SolarPierce: A Solar Path Based Generative System

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Abstract. In hot and arid climates, limiting solar heat gain while also providing daylight into a structure is a major concern in building design. Building skin that gradually changes in porosity can help limit solar heat gain. Since solar heat gain is primarily a problem during summer, the path the sun follows during summer must be taken into account in determining opening sizes. In this paper, the researcher reports on a study where a generative system called SolarPierce was developed using AutoLISP, the scripting language of AutoCAD, to generate solid geometry for a building skin based on the sun’s path in a given geographical area. The system automatically punches different size openings in a given shell structure where openings facing the sun are the smallest and those fully facing away from the sun are the largest. Opening sizes gradually change from a given minimum to a given maximum depending on how much they face the sun.

Keywords. Solar; generative system; building skin; dome; shell structure.

INTRODUCTION

In the study reported in this paper, a generative system called SolarPierce was developed by the researcher and implemented through AutoLISP scripting language in AutoCAD where the path of the sun given in azimuth and altitude angles was used to determine opening sizes for a dome or any other given shell structure. The paper reports on the implementation of this generative system and some of its initial results. A major challenge for algorithm designer of a generative system is providing as much freedom as possible to the designer while incorporating performance related constraints into the system. In the solar generative system developed here, it was decided that any shape opening the designer wishes to use as well as any shape shell structure will be allowed (Figure 1 and 2). However, this paper primarily focuses on domes as shell structures.

PERFORMANCE BASED DIGITAL DESIGN

Generative systems have been around for a very long time where typically complex geometry is generated algorithmically using digital tools. Often these forms do not meet functional, acoustical, climatic, cost, etc. requirements of a given design problem, since performance is not a criteria in generating the forms algorithmically. On the other hand, analytical software are primarily designed to work on projects that are already fairly well developed. Therefore, generative algorithms that respond to real world performance of buildings are needed in order to incorporate them into architectural form-giving from the very beginning of the design process.

From early on, it has been obvious to designers that incorporating site constraints such as setbacks, limits in building heights etc. through the use of associative parametric objects can help guide the form giving process, although this is not necessar-
ily a strictly generative process. It can however be considered an early example of performance based design process, since the final form of the building is affected by the constrained parametric objects. Designs with algorithmically generated complex geometries often require additional analysis from building performance and constructability perspective. For example, in Foster’s Swiss Re building, its geometry was tested at post-design phase to make sure that all of the glass panels were flat. Furthermore, in this building the overall shape of the structure was intended to deflect air and thus minimize draft at the street level (Kolarevic, 2003, p. 458.) On the other hand, in the Sinosteel Int. Plaza, in Tianjin, China (by MAD architects, due to be completed in 2014, [1]), the building skin was delineated through complex geometry based on cultural performance criteria. The hexagonal modular skin is described by its designers as: “This façade is made up of five standardized units of hexagonal windows; it signifies the heritage value in Chinese architecture. These windows flow across the building in a naturally evolving pattern, as if organic cells multiplying.” In this case, the reason for varying opening sizes is articulated to be cultural and aesthetic rather than environmental or external (some scholars group cultural factors as performative.)

Exploration of geometric forms to create complex surface effects or to punch holes through the skin of a building is now very common in an increasingly global design language. Often these geometric explorations are based on the idea of creating ionic buildings, sometimes overlapping with the idea of providing shading or addressing some other...
type of environmental concern. For example, Zaha Hadid’s Bethoven Concert Hall in Bonn, Germany has an articulated building skin with geometric holes punched through it, bringing daylight into the structure [2]. On the other hand, regarding a contemporary building shaped by sunlight, the Sun sliced Porosity Block, an office complex in Chengdu, China, architect Steven Holl talks about his form-giving concept as follows: “truly ‘shaped by sunlight’ both in the dematerialized geometry and in the subservience of built space to elegant ribbons of circulation, gentle slopes, and generous plazas.” In this building, the overall geometry of the structure as well as some of the surface effects were formulated based on the direction of the sun’s rays [3].

