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Thermoheliodome design, optimization and fabrication

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Abstract

The Thermoheliodome, a digitally fabricated radiant cooling pavilion, addresses the energy challenge of buildings through a novel form and concept. We control the effective radiant temperature of a large area by expanding the surface area through reflection, which minimizes convective losses. Our novel geometric analysis for capture and concentration of diffuse heat emission from bodies resulted in a cone-shaped 'lamp' form. The optimization resulted in a hexagonal array of 55 cones across a 6 meter dome, which expands radiant emission surface area by a factor of 6, shifting outdoor comfort perception with minimal losses to the outside air.

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Keywords: Radiant cooling; pavilion; pavilion cooling; thermal comfort; passive cooling

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1. Background

We present a systematic geometric analysis and fabrication methods that result in the design and construction of the 'Thermoheliodome' - an experimental, digitally fabricated radiant cooling pavilion. In particular we discuss (1) the reflection model used to design the reflective dish which formed the basis of the dome's design, (2) our fabrication constraints and how we used a particular spherical sub-division to enable construction, and (3) our methods for robotic fabrication of the pavilion.

The research and development for the Thermoheliodome was under a program entitled 'Beyond Shading' where we aimed to assess the potential for passive or low-exergy systems to cool buildings with performances greater than those achievable with shading systems. Our control scenario is an outdoor pavilion providing complete shading for a group of occupants. Without an enclosure, conditioning air is not practical, and our experiment looks to controlling the occupant's mean radiant temperature, or MRT, in order to increase comfort. A 1 °C drop in MRT is experienced as a 1.4 °C drop by the user [1], and we are hopeful that this kind of cooling may offer cost-effective and environmentally friendly comfort solutions for outdoor environments. Changing the perception of comfort using radiant exchange is effective across a wide range of temperatures [2], but it is important to avoid asymmetry in the heat exchange, which causes discomfort due to uneven sensation. Radiant temperature control often uses capillary mats paired with a thermal mass and emissive surface. With the Thermoheliodome we look to use reflection in order to concentrate a large amount of radiant energy into a small surface area, minimizing losses due to convection into the unconditioned airflow.

1.1. Evolution of Concept

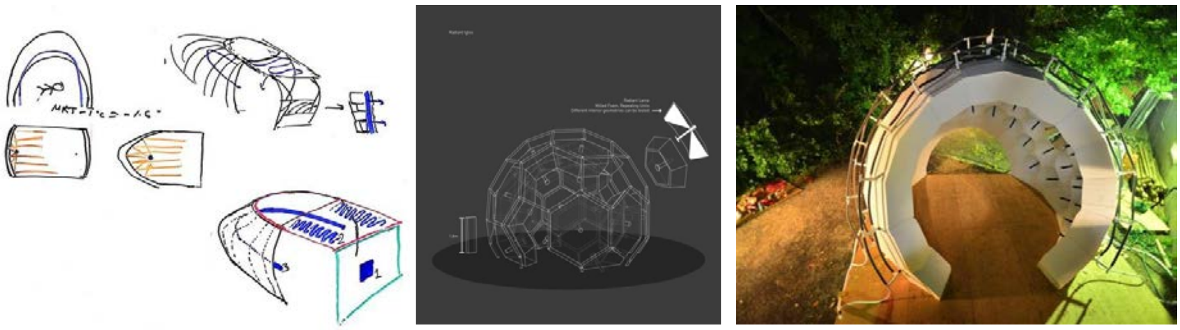

Fig. 1. (a) Initial concept drawing (b) Second concept with lamp and bulb section (c) Final structure

We explored an extruded parabolic form at first (Fig. 1a), concentrating emitted radiation on a single black-body pipe (which was to carry cooled water). We imagined this design would be easy to construct and could successfully concentrate radiation. Unfortunately that was only true for the heating case. Our investigation of the geometry of radiant reflection revealed that when the emission source is not at the focal point of the parabola, but instead it is the emission sink (in the case of cooling), the concentration effect is no longer achieved because the emitter is emitting diffusely at many angles of emission rather than the parallel rays that required by a parabolic reflector. This is also the reason parabolic rough solar concentrators don’t work when it is cloudy. So for our adaptation we wanted a roof for our pavilion to increase the solid angle of the to increase the surface for radiant exchange, and we also needed to devise a geometry that could collect the diffuse radiation at multiple angles. We also preferred our pavilion to occupy as much of the solid angle surrounding the user to maximize the radiant heat exchange.

