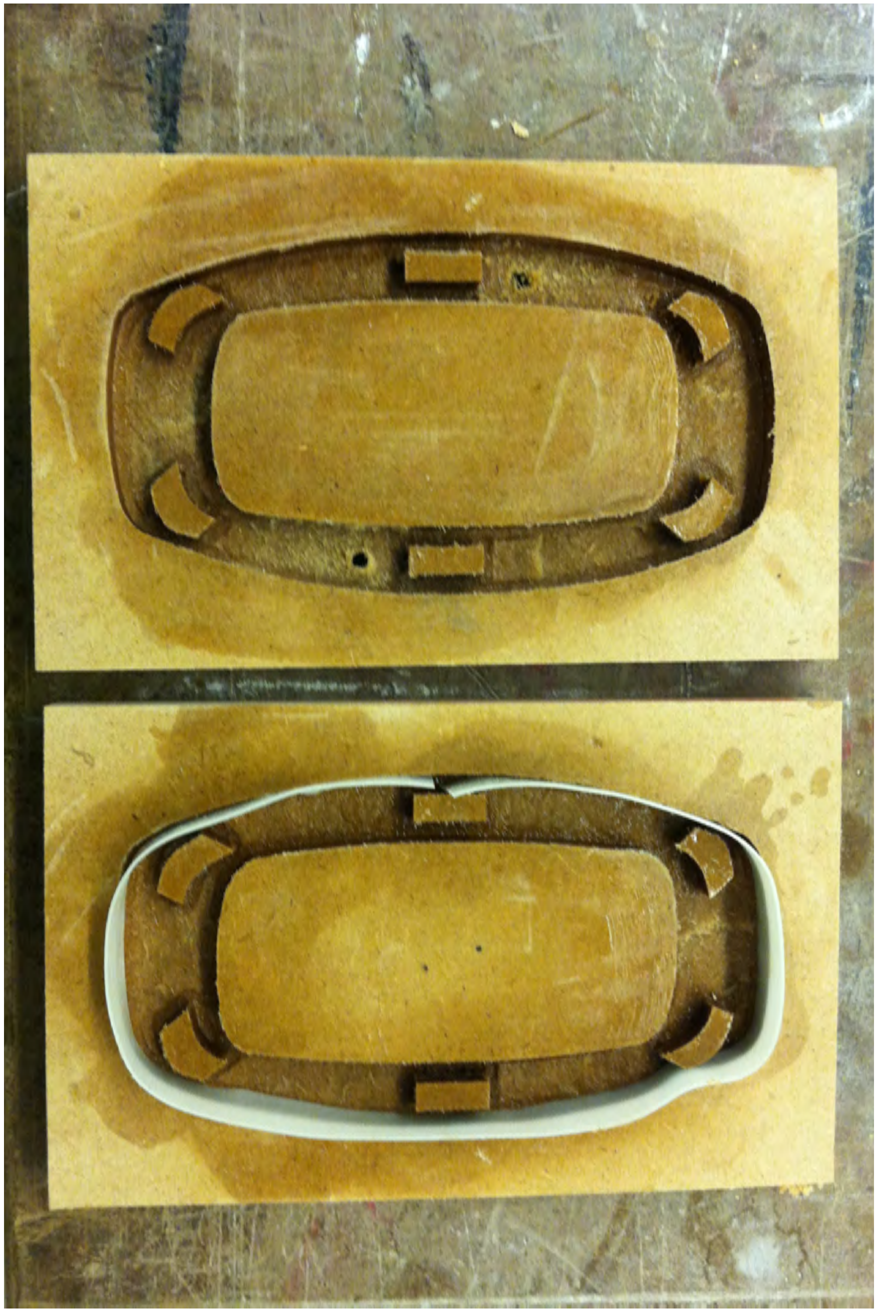
The goal is to create a device that translates horizontal force into vertical movement. The unit has an elliptical profile when in its relaxed position and transforms to a rounded, circular profile when in its activated position. Model activation is by heat gain. In order to facilitate the transferal of lateral force to longitudinal motion, the Nitinol wire is directly connected to the composite silicone membrane and held in tension until activated. The silicone membrane's thickness and openings are designed for maximum unit expansion in unison with the Nitinol contraction.

In addition to the model's expansion and contraction, consideration is given to incorporating additional materials that change in color, opacity or luminosity. These materials allow the model to provide a more interactive experience during times when the model would not otherwise be activated. Such materials include glow-in-the-dark tape and color-changing fabric.



Left Page: 'Brick' unit

Right page, Clockwise:
CNC milling of molds, silicone casting, Quality Metal Works sand casting, Ransom & Randolph pressure casting



Left: Silicone molds for prototype,
Right: pressure mold at Ransom & Randolf

Material Testing: Expansion/Contraction

The flexible silicone structural membrane is essential to the model's design and performance. Therefore much analysis was done to determine the appropriate silicone composition to use in the molds. Durometer is the measure of hardness of a material. We tested silicone with two different durometer readings in the molds, the first had a higher capacity for flexibility (lower durometer) than the other.

The Molding Process

Initially the mold was CNC milled out of MDF and coated in Polyurethane. Cutting the mold was a bit tricky – MDF has a tendency to peel apart because it is essentially compact saw dust. The initial form was a circle with evenly spaced punctures. There are holes puncturing the ribbon to help with flex and when cutting. However during the molding process the machine knocked a few of them loose so this had to be compensated for. Once the silicone frame was set and removed from the mold it had to be connected to the model actuating device – the Nitinol spring. The Nitinol spring was attached to the silicone frame from midpoint to midpoint with a nut and bolt.

Silicone Membrane Variations

After the initial model was constructed, it was ready for activation. Being 1" thick and having a 5" radius, it was a little heavy and the material tended to droop due to its own weight. There was also no real control of the bending points since the holes were evenly spaced.

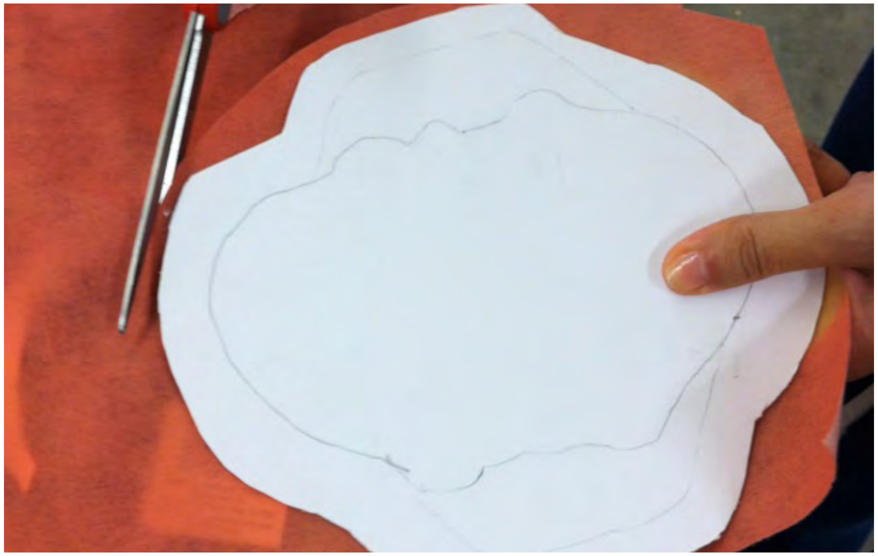
The next phase of experimentation involved casting three molds. These molds had more controlled punctures – focusing on areas that are critical in the model's expansion and contraction. The holes were placed on the four corners to control where the silicone bends and also provide for better spring back.

The first model had the corner punctures as well as on the midpoints of the top and bottom strand. This was decidedly too flexible and would not work properly. The second model had the corner punctures, but none anywhere else. The thickness was also half of the first model, .5". This model held its shape and flexed properly. The third model was similar to the second model but had an increased thickness. This model did not retract as well, and the weight of the silicone made it droop.

The shapes of each of these three models were also adjusted to be more elliptical in relaxed form, in order to provide greater differential between the relaxed and activated states. The C- shaped sides were also made wider than the rest of the model.

Each of the three new model iterations had a strip of illuminating ribbon laminated on the exterior radius. The ribbon held well in the silicone for the most

Material Testing Process



part, but in some cases the silicone was too thin to properly attach. The band that laminated the best was on the second model, which also turned out to exhibit the best expansion and contraction of all the models tested.

In the future, when laminating the ribbon to the silicone it would be better to create a channel in the center of the mold for the silicone to sit in. That way the illuminating ribbon would be set into the silicone frame rather than sitting on top of the frame, and therefore be more secure.

Working with Nitinol

The Nitinol wire was attached from center point to center point of the C-channel sides. After pulling Mold #2, holes were drilled for the nut and bolt to fit within the silicone and provide a secure connection for the Nitinol. The silicone reacted appropriately with the Nitinol attached so we proceeded with the attachment of the temperature sensitive material. After a few struggles getting the materials to appropriately attach, the model was tested again. Adding the temperature sensitive material increased the model's resistance to the Nitinol wire. The wire was still activating, but the silicone was no longer moving appropriately.

Material Exploration

The initial idea for the temperature sensitive material was to cover the silicone shape like a drum skin so that it would be stretched and pulled with the activation of the Nitinol. We initially tried to sew the material through the silicone to cover it all. However, not only did the material prove resistant to the attachment method, but it also exhibited reduced flexibility.

Since using the material as a sheet proved ineffective, it was removed and cut into a ring strip that wraps the silicone frame. The material was sewn to the circular frame at the top and bottom and left loose in the center. This reacted allowed the model to react in an appropriate way, but did not provide the desired coverage for the center of the model – the central shading mechanism.

Frame Attachment

In order for the unit to be applied as a building skin, it has to be mounted to a structural framework that can be attached to the building. The self-healing quality of the silicone allows for the insertion of plastic tubing. This tubing provides a runway for a braided cable to be pulled through. On the other end the cable is fixed to the silicone. The cable is then stretched through the top and bottom of the frame to hold tight.

Providing one fixed point and one flexible point of connection allows the model to expand and contract independently while remaining in a fixed position on the building's façade.

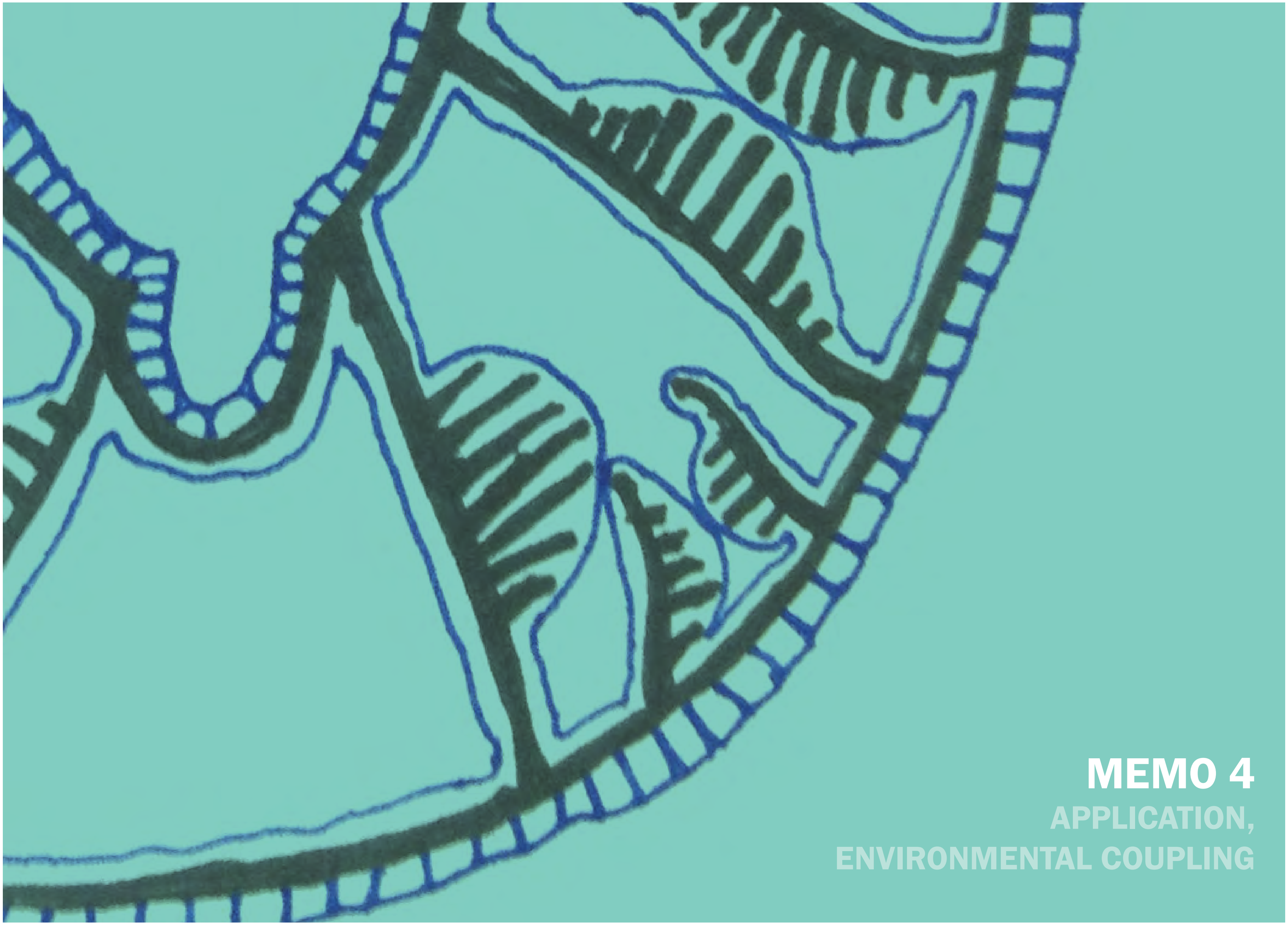
Model Progression

Once the mechanics of the model demonstrated functionality, it was a matter of refining the model's motion. Two Nitinol springs were added to give the unit more power. This was effective but the model experienced a lot of torque. A hinge system was added to help counteract this torque and help to control the temperature sensitive materials' compressed position.