One reason for specifying a multitude of opening sizes in the skin of a building is the need to control the amount of direct sunlight coming into the structure in order to limit solar heat gain while also providing sufficient amount of daylight. Although there has been plenty of efforts to design building skins that are responsive to such solar concerns [4], typically through shading devices, such principles are typically not incorporated into generative algorithms.

Among the rare generative systems that respond to energy performance requirements of a building is Caldas and Norford’s generative system that incorporated Alvaro Siza’s complex form-giving principles for the School of Architecture building in Oporto (Caldas and Norford, 2001) into their algorithm. In this building, Siza was concerned about the control of daylight to reduce solar heat gain. A genetic algorithm was designed and implemented by Caldas and Norford to generate façade solutions for the building by using day lighting verses solar heat gain principles. This study however limits the general form giving principles to those of Alvaro Siza’s, and does not provide a framework for exploring other forms.

Providing differential size openings as a factor of the orientation of the fenestration is often a method used to balance the two competing performance criteria of limiting solar heat gain and bringing daylight into a building. Since solar heat gain is primarily a concern during summer, the path the sun follows during summer must be taken into account in determining opening sizes. Building skin that gradually changes in porosity can help limit the amount of heat gain due to the direct sunlight coming into a structure. Such an integration can not only create deep shadow patterns that give depth to the façade but also allow infiltration of sunlight into the structure to create daylight effects that change by time-of-year and time-of-day. An additional conceptual dimension of this approach can be in the degree of iconic condition created by the resultant opening patterns and the design recognition this can bring.

OPENINGS IN DOMES AND SHELL STRUCTURES

Typically structural concerns for domes and other shell structures are the main performance concern during design. Starting with the Romans, domes have been successfully used to span large spaces in masonry buildings across the world. Often the nature of the material used, for example, stone in historic structures, concrete in shells, and light weight steel elements in Buckminster Fuller’s geodesic domes determine the nature and the size of the openings in such structures. Particularly shell structures and stone domes must be designed to carry their own weight along the skin of the structure, thus openings must be carefully placed to meet this structural need. Furthermore, the base of the structure must be supported laterally to counteract the thrust exerted by the dome or the shell structure.

As a historic example, the dome of Hagia Sophia is structurally comprised of 40 ribs with 40 windows in between at its base (Figure 3), where each rib works like an arch. Great architect Sinan has certainly stretched the boundaries of how bright the interior of a stone building can be when he erected the Selimiye Mosque in Edirne, Turkey. The grandness of the feat achieved by Sinan in bringing daylight into a stone structure can be best appreciated at this mosque (Figure 4) where the load of the dome is carried artfully through a series of arches and half domes, each with plenty of window openings.
in themselves. Radial symmetry for the openings around the dome in both Hagia Sophia and Selimiye Mosque as well as in many other historic domed buildings was certainly an important consideration, primarily for structural purposes, but also from formal and aesthetic perspective of their era.

However, new materials no longer require radial symmetry for openings in domes or other shell structures, thus provide greater flexibility than that was formerly possible. The invention of reinforced concrete as well as steel has dramatically changed the constructability of innovative domes and other thin shells. Openings can now be opened anywhere on the dome as long as the load of the structure is successfully transferred along the vertical curvature, and reinforcement now resists the tensile forces at the base successfully, allowing even larger openings at the base.

Among the other methods used in bringing daylight into a structure through a dome or a shell is the process of embedding chunks of glass or circular windows (skylights) into the fabric of the structure throughout the shell. A good example of this can be found in historic Turkish baths built during the Ottoman times where small openings are evenly distributed throughout the dome rather than larger openings/windows only at the base of the dome (Figure 5). Domes of Turkish baths have always had quite fancy openings distributed throughout the dome. For example, the old bath in Prizren, Kosova which was built by Gazi Mehmet Pasha at Ottoman times has embedded venetian glass skylights in its dome [5]. The process of embedding transparent or translucent materials throughout a shell structure can be a good model for digitally fabricated contemporary shells where a combination of multiple materials is deposited during the fabrication process, typically using 3D printing technology. This is further discussed below in the section regarding materiality.