2. Methods: Design and Optimization

The design we implemented was a cone-shaped, reflective 'lamp' with a coaxial water-carrying 'bulb' down its center (concept diagram Fig. 1b). We imagine this model could be easily adapted for panelization across any shape of surface, as is common in digital manufacturing practice today. The success of this design was dependent largely on the lamp's geometry, and we built a spectral reflectance modeling tool in grasshopper to assess design options. The geometry of this unit is tuned with a finite ray-casting analysis, looking for the geometry that would allow for the emission source (i.e an occupant) to move off-axis from the cone without drastically reducing its performance, something that would be a problem for a parabolic reflector (Fig. 2). The model uses a single emissive point and ray-casting, with a reflective model and solid intersections to determine whether or not rays cast from the emissive point contact the bulb. We measure the percentage of 'coverage' as the emissive point travels farther away from the bulb's axis. We wanted to determine what shape (depth and diameter) was best to optimally cool the occupant, while still performing as the occupant moved about within the pavilion. This exploration resulted in a relatively ‘deep’ cone, where the ratio between the depth and diameter is about 4/5. All shapes will work while the occupant is centered in the pavilion, but this is not a reasonable expectation for any space, and our assembly was static.

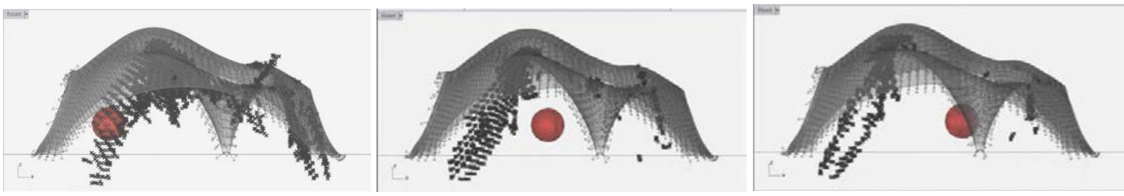

Fig. 2. Geometric analysis of radiation reflection under complex geometries (light gray surface) to visualize the amount of surface receiving direct reflection (shown in dark grey) from the emissions of energy at a diffuse source (the red ball) as it moves through space.

Another contributor to performance and maximum solid-angle-coverage was the packing of these dishes across the pavilion's shape. We use a dome because the normal vectors all point towards a center, where we expect an occupant will spend the majority of their time. In a larger pavilion hosting more than a few guests at a time, a different form may perform better. We used our lamp model to estimate an ideal circumference and depth, and looked towards some ideal packing of this shape onto the surface of the dome.

We used a robot arm to fabricate the dome, and because operation of the arm was a new experience for us, we chose to avoid complete mass-customization of the pavilion's components. Instead, we designed a subdivision of the dome, which would ideally produce a minimum of different-shaped units with which to assemble our dome. The ideal spatial packing of spheres on a flat surface is hexagonal, with an efficiency of 90.6%, and we wanted also to replicate this on a spherical surface. Adding complexity to this problem, we planned to fabricate each cone out of 6 other cone-sections, this way we were able to 'turn' the concave sections in slices, on the robot, without the need to invent a complicated manufacturing process for a single dish.

Using Grasshopper, a computational modeling tool for Rhinoceros, we divide a sphere into regular bands. These bands are not evenly spaced, although they do have an even number of division points. By alternating the points across each band, we get an essentially hexagonal distribution of centers across the dome (Fig. 3a-c). Parameterized in our model are: the number of bands, the number of centers on each band, and distance between each band. We used a rather 'brute-force' genetic algorithm (integrated in grasshopper) to solve for some optimum configuration, with a bias towards an average lamp size as determined with our ray-casting model, and towards highest efficiency in circle packing.

The model was also constrained to contain no more than 6 bands, and therefore only 7 different sized members to program. Coverage in our spherical packing came near the maximum achieved with planar hexagonal packing, (90.6%) at 88% [3]. Our constraints also considered a design based decision, which was to model the shape of our pavilion on the sun's seasonal trajectory - thereby maximizing available shade and also minimizing mean radiant temperature by ensuring the floor of the pavilion would be in shade for a majority of the time.