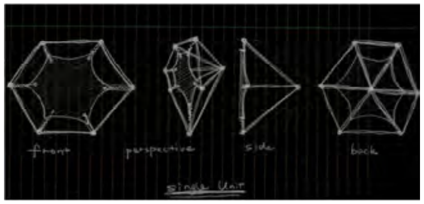
The functioning model was taken outside to see whether it would work in a "real world" application. The exterior temperature reached 100 degrees Fahrenheit with full sunshine. The model's expansion and contraction were noticeable. The fabric around the perimeter of the model also glowed when it was removed from the sunlight and put in a darker environment, which is desirable for the nighttime application of the unit.

Additional modifications and refinements are still needed. For example we are reconsidering the use of super elastic plastic material as a skin because of its ability to stretch and change opacity. However the results of recent model experimentation prove promising.

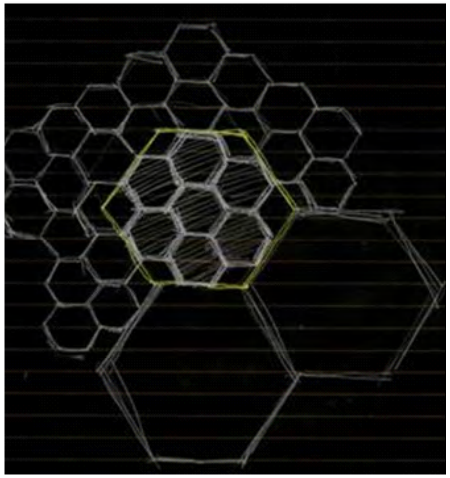
Material Testing Process

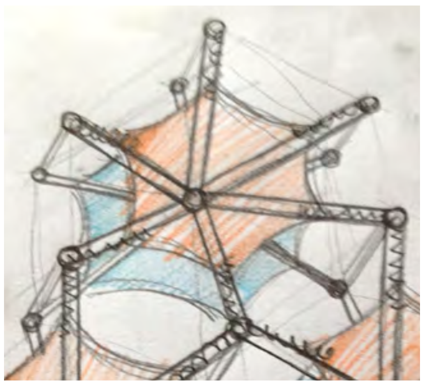


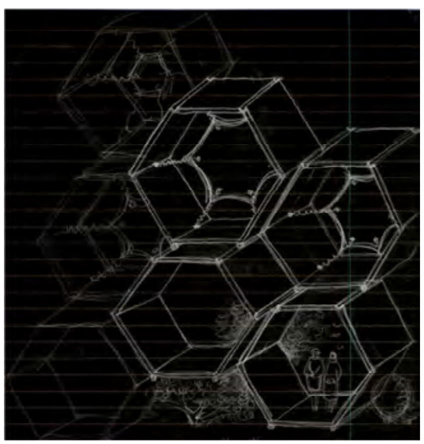
MEMO 4
APPLICATION, ENVIRONMENTAL COUPLING

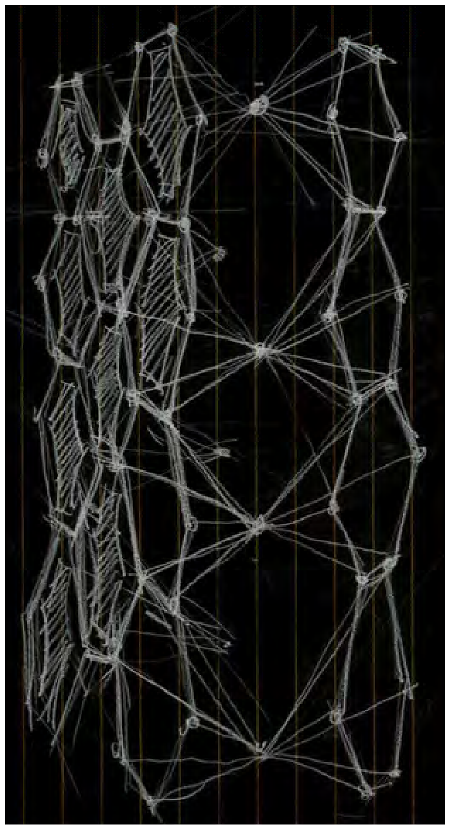


Memo 4: Concept Sketches









Final Prototype: Unit

Analysis of Memo 3 model experimentation led to the search for an adapted unit based on the original concept of expansion and contraction. The initial prototype was not providing adequate coverage for light diffusion and was too static to serve as an exterior shelter from the elements. The materials were too incongruous, discouraging the seamless integration the Team was seeking for the system design. Also, the structural frame required supporting connections to the building which inhibited expansion into the surrounding site context.

The Team returned to the original concept of the tube anemone's expansion and contraction for inspiration when exploring alternative designs for the unit. While it can be shaped and formed, the anemone's tube does not expand and contract in itself. Its purpose is to create a framework within which the flexible membrane can move. Therefore rather than creating an integral frame that expands and contracts, the Team sought to create a frame that can be shaped and formed in response to the context in which it is placed. Then the expansion and contraction can occur within the flexible membrane that is placed in that frame.

The Team experimented with various configurations for the frame and membrane in order to find the most effective combination. Preliminary polygonal shapes included squares and pentagons. The hexagon was selected for its inherent stability and symmetry.

Initially the outer frame was deep and stackable, which allowed it to be self-supporting. The thought process was that the units at the lower levels could be larger, and wrapped with permeable perforated materials that allowed them to be inhabited, perhaps marking entrances to the building and other site zones.

Simultaneously, the Team developed what they call a "spider frame" – a lightweight structure based on space frame design. The spider frame design is based on point connections rather than panel design, and is more open and flexible in nature than the hexagonal frames. The Team experimented with various configurations for the spider frame and membrane in order to find the form which would produce the most effective expansion and contraction.

Memo 3's initial prototype dealt with layering modules within the system. Through investigation it was discovered that the point connections of the spider frame system provided opportunities for endless pathways, creating the framework needed for multiple layers that could be offset. The central nodes that serve as bases for the module unit also enabled the tube extensions to be various lengths. This allowed for more dynamic surface undulation and gave the Team opportunities to shape the system in response to the building and site context.

The Team initially considered combining the two system types, putting the deep frame system on the bottom to create habitable spaces, and then using the spider frame system above. However the final consensus was to use the spider frame system throughout. The flexibility of the system allowed for the creation of modules of varying sizes and configurations. Larger modules could create habitable spaces and more structural support at the bottom while smaller more lightweight units could provide needed shading and shelter above.

The Team also looked into how the membrane would be attached to the spider frame. The constant tension at the point connects would create large forces that could tear the membrane, so it had to be strengthened. Fortifying the areas around the point connections would be vital.

The Team investigated sailcloth design as part of its research and discovered that manufacturers take fibers that are laminated with other materials to make them stronger and weave these fibers into the sailcloth at connection points to form denser reinforced areas. Another technique used is to weave ripstop into the sailcloth at load points. Ripstop fabrics are nylon fabrics that are reinforced to be more resistant to tearing and ripping. Ripstop is typically interwoven into other fabrics in a crosshatch pattern.

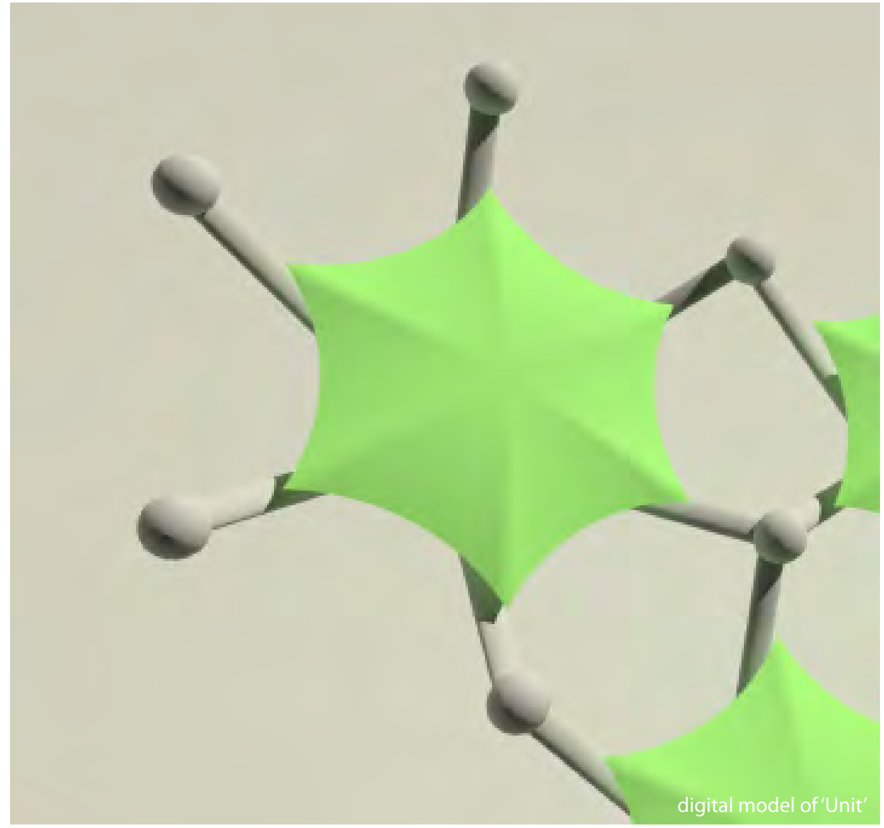
Sailcloth and other fabrics do not have the flexibility and transparency needed for the desired system so the Team decided to stick with using a silicone membrane. Silicone by nature does not allow for interwoven materials, however the team discovered that some materials can be embedded in the silicone membrane that help strengthen it at the point connections. This could also be accomplished by thickening the membrane, perhaps even extending the thickened areas to form a web-like shape.

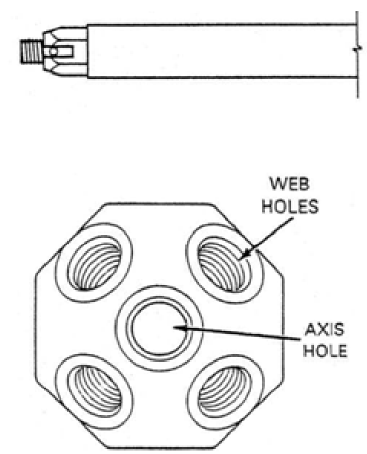
In addition to researching options for the membrane, investigations were made into space frame systems to determine how the spider frame could be supported and held together. A common thread involved using ball connections which housed tubes that extended out to form the framework.

Once the preliminary design parameters for the module frame and membrane were established the Team experimented with materials to find the most effective combination for the system.

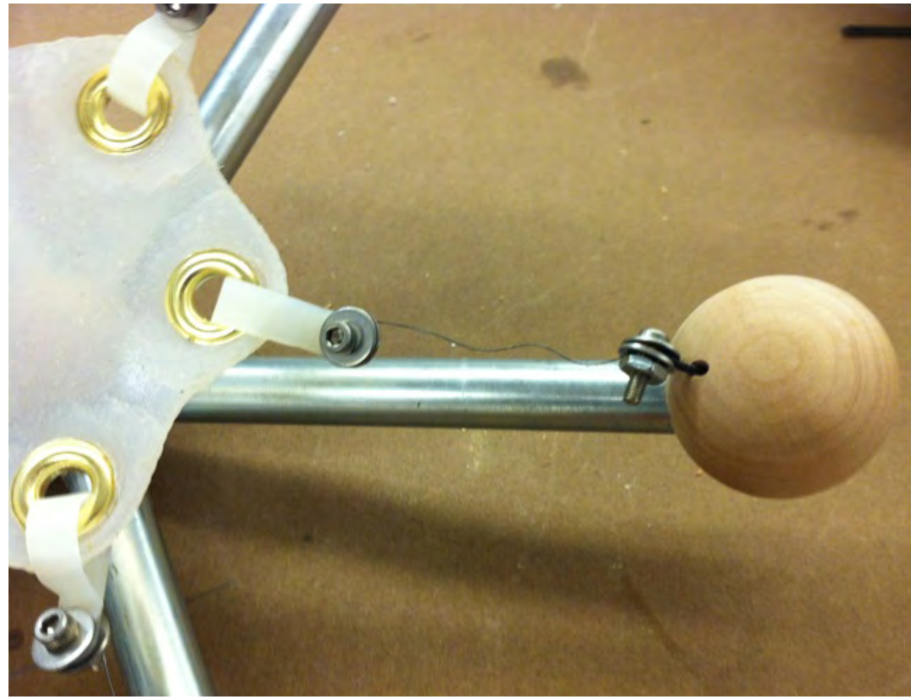
Super-elastic plastic material was available for immediate experimentation so the Team made a quick model using it as a membrane to see if the concept would work. The final model unit materials became wood, aluminum tubing, Nitinol coil wire and silicone.