One question that often comes up is how to size the openings of a structure in response to the climate of the region where the proposed design is to be built. Often shading devices are proposed and used to control direct sunlight that can lead to undesirable solar heat gain in hot and arid climates. Sizing the window openings in a dome or a shell structure in response to the path of the sun makes sense, as this approach can potentially provide plenty of daylight while also minimizing solar heat gain. Therefore, this researcher posed the question of what if opening sizes were in response to the path of the sun in a specific geographical area. This certainly indicates that opening sizes need to vary depending
on their individual orientation as well as depending on the longitude and the latitude of the location at which the building is to be built. A generative system was developed and implemented by the author in AutoCAD using AutoLISP scripting language where opening sizes were generated based on the orientation of each opening and the azimuth and altitude angles of the sun throughout any given day of the year. As mentioned earlier, the software was designed so that designers can use any shape opening and any overall geometry they want.

**SOLAR BUILDING SKIN GENERATOR (SOLARPIERCE)**

Obviously sun’s path depends on the geographical location of the site. Points along the path of the sun can be defined in azimuth and altitude angles. This was incorporated into the algorithm of the AutoLISP code for SolarPierce where the sizes of the openings facing the sun are automatically calculated based on the minimum size determined by the designer and the sizes of those facing away from the sun are gradually increased, ultimately north facing openings reaching their maximum size. The gradual increase was based on five different intermediate sizes depending on the degree of sun exposure. Although computationally, it is possible to generate a very large number of opening sizes, from construction perspective it made sense to limit the total number of opening sizes. Having a very large number of sizes that vary from each other in small amounts will certainly drive construction costs up. Therefore the number of increments was limited to five, but this can obviously be changed as needed.

The algorithm uses spherical symmetry and works for sun’s path at any day of the year and for any geographic location (Figure 6). It is up to the designer to choose the time of year that makes sense for the geographical location of the building under consideration. This basically means the pattern and size of openings generated for Phoenix, AZ for summer solstice (June 21) would be different than those generated for Calgary, Canada for the same day of the year. It also means the opening patterns and sizes generated for winter solstice (Dec. 21) for any location in the world would be different than the opening pattern and sizes generated for summer solstice (June 21) at the same location.

The azimuth and altitude angles for the sun’s path were derived from sun charts for a specific city or location for a specific day of the year. These angles had to be converted to the angle convention of AutoCAD where 0 degree represents East direction, whereas in most sun charts 0 degree azimuth represents North orientation (sometimes 0 degree azimuth represents the South direction in sun charts) [6], [7].

As an example, below is the format in AutoLISP using AutoCAD’s angle convention for representing the sun’s path for Phoenix, AZ on June 21 from sun-
rise to sunset:
   (SETQ sunpath (LIST 15 (LIST 24.2 7.2) (LIST 17.0 19.0) (LIST 10.0 31.1)
   (LIST 2.8 43.5) (LIST 354.1 56.0) (LIST 340.6 68.3)
   (LIST 307.2 78.6) (LIST 270.0 80.7) (LIST 232.9 78.6)
   (LIST 199.4 68.3) (LIST 185.9 56.1) (LIST 177.2 43.6)
   (LIST 170.0 31.2) (LIST 163.1 19.0) (LIST 155.8 7.3)
   )); end of list
   ); end of setq

The script runs to generate voids that are actually solid objects in AutoCAD. These can then be subtracted from a solid dome or some other type of solid shell structure. The location and general orientation of the voids are spherically symmetrical in 3D. A decision process for determining the opening sizes was implemented based on the “degree of sun exposure”, algorithmically defined as a factor of the difference between the azimuth angle of the opening under consideration and the azimuth angle of points along the sun’s path as well as the difference between their altitude angles:
Degree of sun exposure = (AND (azimuth of opening – azimuth of point on sunpath) (altitude angle of opening – altitude angle of point on sunpath)).