A more permanent installation could have been built with a thermally massive foundation, such as concrete, which would also include a radiant slab cooling component to further reduce the mean radiant temperature within the structure. However, the experimental nature of the dome did not warrant a permanent foundation. Instead, a wood-framed deck was chosen to facilitate the construction process and allow the system to be moved.

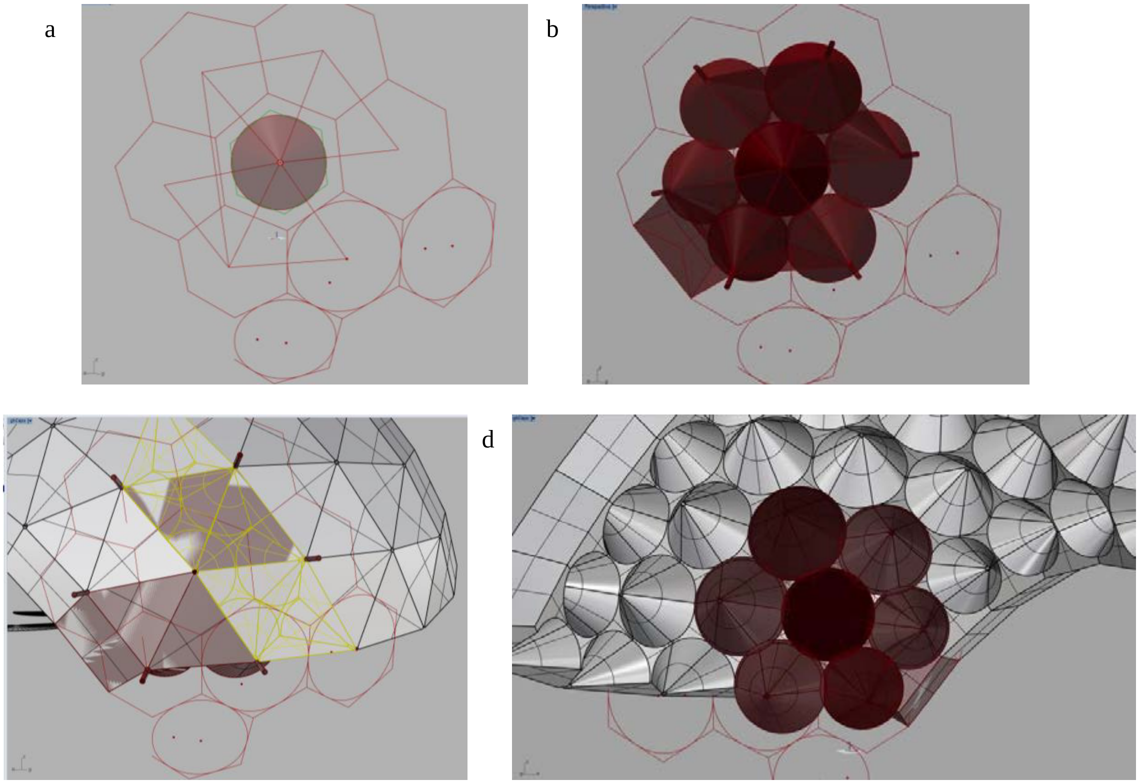

Fig. 3. (a) Spherical hexagonal packing with triangular grid of individually fabricated members (b) Final dish geometry in multiple packing formation (c) Solid forms for for fabrication (d) Interior solid condition

3. Results: Form and Fabrication

The final form used the dome cut to follow the path of the sun on the summer solstice. The dome has a 6 m diameter. Each cone was between 0.7 to 0.8 m in diameter to fit the packing. As in the design and optimization of the dome, we used Grasshopper to program our robot for fabrication. The system consisted of the ABB IRB 6400 of the Embodied Computation Lab in the Architectural Laboratory at Princeton's School of Architecture. An end-effector was specially designed to grabs blocks of foam by stabbing them, and a hot-wire cutter made with 8020 aluminum extrusion. (Fig 4). We used Mussel, a grasshopper plugin developed by Ryan Luke Johns / GreyShed [4] to turn the positions described in our grasshopper program into commands for the robot to follow. In order to position rough-cut blocks properly, we programmed in a set coordinate in the robot's world XYZ space for pickup, and used a template to ensure blocks were positioned properly prior to 'stabbing'.

We rolled 140 members on the hotwire over the course of a few weeks. EPS foam was ordered in 24'x4'x2' members, which we rough-cut by hand with a second hot-wire tool.