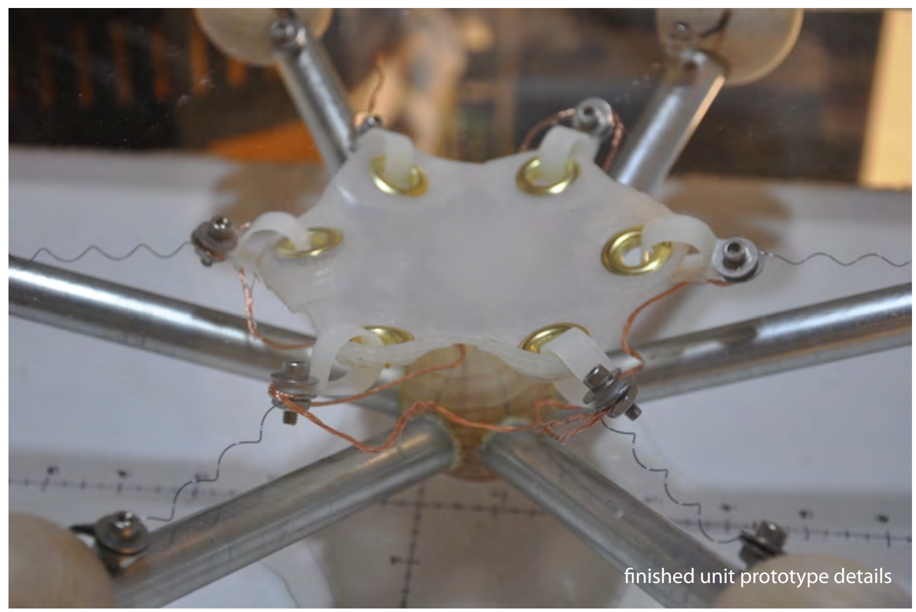
Designs were made for the areas of the membrane which would experience concentrated point loads at the Nitinol wire connections. The Team decided to thicken the silicone membrane at connections and use grommets for attachment points. Glow-in-the-dark silicone dye proved too expensive to incorporate into the model. However, it can be utilized in the final system design and is demonstrated in renderings and images. Additional materials were tested in the membrane such as fabric and elastic strips for enhanced light diffusion.


digital model of 'Unit'

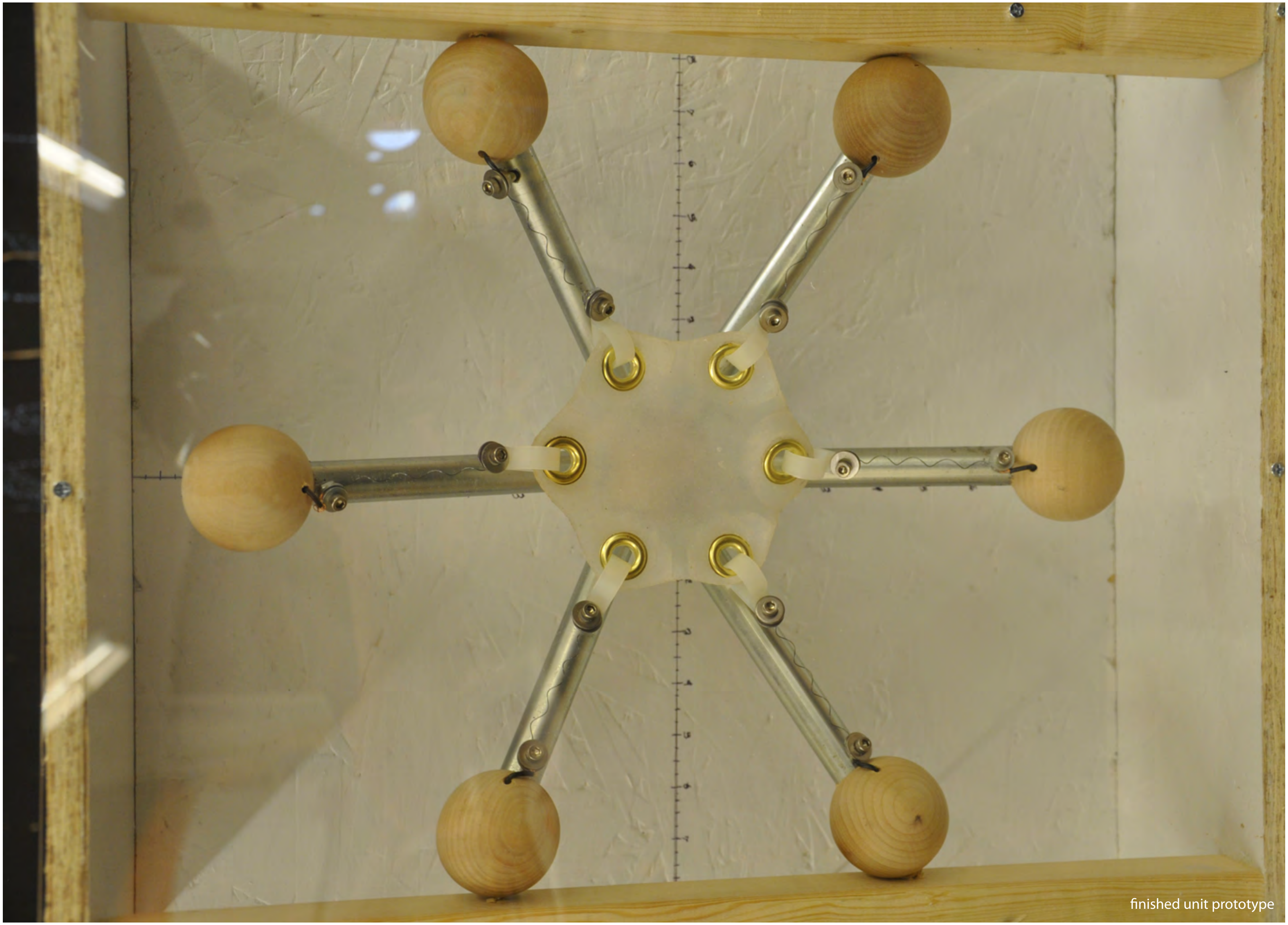


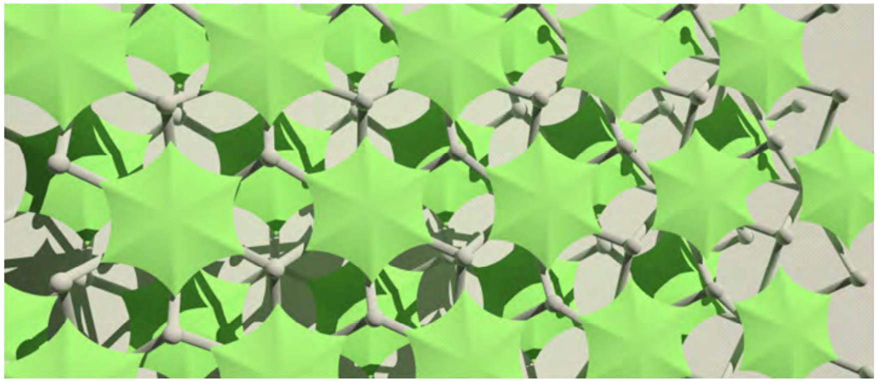
model precedent studies

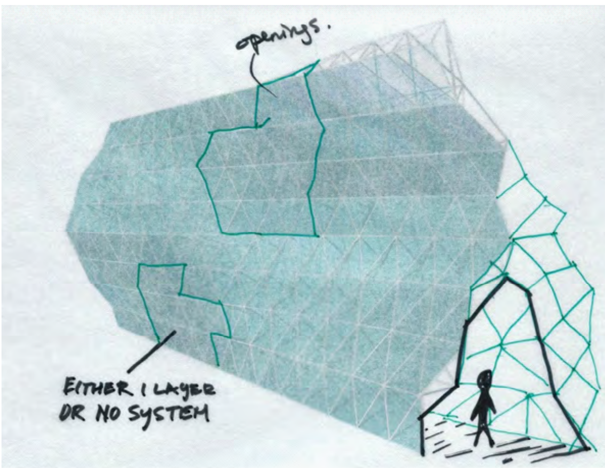




finished unit prototype details


finished unit prototype





Top to bottom:
Digital rendering of system,
Sketch of occupied system,
Sketch of system on campus

Final Prototype: System

As the form and motion of the unit are developed, they can be applied on an architectural scale and replicated as part of a system that envelops a building and extends into the surrounding context, creating interstitial spaces for habitation. The system impacts the mood and quality of interior spaces while altering and reflecting the microclimate around the building. The system has three levels: the brick, the patch, and the infill.

Brick

The "brick" refers to the self-regulating unit of the system, which is fully and independently functional. As developed in the model exploration, the brick is comprised of a central node which serves as the base for the "spider frame" tubes. The characteristics of the frame allow the tube lengths to vary, creating an undulating membrane surface.

A flexible membrane is attached to the hexagonal spider frame by Nitinol coils that are held in tension. The basic membrane is composed of silicone. Variations of the membrane include incorporating different materials and patterns in order to achieve a variety of effects on the building and its surrounding environment. The coils contract when the brick is activated, expanding the membrane. The brick can be activated by solar heat gain or by electricity via wires which are built into the tube conduits. The option for electric activation allows opportunities for manual overrides and for activation in cooler settings.

Patch

While the bricks are dynamic in form and function, in single formation they do not provide adequate coverage to effectively filter out the elements. They have to be layered in alternating courses. Each brick unit is mounted on a supporting ball base or node. By mirroring the brick about this node and shifting it, a secondary layer of bricks can be formed which provides additional filtering. This double-layered formation is referred to as the "patch". Because the spider frame is a series of point connections, the patch network can incorporate brick units of various sizes, orientations, and even shapes.

Infill

Each structure has a unique microclimate. The size, shape, and organization of the patches on and around a building are designed for that particular building's needs and location.

The “infill” is the arrangement of patches on a building’s façades, and the system’s extended application into the surrounding context. The infill is customized for each side of the building.

Analysis of O’Dowd Hall at Oakland University identified key areas for system application. Naturally, the system would have to provide adequate shading for the building’s glazed storefront. The Team also used the system to create gathering spaces at main entries into O’Dowd Hall and provide additional areas for social interactions on the rooftop.

The extension of the system into the surrounding landscape targeted areas that were conducive to gathering. For example, on the northwest side of O’Dowd Hall there is a convergence of pathways that meet at radially scored paving with a concrete pedestal. There are similar opportunities for system application at other areas throughout Oakland University.

Site considerations for system application

This system can be used throughout the campus as a configuration of canopies at various locations along pathways and adjacent to water and green spaces, creating a network. This network can provide areas of shelter for the students to mitigate cold winds and snow during the winter, provide shade during the summer, and help reduce the impact of rainfall, making walks between classes more endurable for students during inclement weather. It also creates opportunities for social interaction. Students can gather under these canopies during the summer, enjoying cooler temperatures and breezes.

Students and faculty within O’Dowd Hall will benefit from the system as they are able to escape from the confines of the climate-controlled interior and enjoy fresh air and breezes from outside. This increases productivity and stimulates creativity. Students can also feel a sense of comfort because they can have a closer connection with nature instead of being confined in a man-made environment. They may feel more “at home”, more comfortable and freer to think and explore new ideas. The psychological impact of this system can create more of a community environment and give the campus more character.

System Features

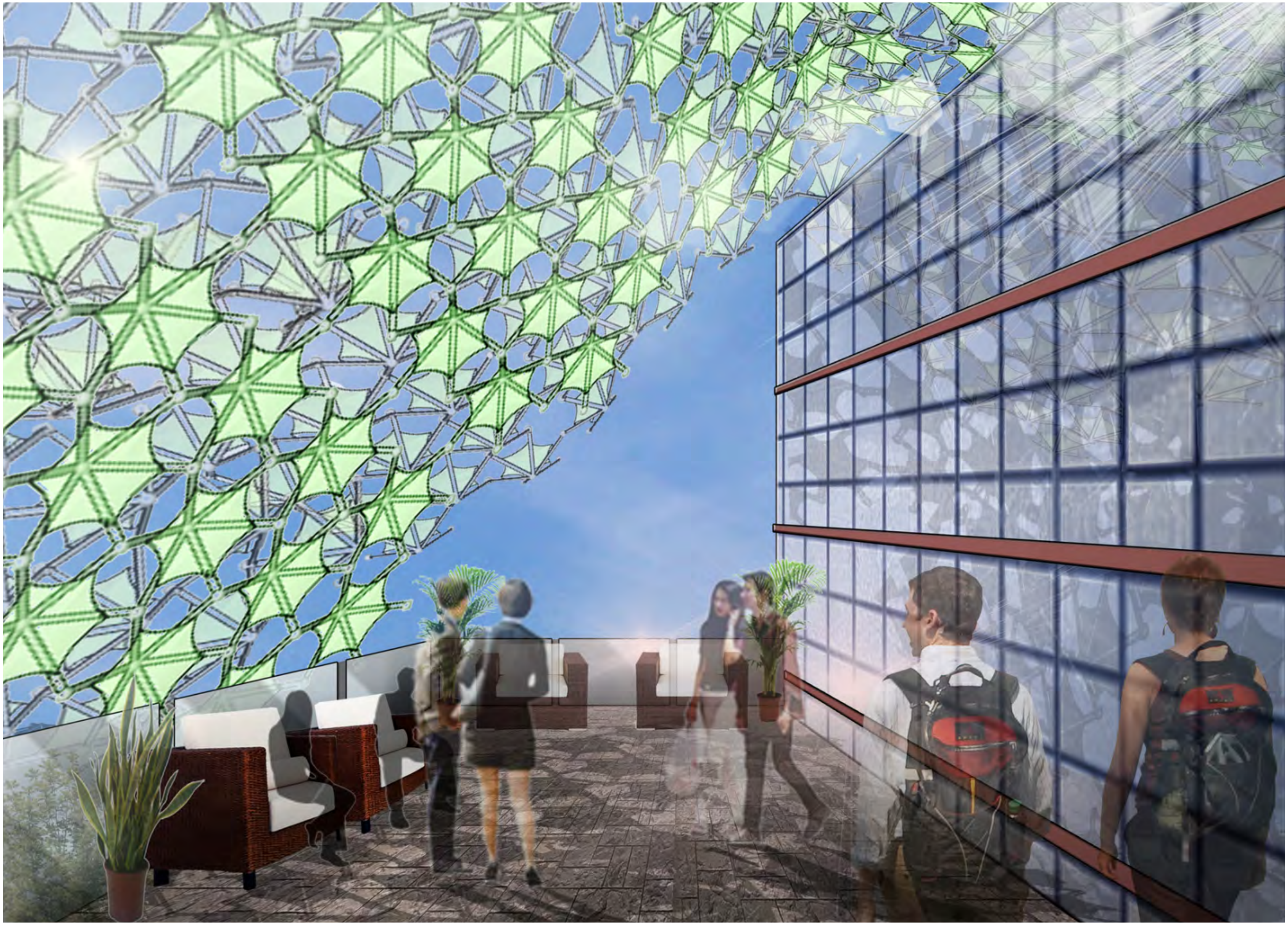
Key components of the system include the integration of features which make it more interactive. The initial intent of the system was to react to the environment in a passive manner. No additional manipulation would be involved. The system would be activated by solar heat gain, causing the unit membranes to automatically expand and contract. This type of application is desirable. However, it would only be effective during the warmest times of the year, during the peak hours of the day. The system would remain dormant at other times.