In the scripting language of AutoCAD, i.e. in AutoLISP format:
   (SETQ solazi (CAR (NTH num sunpath))
   solalt (CADR (NTH num sunpath))
   diffazi (ABS (- solazi azi))
   diffalt (ABS (- solalt altang))
   ( (AND (< diffazi 10.0) (< diffalt 10.0)) (SETQ openingsize (/ vsize 10))
   ( (AND (< diffazi 10.0) (< diffalt 20.0)) (SETQ openingsize (/ vsize 6))
   ...

Based on this decision algorithm, the degree of sun exposure is tested for multiple ranges, where for example, if the difference is less than 10 degrees for azimuth or altitude angle, then the opening is assumed to face the sun (leading to the selection of a minimum size opening). This often led to smaller openings at the lower parts of the structure facing directly east and west, due to the low altitude angle of the sun in those cardinal directions, as well as smaller openings at the top of the structure facing south due to the high altitude angle of the sun at noon. This works well for both summer and winter exposure, since it allows larger openings in the south at the lower parts of the structure which is desirable in the winter. The system in a sense leaves a footprint (Figure 7) of the sun’s path on the structure by shrinking the size of the openings along the path where the sun directly hits the structure. This is most obvious in bird’s eye view of the structures generated.

This clearly led to a very wide range of design explorations using a variety opening shapes and sizes for a variety of geographic locations. Domes and shell structures were particularly targeted for this
project as this can provide a more holistic approach to the design of building skins. Forms generated by the system are more suitable for constructing out of relatively homogeneous building materials with plasticity such as reinforced concrete or polymers as the underlying algorithm utilizes solid modeling methods. This however does not mean the algorithm cannot be modified to include more a modular approach which is conceptualized for the next phase of the project.

MATERIALITY AND FORM
Such a variety of opening shapes obviously brings up the question of materiality. For example, the domes seen in Figures 6 (right) and 8 can only be manufactured if they were conceptualized as mono-coque structures where a single isotropic [8] material that can take carry loads equally in all directions is used. Some of the current 3D printing technology may lend itself to manufacturing such a lacy structure. Currently it is already possible to fabricate monocoque structures that have more than one type of material distributed throughout the structure during manufacturing. This technology is evolving rapidly, which will allow for example transparent or translucent material to be deposited in where the openings are located and more opaque material deposited in where more solid looking areas are located. This would be a composite structure that is fabricated all in one shot thorough digital fabrication techniques. Ideas for such composite manufacturing techniques are already being explored at a number of academic institutions (e.g., see MIT, Media Laboratory, [9]).

These designs also intend to challenge the material science field in developing new materials and techniques that can manufacture such complex forms. Therefore, one of the intentions of this study is to challenge the boundaries of traditional thinking regarding materiality. On the other hand, because the algorithm utilizes spherical symmetry in placing the openings along the skin of a given surface, it is possible to adjust the spacing of the openings so that a structural system akin to ribbing (Figures 1, 2 and 6 left) seen in concrete and some masonry structures; or a modular grid system along the skin of the shell can be used to carry the load of the structure. It is possible to modify the algorithm further to generate modular panels that gradually change in overall size, each with a different size opening. These panels can then be assembled to construct the total structure. Obviously digital fabrication techniques will need to be used for manufacturing such a wide range of iterations of design for the panels. This researcher is currently exploring all of these ideas within the scope of different fabrication technologies.

LOOKING FORWARD
As a summary, the generative system titled Solar-Pierce was found to successfully generate openings
in a dome or other selected shell structures based on the sun’s path and the orientation of each opening. The system is being further developed to incorporate a modular system as well as to address issues of materiality and constructability. The implications of the designs generated by the system are being explored for a variety of real world applications, taking into account the fact that a very large number of alternatives can be generated due to the flexibility in the shape of the openings generated and the overall form of the structure.

REFERENCES
Kolarevic, Branco 2003 “Computing the Performative in Architecture”, eCAADe 21 conference Proceedings, Graz, Austria.