Once the dome structure was finalized, calculations were performed that compared the surface area of the bulbs to the surface area of the circles in Fig. 3b to establish the ratio of convective heat transfer to radiant heat transfer. Bulbs were constructed with 1.5” PVC piping, which has an actual external diameter of 4.826 cm. Each cylindrical bulb had 80 cm of internal exposure, which has a total surface area for all 55 bulbs of 0.12 m^2, the total surface area over which convective heat transfer may occur.

The circles from which the conical reflective dishes are subtended through which radiant heat transfer occurs have individual diameters of roughly 1m. The entire combined surface area of these circles is 43 m^2. Therefore the surface area for radiant heat transfer is nearly 400 times that for convective heat transfer, drastically reducing the cooling lost to the transient movement of air through the pavilion.

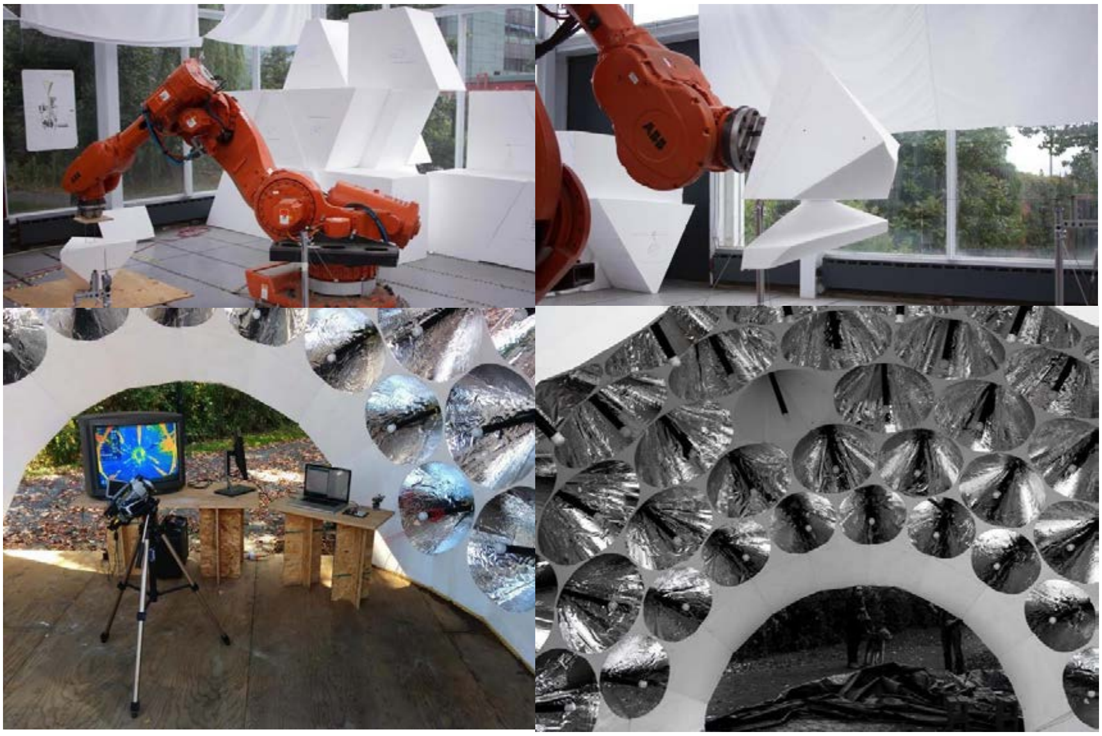

Fig. 4. Dome fabrication and construction

4. Conclusions

Results from the Thermoheliodome experiment (as well as a better explanation of it's plumbing and data collection systems) are published in a separate paper [5]. Our construction and design methods were a relative success when considering time and resources available, but there are a number of things we would like to have done better. First off would be a more thorough review of our chosen geometry. The bulb configuration makes for a lot of excess plumbing, where one of our original goals was to minimize this complexity and opportunity for heat-loss. The construction of the bulbs is also not ideal: being PVC and about 5mm thick, we loose some cooling power to the insulation across the wall. The robot end-effector was not able to secure our foam blocks within 2°, which added up to considerable error in construction; a re-design of the end effector would be worthwhile as well. The hot-wire itself was also difficult to tune and calibrate, and would often break during cuts.

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