To get more use out of the system a secondary activation trigger was built in – activation by electricity. The module tubes can be insulated to serve as conduits for wires which form closed circuits when connected with the Nitinol wires. Solar collectors store energy which can be used to activate the system. Traditional backup energy sources can be used for system activation during times when there is inadequate sunlight for solar power.

This secondary electrical wiring allows the system to be activated when it is raining, snowing, or windy outside, helping to shield the building and pedestrians from the harsh elements. The system can also be activated during special events such as graduation ceremonies.

In addition to the expansion and contraction of the membranes, the module units have the capability for integrated LED lighting. This lighting can also be connected to the electrical subsystem on a separate circuit, allowing for additional overrides in the system. For example, sensors in the rooftop can detect atmospheric pollutants or be linked to a weather center. Or a manual master control could be built in that would allow customization of the lighting, perhaps tied in with a campus warning system in the event of an emergency. When a triggered, the LED lighting could be used to relay a message to the students and/or community.

Another feature of the system involves the use of natural vegetation. This feature is explored in further detail in the 10-year plan.



Testing: Prototype Performance

The design intent of the model unit was to create a silicone membrane that could stretch when the Nitinol wires were activated, creating shade. This concept was explored in various methods. Initially we molded multiple thicknesses of silicone. Some membranes were embedded with color-changing fabric, others with color pigment.

The tests results were promising, as the silicone demonstrated the ability to stretch to a larger size. One thing learned during the testing was that in order for the unit to function most efficiently, we needed to develop a solid connection for the Nitinol wires to adhere to the silicone. We also needed to create a structural system that could hold, operate and function in harmony with the design intent.

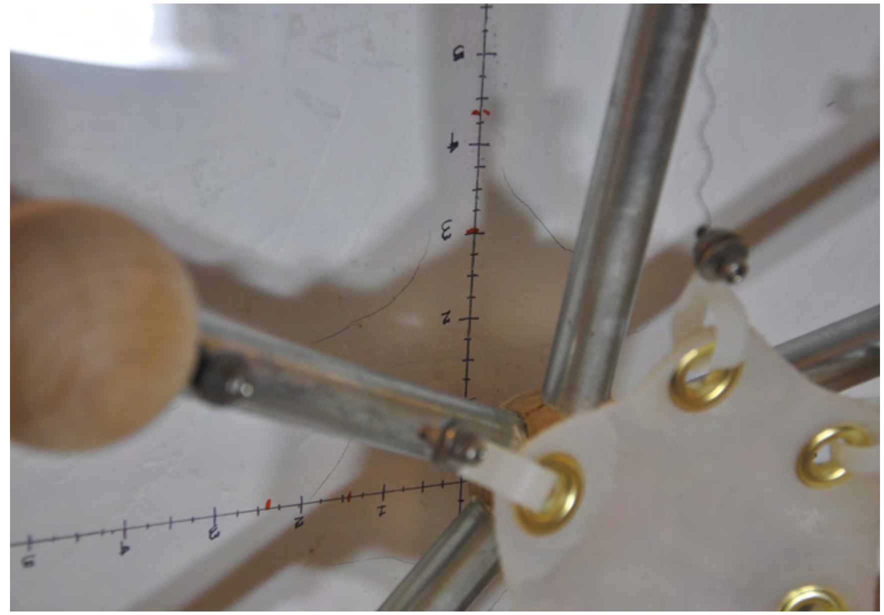
Metal conduit was used for the spider frame tubes and connected to wood spheres. A jig was created on the CNC machine to hold the sphere in place while the holes were drilled at the appropriate locations and angles. While some spheres have more points than others in the design the angles of the metal supports were all consistent.

Once the angles were in place, the center of the central sphere, or base node, was cleared out to allow for a system of wires to interconnect from the end points of where the Nitinol were attached. These wires allow for the electric activation, or manual override of the system.

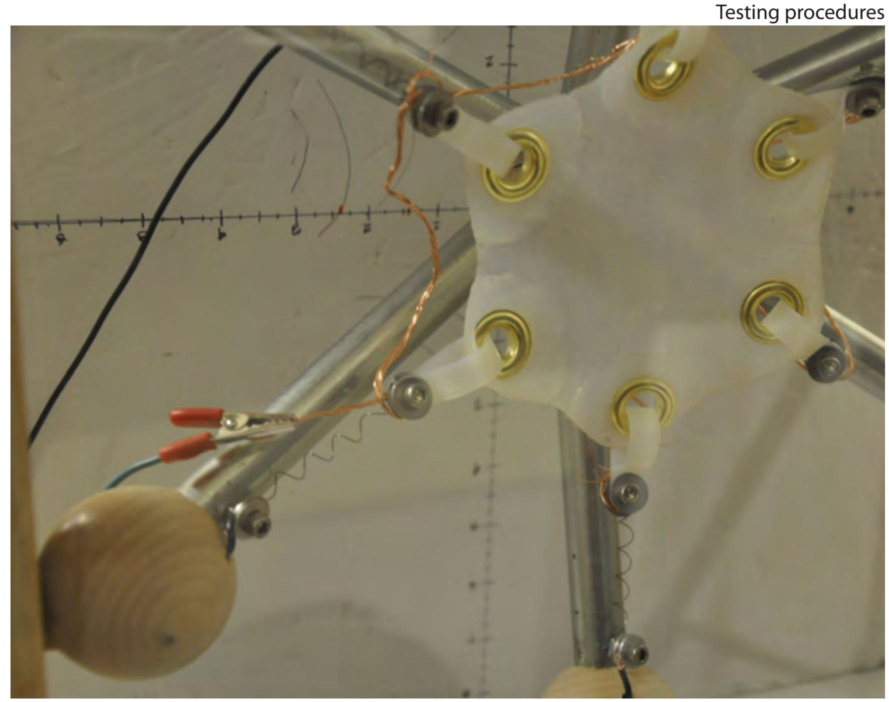
The Nitinol wires were then attached to the wire coming from the spheres on one end. The other end is attached to a nylon hook, which wraps through a grommet that is secured to the silicone itself. The grommet was introduced into the design process during the design of the silicone mold. It (the grommet) was initially tested on a thin layer of silicone. It appeared to form a secure connection but when under stress the grommet detached from the silicone membrane.

To explore remedies for this situation the thickness of the grommet was taken into consideration while determine the formation of the silicone membrane. Two variations were tested. Both membrane options had a 1/32" thick center which gradually shifted to slightly less than 1/8" thick. This thickness allowed for a more secure connection with the grommet. However one membrane had a solid 1/8" ring, while the other had a split 1/8" ring. There was a 1/32" strip separating the thicker ring, which allowed each connection to act independently and also provided less resistance to the stretching of the membrane.

The idea for the reinforcement of the silicone membrane at the grommet connections originated from the design of sail cloth. The intent was to reinforce the corners so that the material could withstand the forces applied to it.



Testing procedures



Test Chamber

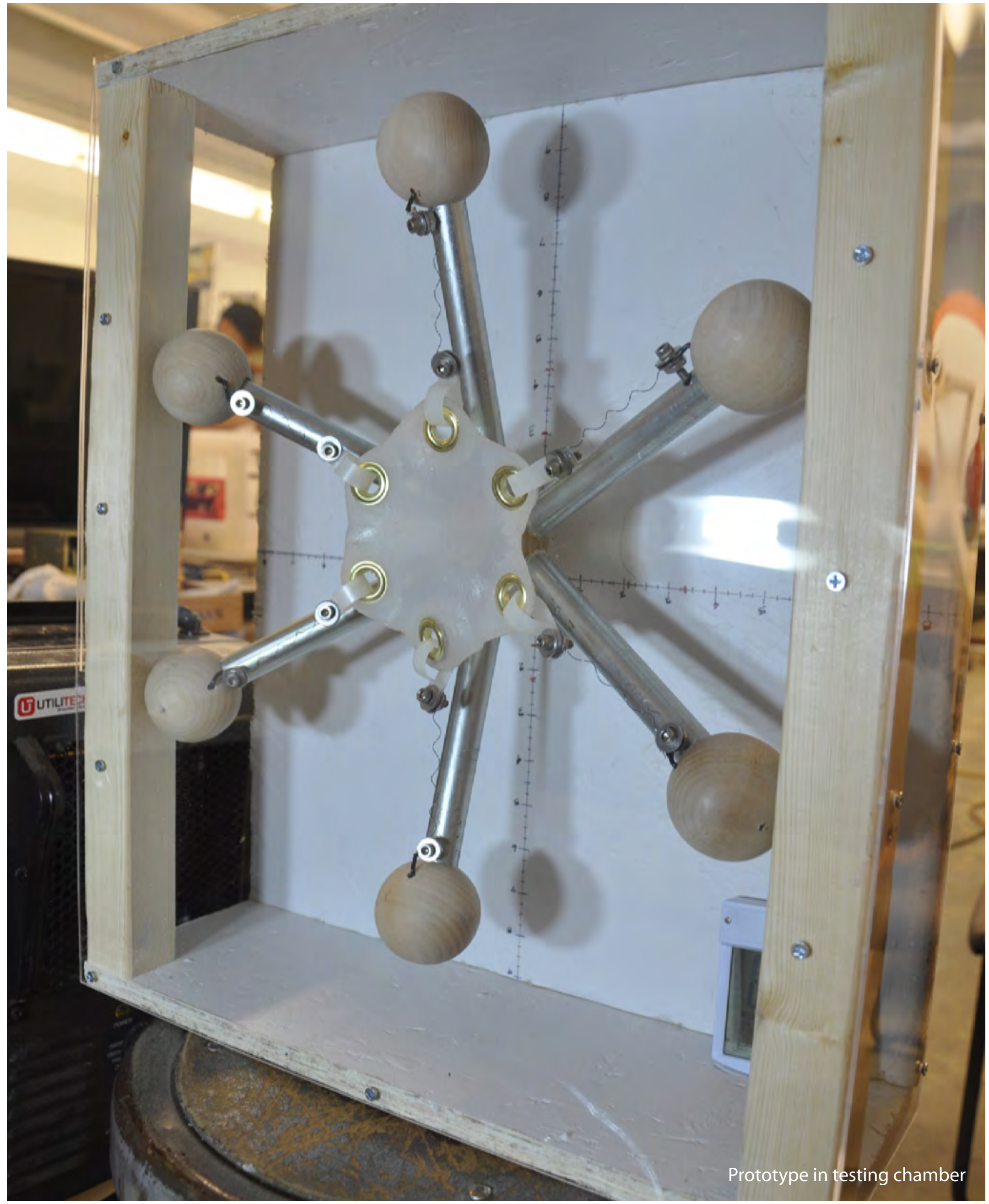
The Test Chamber included a thermometer and a 4-way ruler behind the silicone hexagonal membrane. A light was placed in front of the unit so that it could project a shadow upon the measuring device during model activation, enabling measurement to be taken to determine the amount of expansion of the silicone membrane.

The heat test was measured from a starting point of 68 degrees Fahrenheit. As the temperature was raised to 120 degrees the membrane experienced radial expansion of approximately 1" across its surface. The initial radius of the membrane was 2". By the conclusion of the test the membrane had expanded to 3 1/2".

The Nitinol wires were also electrically activated, producing similar results to the activation by heat, but with quicker movement.

Next, a triangle was tested so that each point could double up on Nitinol springs, increasing the linear force exerted on the nonlinear membrane. Although each corner of the triangle stretched faster with two springs than with one the shadow coverage was not significantly different than with previous experimentation.

In order to provide great expansion and contraction the model unit would need a stronger actuator than the Nitinol wire. Once one point was pulled, the spring would condense, but it would make the opposing point resist. Therefore, opposing Nitinol springs were creating forces that were cancelling each other out, weakening their effect on the silicone membrane. However, the test results did prove that the initial concept of a linear force creating movement in a nonlinear membrane could be accomplished.



Prototype in testing chamber

Application: Self Regulation

The contraction of the tube anemone's longitudinal retractor muscles alleviates hydraulic pressure within the organism's body cavity, facilitating its collapse in response to external stimuli. The tube anemone then uses diffusion through its body wall in order to return to its state of equilibrium (distended form), placing the body wall in a state of tension.

The model exploration of the expansion and contraction process focused on three (3) areas of the tube anemone's anatomy and biological processes:

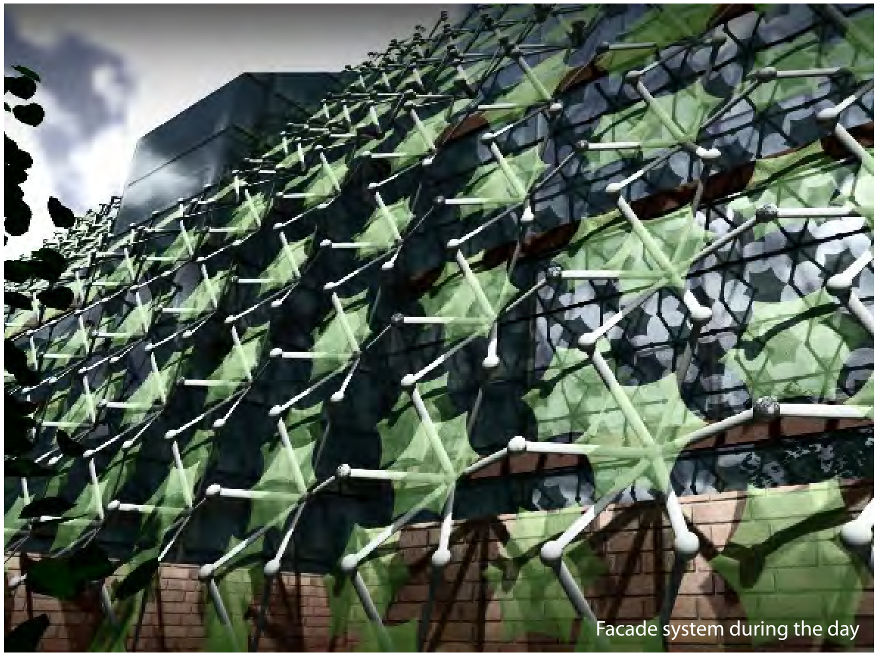
1. Vertical motion of the longitudinal reactor muscles and the subsequent release of hydrostatic pressure through the opening in the aboral foot (and oral disc).
2. Build-up of hydrostatic pressure that creates tension across the surface area of the column wall through diffusion.
3. Variations in the density and opacity of the porous column wall due to tensional fluctuations.

The applied system uses opposing forces of tension and compression which are conceptually based upon the tube anemone's contraction and expansion. The membrane is designed to maintain a condense d form when at rest (in equilibrium). The base unit converts the linear compression of the Nitinol coils into the nonlinear expansion of the tensional membrane by means of heat or electric activation, opening the unit to provide shade and diffuse light. As the unit deactivates, the forces within the membrane cause it to return to its original shape, stretching the coils.

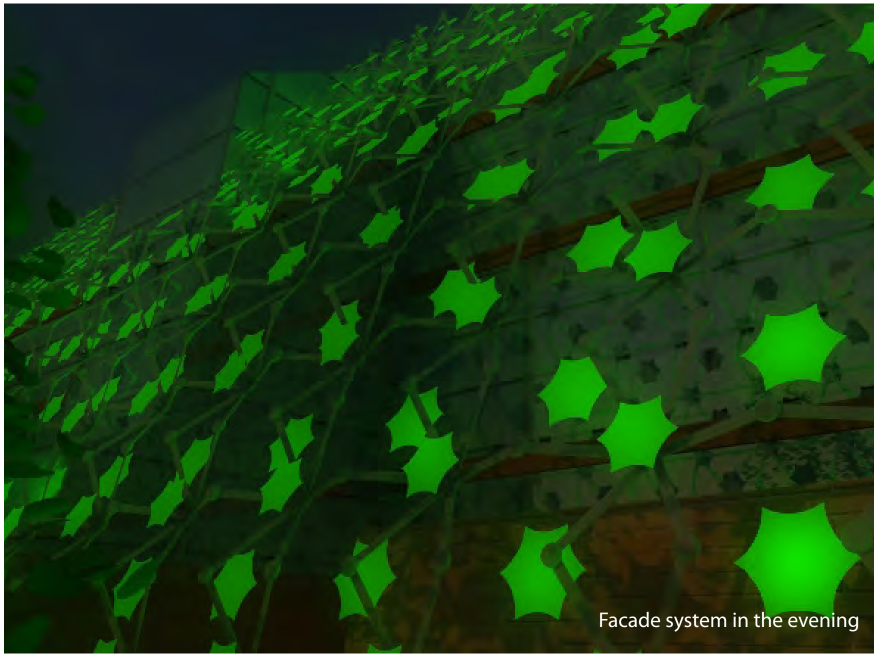
Theoretically, as the sun travels across the system the membranes would mechanically shift in a wave that mimics the sun's movement, causing pattern alignments that diffuse the sun's rays. It would also reflect surrounding context that reduces solar heat gain, such as shade from nearby buildings and trees. After the heat subsides, the units return to their original state.

Research revealed a direct connection between membrane opacity and surface tension. Investigations were made into materials that could exhibit fluctuations in opacity/transparency in response to changes in ambient heat, light, humidity or direct pressure (tension). One of the materials that proved promising during the course of research is silicone (both in sheet form and moldable form). Another avenue of exploration involved multiple-layered skin systems, with a liquid or gel middle layer that could demonstrate variations on opacity, color, and/or luminescence.

The system reflects this research by incorporating materials that visually react to changes in the environmental context, such as variations in ambient temperature or manual overrides. These responses can include changes in color, texture, opacity and/or luminosity. All of these interactive features are inherently reversible – after the external stimuli pass the units return to their original state.



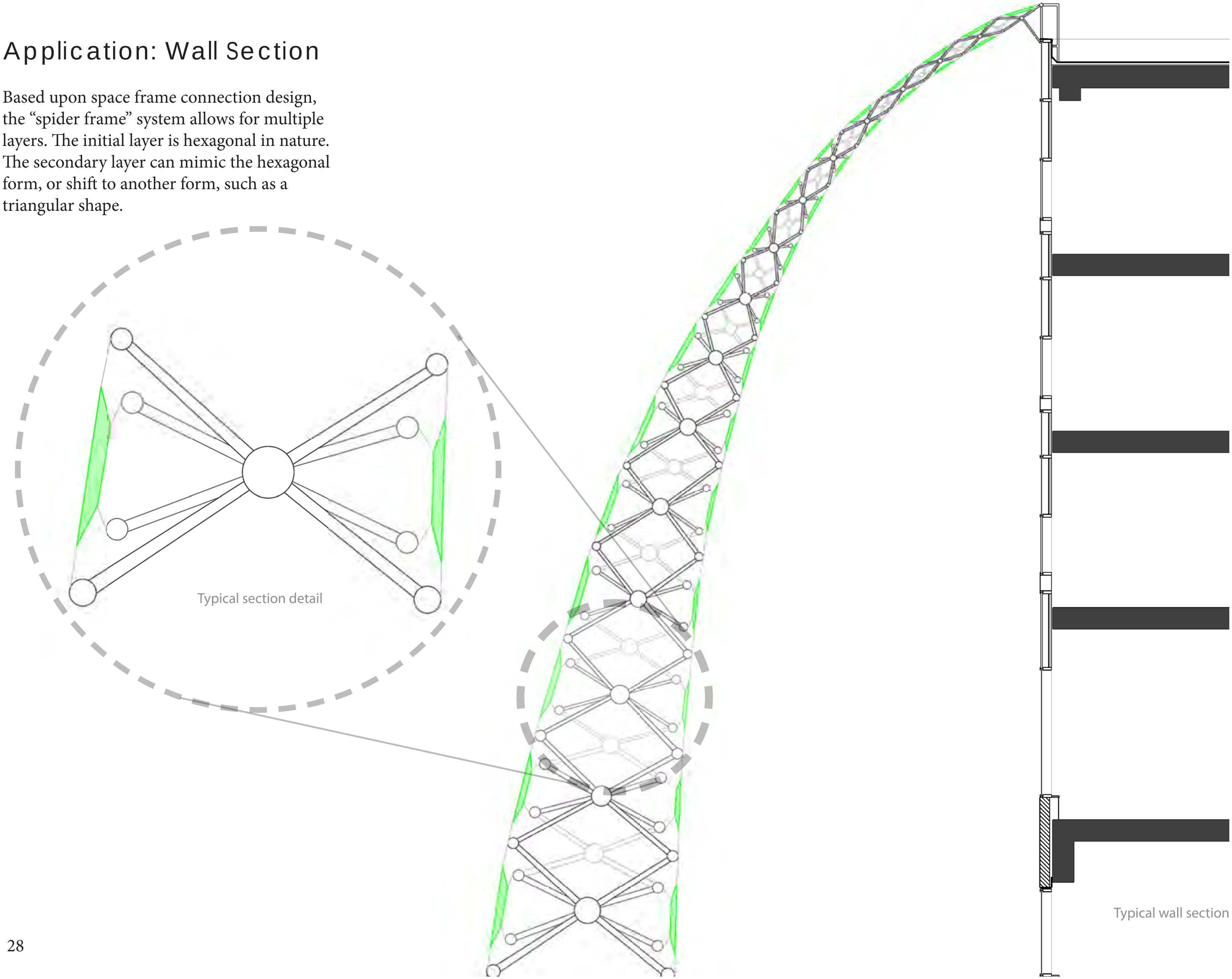
Facade system during the day



Facade system in the evening

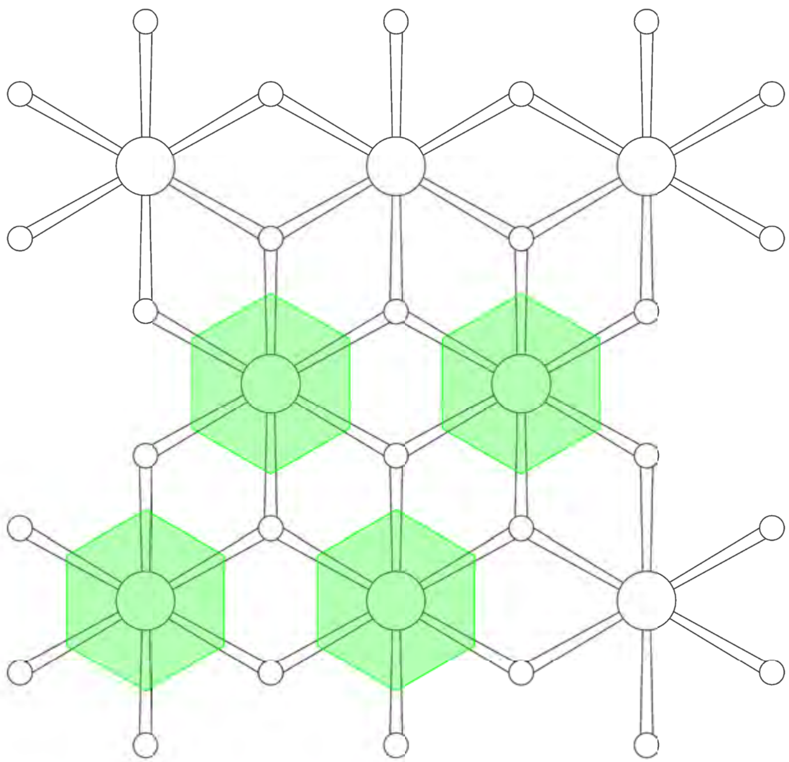
Application: Wall Section

Based upon space frame connection design, the “spider frame” system allows for multiple layers. The initial layer is hexagonal in nature. The secondary layer can mimic the hexagonal form, or shift to another form, such as a triangular shape.

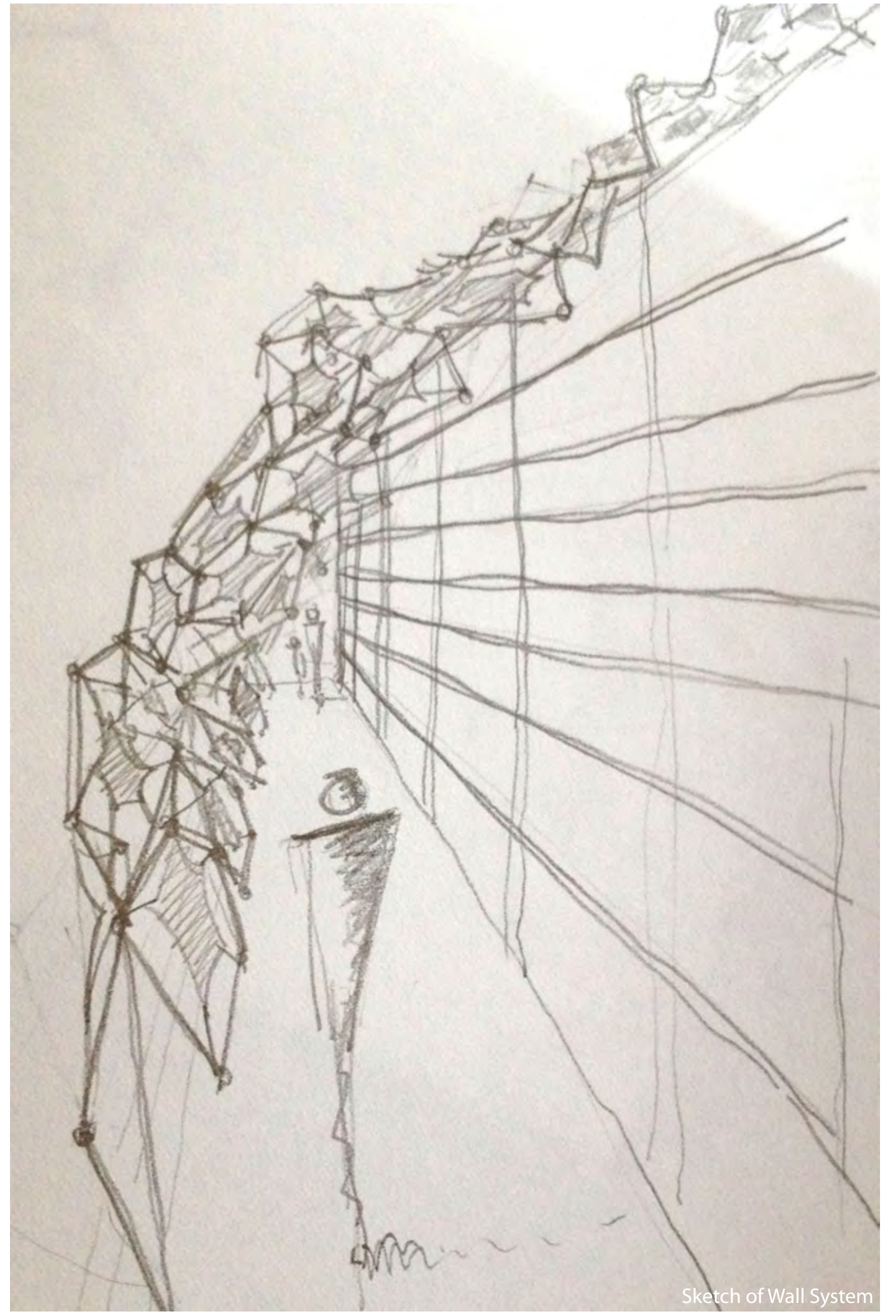


The point of connection to the primary framework is through node connections. The base node of the module unit can be sized to accommodate a mirrored unit on its reverse size. Or another sub-node in the system can be selected as the point of connection for the secondary layer. Another option is to insert a linear element which connects base nodes of the primary and secondary layers but directly applies a shift in the system. In either case, in order to provide adequate system coverage for shading, the plane of the secondary layer has to be shifted from the primary layer in multiple locations.

This system application can get very intricate very quickly, because in addition to providing a shifted secondary layer the system still has to respond to the site and building context. It has to be able to morph and bend between and around elements while creating interstitial spaces that can be inhabited. Also, the lengths of the module tubes vary, adding to the dynamics of the undulating surface. A customized analysis has to be undertaken for every specific application in order to successfully integrate the spider frame system into a given setting.



Elevation Detail of System



Sketch of Wall System

Performance: Thermal Collage and Diagram

The selected site application, O'Dowd Hall at Oakland University's campus in Auburn Hills, MI has several microclimate factors that impact the shading system's design. The body of water to the north provides cooling breezes when the wind blows across the water surface towards the building. Areas which are exposed to direct sunlight during the summer, such as the south and west façades, require more light diffusion than other areas of the building. East of the building is a large parking lot which creates an urban heat island and warms the air around adjacent to the site. Areas such as these are shielded by the system. Portions of the building that do not require as much shielding from the elements are left more exposed, allowing the building's inhabitants to see the exterior surroundings unfiltered.

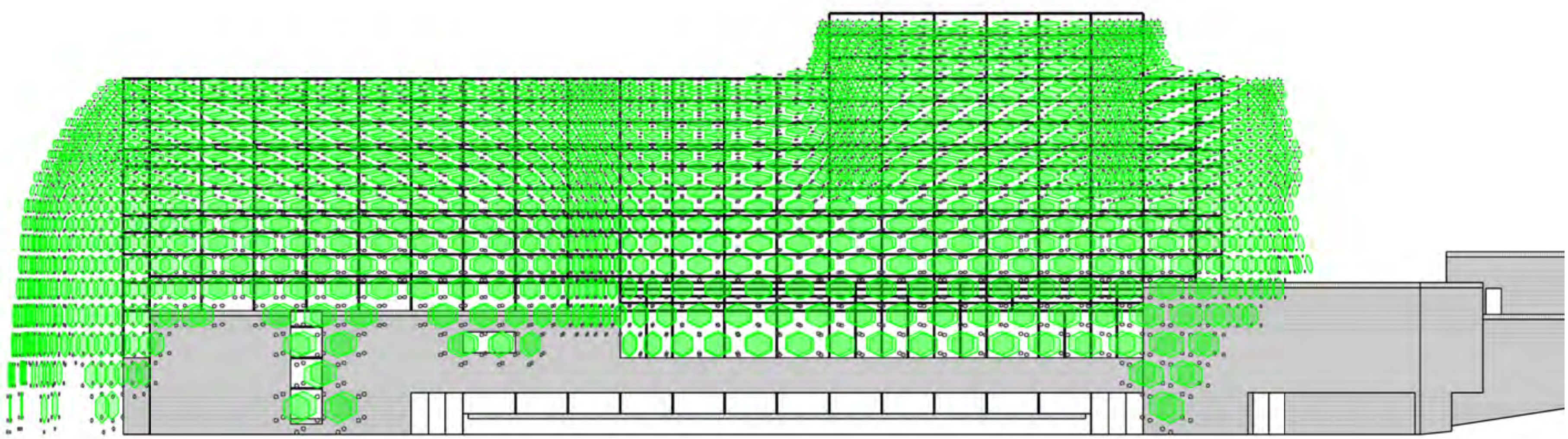
Climate and Energy

The financial savings and impact on the energy grid as these systems are retrofitted to existing structures can be substantial. The results can be seen in lower energy bills and a reduction in the urban heat island effect. During the summer the shade provided by the system creates a cooler interstitial space directly adjacent to the building. This space becomes an extension of the interior, creating a zone that blends the interior climate with the exterior climate. Within this zone air currents direct heat up and away from habitable spaces. The once static interior can be opened up to the exterior. Light is filtered and diffused, and cooler breezes can pass through the system, reducing the "sick building syndrome" that is prevalent among similar building typologies.

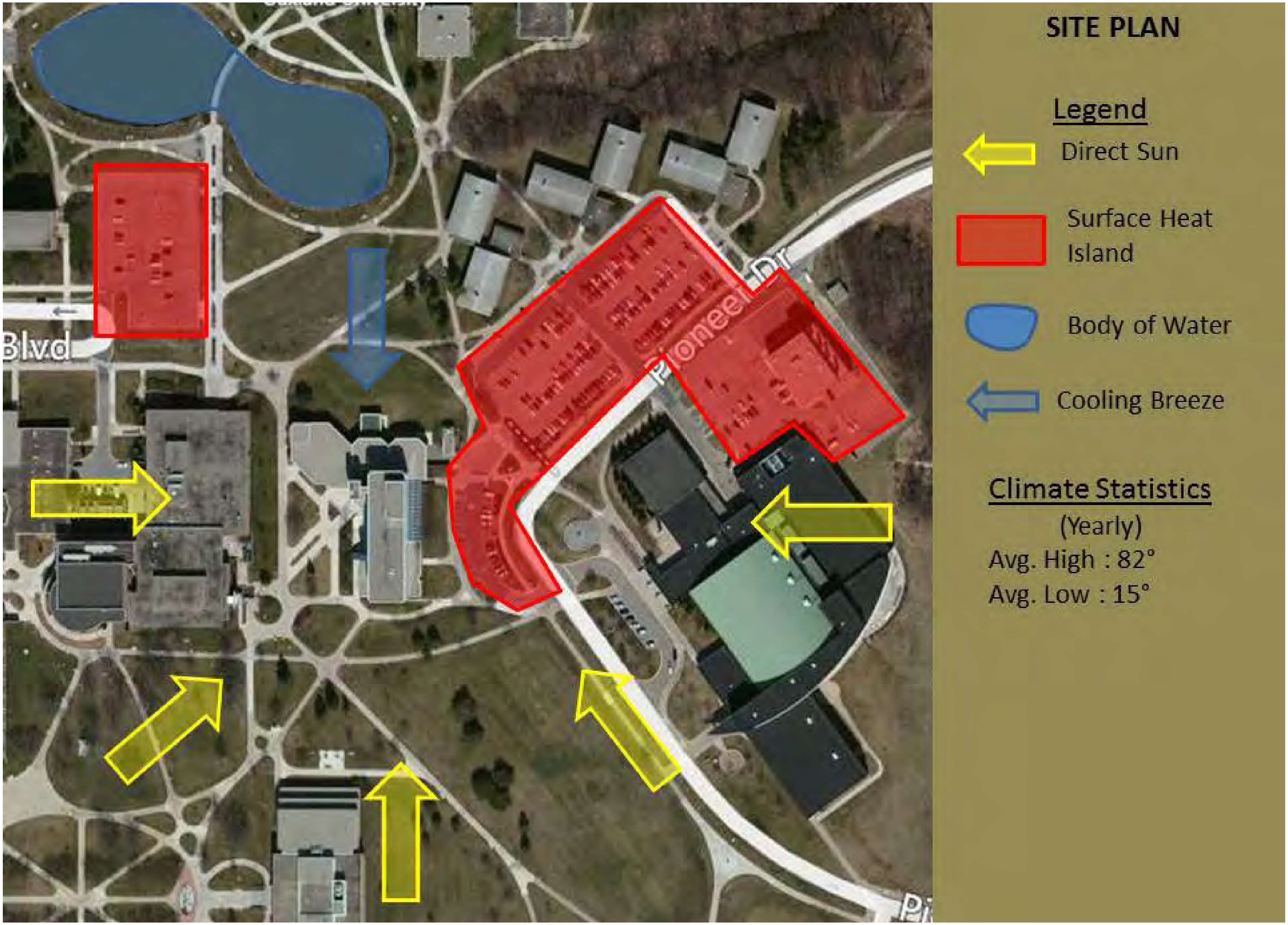
As illustrated in the renderings, the interior spaces of the building directly benefit from the shading system. The shading is immediately discerned by the building's inhabitants. Though the light is diffused, there is still adequate ambient lighting for students and faculty to perform their duties without needing additional electrical lighting. The extension of the system onto the roof of the building mitigates the harsh effects of the sun, wind, rain and snow, providing additional places for learning and social interactions. When these outdoor spaces are used, the interior spaces can remain unused, requiring less heating, cooling, and lighting in the interior spaces.

During the winter the system can be used to block wind and snow from the building and surrounding site. This shelters the area from more extreme temperatures, reducing the heating demands inside the building. Placement of the system at exterior areas throughout the campus creates similar effects on the microclimate. The students experience more moderate conditions as they pass through and seek shelter within the system.

A less direct effect of the system is its impact on the surrounding ecosystem. Over time the benefits experienced at Oakland University will trickle into the energy grid. As less energy is required to heat and cool the buildings on campus, a corresponding reduction in demand on the energy grid will occur. This means less pollution will be created in the production of energy. Granted, the impact of this system on the overall grid may not be large, but every bit helps.



East Elevation

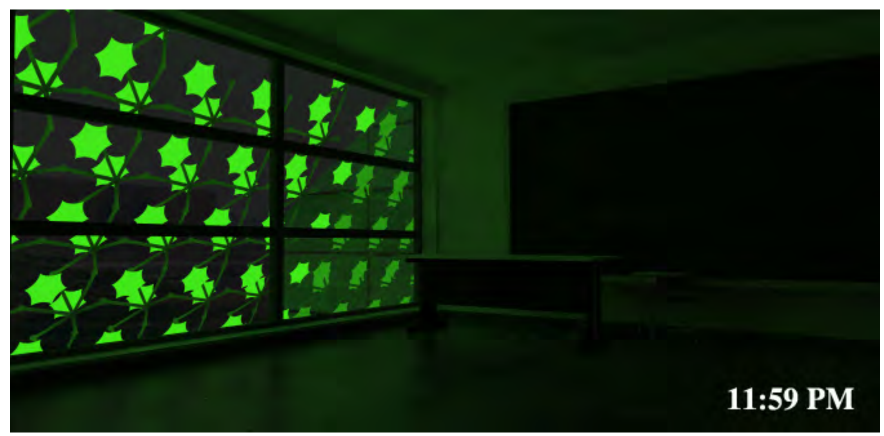

SITE PLAN
Legend
Direct Sun
Surface Heat Island
Body of Water
Cooling Breeze
Climate Statistics
(Yearly)
Avg. High : 82°
Avg. Low : 15°
Blvd
Pioneer Dr

Vegetation

One feature of the system is the integration of natural vegetation, such as climbing vines. This vegetation is allowed to grow along the structure of the spider frame in a controlled manner. The vegetation helps to absorb solar heat gain and provides an additional layer of filtering, cleansing the air and providing oxygen through the process of photosynthesis. During the winter, the leaves also serve as wind-breakers, helping to deflect the harsh wind currents.


Existing O'Dowd Hall


Existing O'Dowd Hall

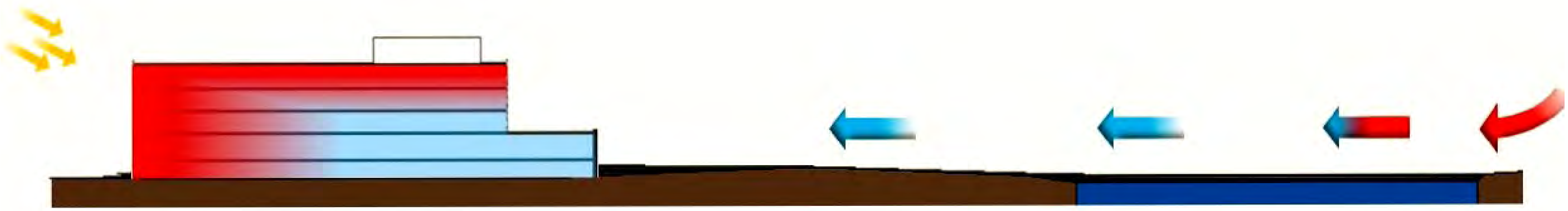


System Activation

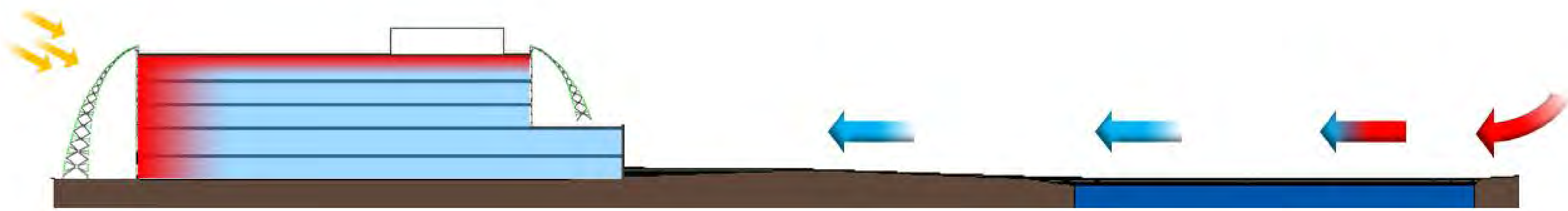
When the system is deactivated the membrane allows ample light to enter the building's interior. When the system is activated plenty of light still enters into interior spaces. The quality and nature of the light change depending on the membrane composition.

If the membrane is composed of more opaque materials, high contrasts exist between the light blocked by the membrane and the light that passes through the system around the membrane. There is concern that in such instances inhabitants could suffer visual side effects from the glare of having to continually adjust to the contrast.

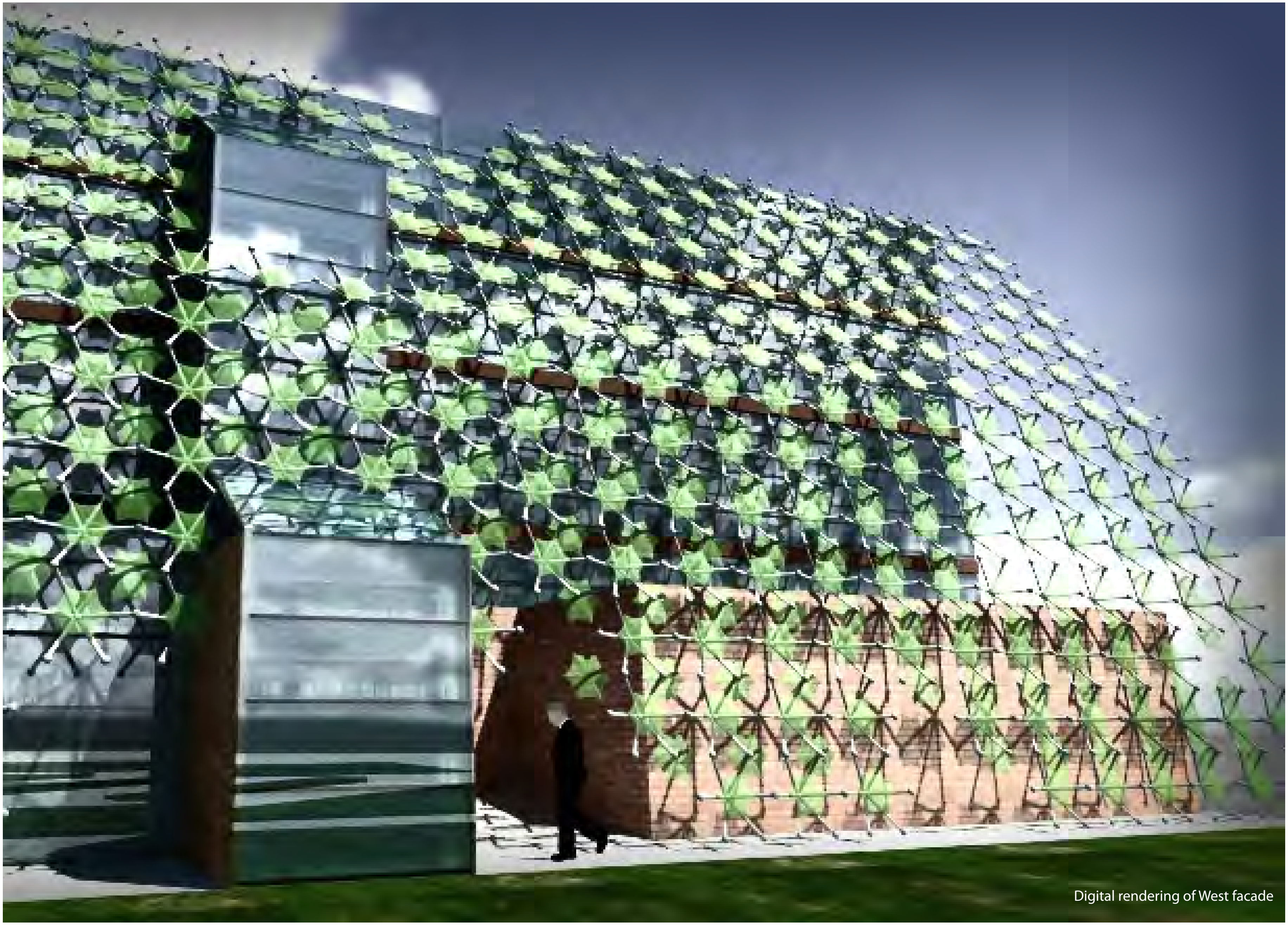
In an ideal setting the membrane diffuses the light, creating a softer, more subtle shift between the ambient light and the light that is filtered through the system. This can be accomplished by creating perforations in a translucent membrane or applying a light dye to the membrane. Another option is to embed materials into the silicone that help to diffuse light, such as strips of flexible cloth or granular substances. In such instances care must be taken to avoid making the silicone so dense that it becomes resistant to the tensile forces it must endure in order to properly stretch and recover on a daily basis.



Thermal Building & Site Analysis: Existing



Thermal Building & Site Analysis: Proposed



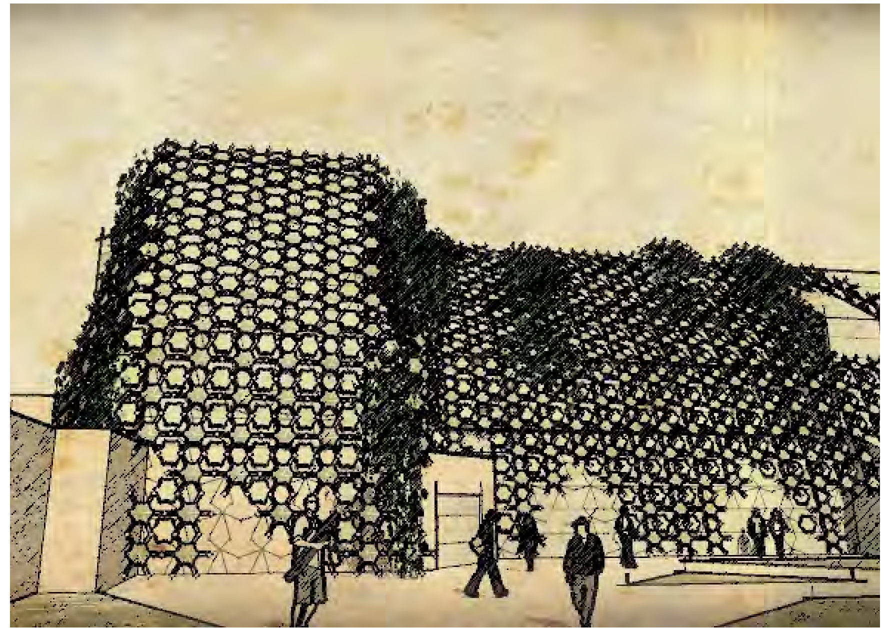
Digital rendering of West facade

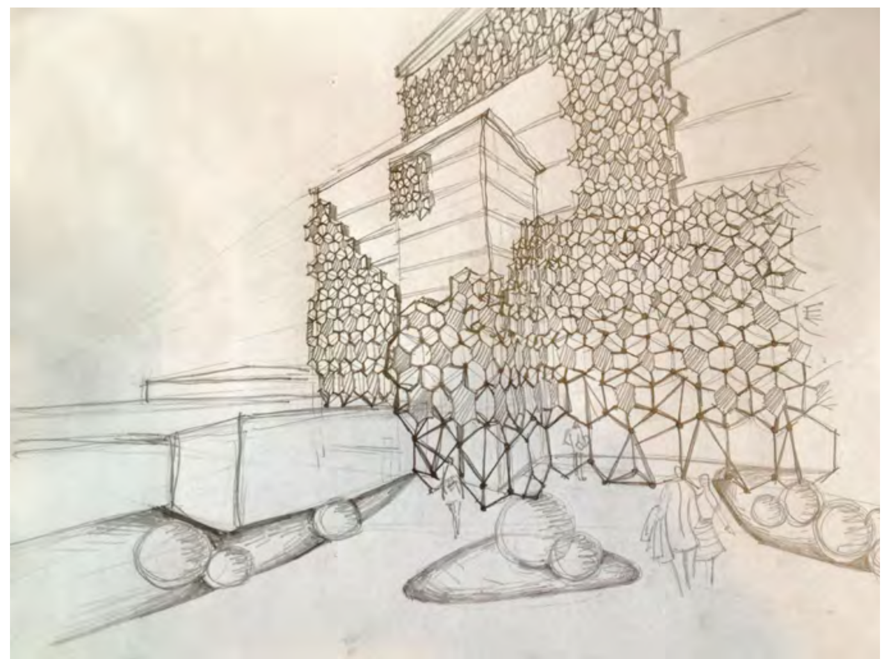
10 Year Horizon

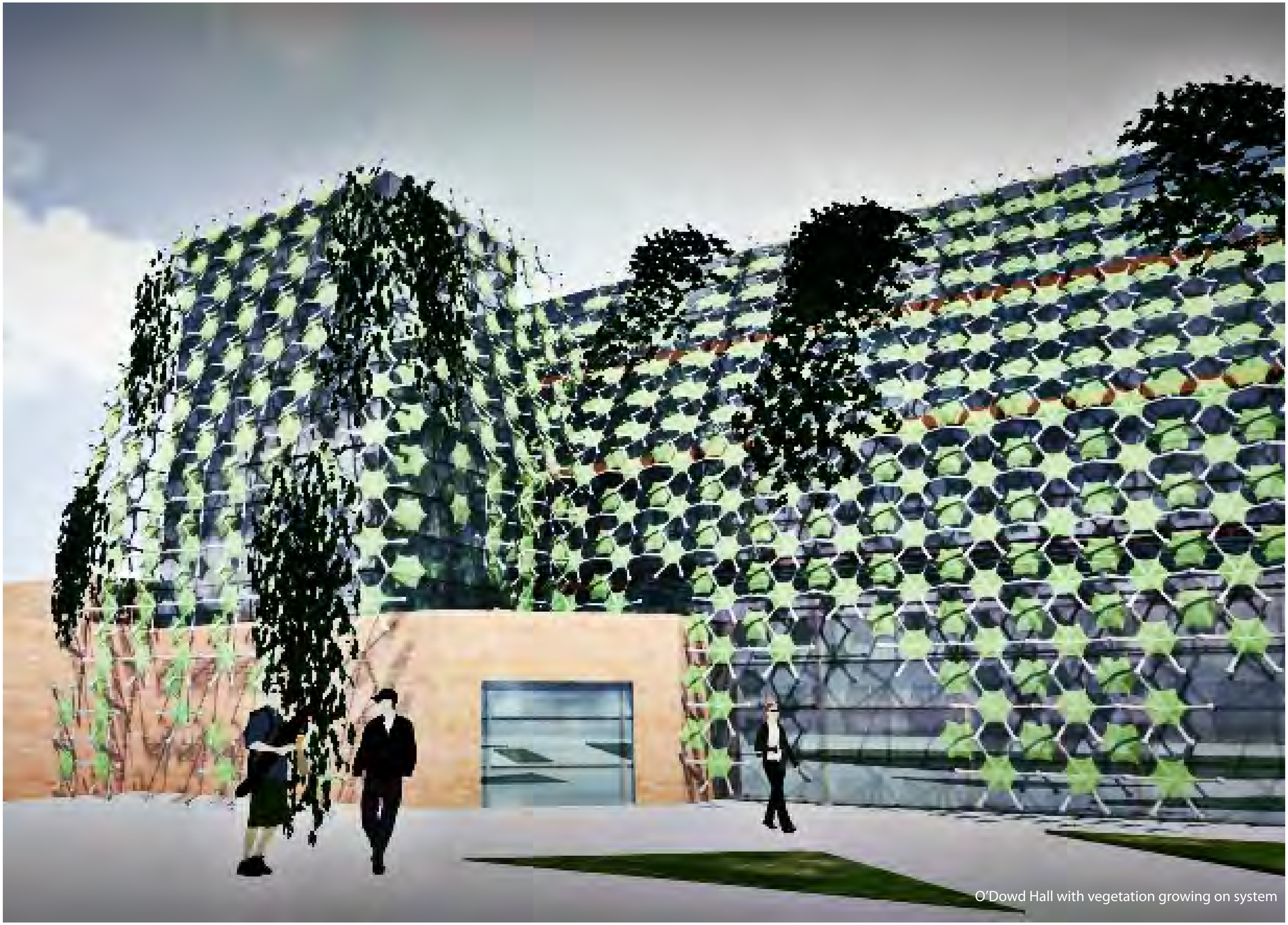
A thermal analysis of the site and building over time indicates that at the initial insertion of the system into the campus there are several areas of heat gain which put a strain on the building and provide unpleasant conditions for students and faculty inside and outside. Over the course of time the system has a cooling effect on the microclimate. The vegetation grows out and contributes to the system's performance. A negative aspect of the vegetation is the amount of maintenance that will be required over time. The vines will have a tendency to creep beyond the spider framework and extend onto the membrane, interfering with the Nitinol wire's ability to move. To help mitigate this, vegetation will be limited to lower segments of the system that are easily accessible for maintenance, and to areas that do not have membrane connections.

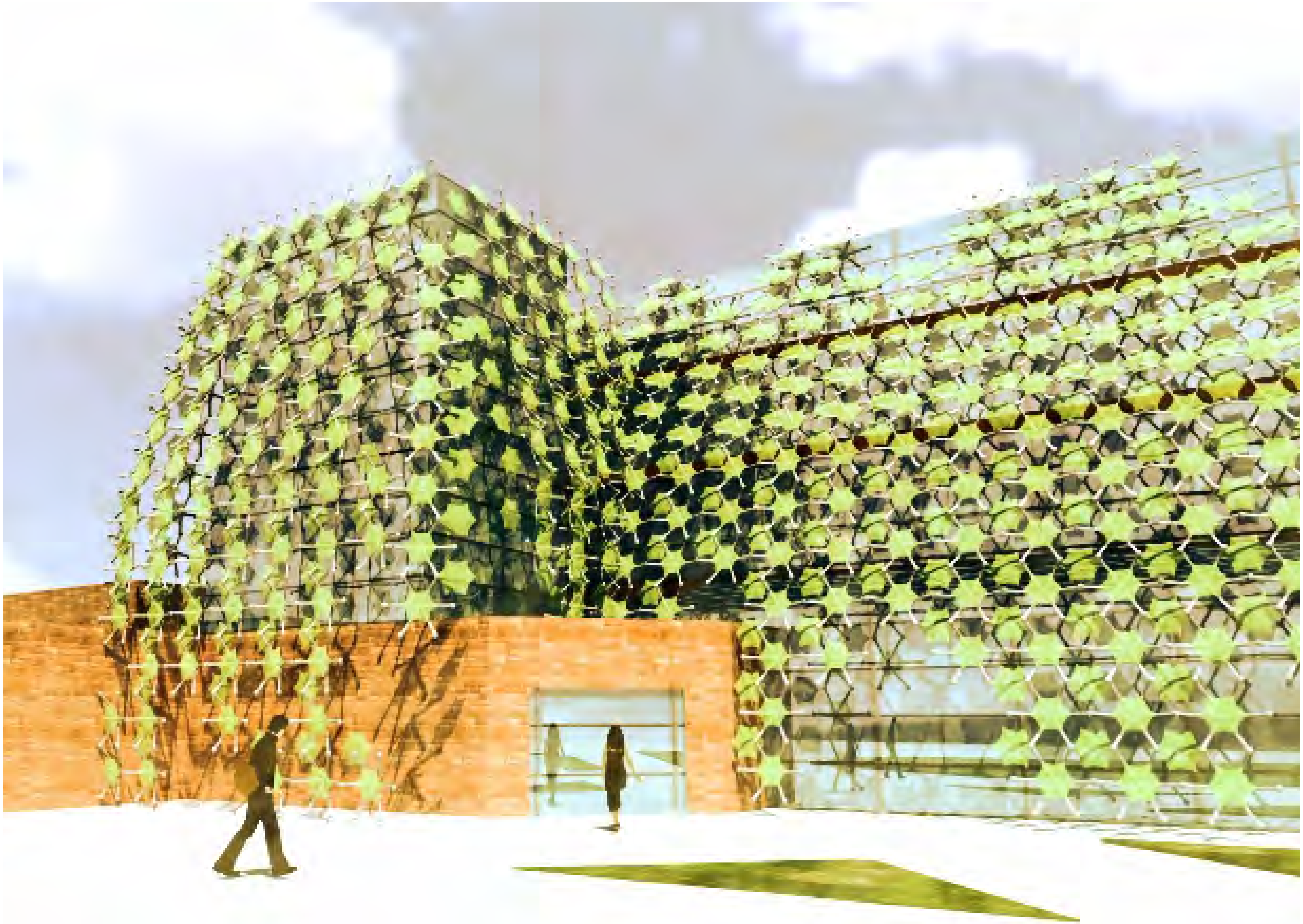
The membranes themselves will also degrade over time. Silicone breaks down. The materials and dyes integrated into the membranes will fade and stop working. These membranes will have to be replaced, along with the actuating Nitinol wires and electrical connections that will be exposed to the environment.

Another material that is present in the system is copper tubing. This copper is present at certain locations in the spider framework. The copper will develop a natural patina, providing a protective barrier that will reduce the amount of painting and maintenance needed on the spider frame. As students watch the copper age over time they can also experience a temporary visual change in the aesthetic qualities of the system. After the copper reaches its final finish it will not visually change further.






O'Dowd Hall with vegetation growing on system



Conclusion

As mankind has progressed throughout the centuries, architecture has become more introverted with the "advancements" of modern technology. We have found more ways to shut ourselves off from nature. As a result we have seen a rise in epidemics such as sick building syndrome, black mold, and the like. Architects are no longer creating breathing, living structures but are heading towards a form of static architecture that is void of life, cold and unfeeling. Often we are more concerned with meeting code requirements, testing standards and avoiding litigation than with designing places and spaces that form a bond between humans and nature.

For example, when we think of a window, we do not necessarily consider how to orient it in order to frame the ideal view. Instead we think of how to make that window as air tight as possible, how to flash around the perimeter, what color tint we want, and how many LEED points we can get out of it.

The purpose of inserting a system such as the one outlined by our Team is to breathe a new life into a decaying setting. This system brings movement, new patterns and variation back into the campus setting. The system becomes a permanent part of its context, as if it were grafted in. But once the system is inserted it does not just sit there. It responds to its surroundings. It grows. It moves. It changes. It is not static. It is dynamic.

Just like grafting a new plant into an old one can impart life, Oakland University can take on the characteristics of the system. It is like the entire site would keep renewing itself. When applied to buildings and extended to sites, the system unites the building with the site, erasing zones previously established and traditionally set aside to distinguish the "inside" from the "outside."

Not only does this system have a real impact on the physical environment, but it also causes psychological changes to those who interact with it. When applied to multiple areas, the system creates a larger network that fosters a sense of community. In addition to the quantitative "look-good-on-paper" benefits of lower energy demands and economic benefits, the qualitative benefits include revitalization of those who use the spaces and places that the system envelopes.

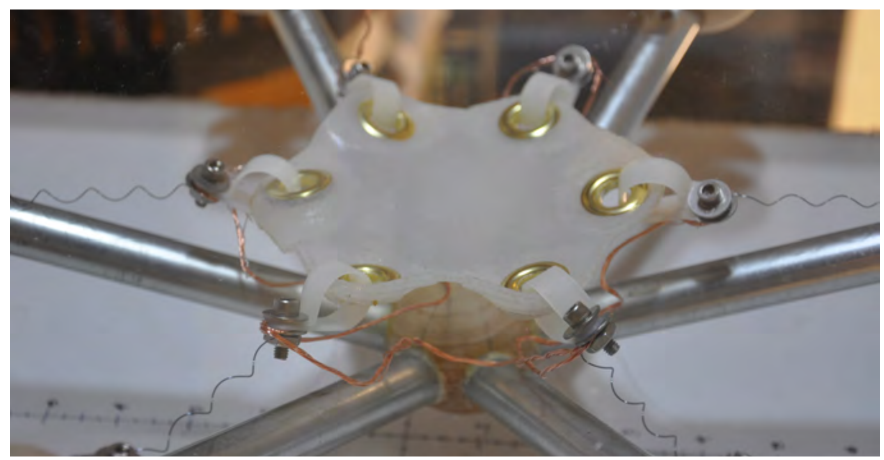
Lessons Learned

We understand the levels of complexity addressed by this summer studio. We looked at architecture from a "softer side" – getting inspiration from nature, abandoning pre-conceived ideas of forms and shapes and allowing our research to drive our design instead of using our design to dictate our research. Our designs should be pliant and flexible, seeking inspiration from multiple sources, even those not traditionally considered architectural in nature. We should seek conflict and resolution to test and improve our designs, not seek the path of least resistance.

We also learned the importance of stepping back and returning to previous ideas when we are going down a path that perhaps is not the best option. Sometimes we become so focused on a design or idea that we are determined to force it to work, even if it is contrary to the nature of the application. This course taught us to listen to our designs and be in tune with them, adjusting as needed when they are just not working.

Another important point deals with experiencing architecture. Often we design buildings and move on. Sometimes we work on a project and once the punch list is done and the project substantially complete we may not even be allowed in the building by an owner who doesn't even know who we are. But we are custodians of the built environment and what we design has an impact on those who inhabit the spaces we shape. We have a responsibility to keep this in mind. When we do, we can create phenomenal architecture rather than practical or functional architecture. While we are designing we should be thinking about how what we create will impact the user. How they will inhabit the space. How they will be impacted psychologically by the forms, shapes and colors around them, even extending to the temperatures, lighting and ambient sounds.

In this sense, the interstitial spaces and dynamic forms of our spider frame design begin to create architectural phenomena – interactive experiences that allow the users of spaces and places to do more than just look at their surroundings. This is where the dividing line between spatial and structural or practical and phenomenal is crossed. As we progress throughout our architectural endeavors it is our goal to further blur this distinction and blend the world we experience with the world we imagine.



Sources

Batham, E.J. "The Fine Structure of Epithelium and Mesogloea in a Sea Anemone." Quarterly Journal of Microscopical Science Vol. 101, Part 4 (1960): 481-485. 10 June 2012 <http://jcs.biologists.org/content/s3-101/56/481.full.pdf>.

Child, C M. "Form-Regulation in Cerianthus: I. The Typical Course of Regeneration." Biological Bulletin V (1903): 239-260. 4 June 2012 < http://biostor.org/reference/6516>.

---. "Form-Regulation in Cerianthus, II: The Effect of Position, Size and Other Factors Upon Regeneration.-- (Continued.)." Biological Bulletin VI (1903): 1-11. 4 June 2012 <http://biostor.org/reference/6519>.

---. "Form-Regulation in Cerianthus, III: The Initiation of Regeneration." Biological Bulletin VI (1904): 55-74. 4 June 2012 <http://biostor.org/reference/6520>.

---. "Form-Regulation in Cerianthus, IV: The Role of Water-Pressure in Regeneration." Biological Bulletin VI (1904): 266-286. 4 June 2012 <http://biostor.org/reference/6522>

---. "Form-Regulation in Cerianthus, V: The Role of Water-Pressure in Regeneration : Further Experiments." Biological Bulletin VII (1904): 127-153. 4 June 2012 <http://biostor.org/reference/6524>.

---. "Form-Regulation in Cerianthus, VI: Certain Special Cases of Regulation and Their Relation to Internal Pressure." Biological Bulletin VII (1904): 193-214. 4 June 2012 <http://biostor.org/reference/6525>.

---. "Form-Regulation in Cerianthus, VII: Tentacle-Reduction and Other Experiments." Biological Bulletin VII (1904): 263-279. 4 June 2012 < http://biostor.org/reference/6526>.

---. "Form-Regulation in Cerianthus, VIII: Supplementary Partial Discs and Heteromorphic Tentacles." Biological Bulletin VIII (1905): 93-122. 4 June 2012 <http://biostor.org/reference/6527>.

---. "Form-Regulation in Cerianthus, IX: Regulation, Form, and Proportion." Biological Bulletin VIII (1905): 271-289. 4 June 2012 <http://biostor.org/reference>.

Dkretz. "Anthozoa." Online posting. 8 August 2011. Classic EB: The Book Inspectors Collaboration League. 23 May 2012 < http://eb.tbicl.org/anthozoa/>.

Fautin, Daphne G. "Ceriantharia." AccessScience (2012). 23 May 2012 <http://www.accessscience.com/content/Ceriantharia/121800>.

Fautin, Daphne G. and Sandra L. Romano. "Anthozoa. Sea Anemones, Corals, Sea Pens." The Tree of Life Web Project Version 03 Oct. 2000. 10 June 2012 <http://tolweb.org/Anthozoa>.

Fox, Richard. "Aiptasia Pallida and Metridium Senile Anemones." Lander University 10 July 2006. 26 May 2012 <http://lanwebs.lander.edu/faculty/rsfox/invertebrates/aiptasia.html>.

Home page. Delta Structures. 8 July 2012 <http://deltastructures.com/>.

Home page. Dimension-Polyant. 9 July 2012 <http://www.dimension-polyant.com/en/D4_Membranes_2_5_1.php>.

Toonen, Ph.D., Robert. "Aquarium Invertebrates: Tube Anemones." Advanced Aquarist III (June 2004). 23 May 2012 < http://www.advancedaquarist.com/2004/6/inverts>.