AN APPLICATION OF GEOMETRIC MODELING AND RAY TRACING TO THE VISUAL AND ACOUSTICAL ANALYSIS OF A MUNICIPAL OPEN-AIR AUDITORIUM

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ABSTRACT

The APRL of The University of Michigan was recently contracted to develop geometric models of a large open-air auditorium on the Detroit River to facilitate computer aided visual and acoustical analysis. This paper is a summary of the approaches taken to construct solid and surface models of the auditorium, and to develop general software for acoustical simulation.

The project was a cooperative effort between: faculty and students of the APRL; Kent L. Hubbell Architects, a local architecture office; Robert Darvas Associates, a local structural engineering firm; and OC Birdair.

INTRODUCTION

During the past few summers the city of Detroit has provided performing arts concerts in an open air auditorium located in Chene Park on the city's river front. The facility was created as part of Detroit's "Linked Waterfront Parks Project", sponsored primarily by the city with some federal support. The city not only provided the land, but constructed a large tent structure roof and contracted only high caliber performers. As a result of the facility's enormous popularity, the city decided to construct a permanent tent structure, stage, and seating for 5,000.

Late in the design, the APRL was contracted to build a geometric model for computer aided visualization studies. Elaborate solid and surface models were built of the tent structure, tent fabric, stage, and seating, and many shaded perspective images were generated.

Much later in the design the Detroit Symphony requested an acoustical study to help determine whether to make the new auditorium the location of its summer concerts. Again, the APRL was contracted to provide the analysis.

BACKGROUND

Our participation in this project was catalyzed through our continuing contacts with the architects and engineers and through their past and present associations with the College.

Kent Hubbell, the architect and owner of Kent L. Hubbell Architects, is a professor and department chairman in the College. Two of his employees, Scott Downie and Eric Sheppard, were students in the College at the time and had recently completed the CAD Fundamentals course.

Norm Barnett, the acoustical consultant, is a professor in the College and has provided Kent L. Hubbell Architects with acoustical advice on other projects.

Robert Darvas Associates, the engineering firm responsible for the foundations and steel structure, is composed largely of graduates of the College. Robert Darvas is a professor and former department chairman. Kenneth Good, the engineer responsible for this project, is a former classmate of one of the authors.

OC Birdair, the engineering firm responsible for the fabric structure, is a division of Owens Corning and has no ties to the College. However, they became aware of our capabilities some months earlier during a visit to Kent L. Hubbell Architects, during which they toured the APRL CAD laboratory for a demonstration.

Kent L. Hubbell Architects and Robert Darvas Associates have collaborated on many projects in the past, and the APRL has provided small services to both firms on an informal basis. Our involvement in this project began informally – a combination of good will, personal interest, and exhibitionism – but evolved into something more.

DEVELOPMENT OF THE GEOMETRIC MODELS

Kenneth Good had developed an Excel® spreadsheet to analyze the elaborate truss structure over the stage. This structure is arched both vertically and horizontally and contains approximately eight hundred members. Except for left-right symmetry, nearly every joint is unique. He asked about the possibility of modeling the truss in our CAD system, GEDIT (APRL, 1990). Several days later, he wrote the geometric data to a simple text file and delivered it to the APRL on a Macintosh disk. We used a "well connected" Macintosh in the APRL to transfer the text file over the campus network to the Apollo ring in which GEDIT operates. There, we wrote a small program to extract the point and line data from the file, re-cast it as instances of a generic solid cylinder, and write the instance data to another text file in a format acceptable to GEDIT. It was then a simple matter to create three-dimensional raster-scanned images of the structure. These were useful not only for visualizing the design, but also for verifying the geometric data in the original spreadsheet.

Scott and Eric came to the APRL a few days later to review the truss model. Partly because of the complexity of the structure, and partly because of their enthusiasm for the medium, they decided to continue developing a computer model of the entire structure in lieu of a scale model. At this point we started to discuss the possibility of importing the fabric data from OC Birdair. Some time earlier, we had developed another small program to import fabric data from Robert Darvas Associates for an earlier Kent L. Hubbell Architects design, and images of that earlier fabric structure provided some of the inspiration and confidence to pursue this new project.

As luck would have it, OC Birdair performs their fabric analysis on Apollo work stations, using an application with data structures similar to those used by the Robert Darvas Associates application. We were given the name of the computer systems manager at OC Birdair, whom we called to discuss the type of data they could provide and the best means for providing it. Kent L. Hubbell Architects visited OC Birdair shortly thereafter and returned with an Apollo cartridge tape containing structural data for the fabric, cables, and struts. We developed another program to extract the geometric data from this file and re-cast it in a form acceptable to GEDIT. The triangular elements of the fabric were assembled into a single triangulated surface geometry, while

Figure 1.
Truss Structure Model

Figure 2.
View of Seating From Back

Figure 3.
View of Seating From Stage

Figure 4.
Side View of Stage

the axial tensile and compressive members (the cables and struts) were cast as instances of generic lines and cylinders similar to the Robert Darvas Associates truss.

Scott and Eric continued to model other parts of the project directly: the stage platform, backdrop, seats, concrete piers, masts, light fixtures, surrounding site, and other details. They incorporated these, the stage truss, the fabric, cables, and struts into one model using the hierarchical instancing capabilities of GEDIT. They used a standard 35-mm camera and tripod to photograph the CRT screen, and the resulting slides were used in a presentation to the client.

Two parallel developments, though initially unrelated, ultimately contributed to this project: Harold Borkin, a professor in the College and one of the principal figures in the APRL, spent much of his sabbatical working with Ardent Computer to incorporate GEDIT's core solid modeling routines into the Dynamic Object Rendering Environment (Doré) of their graphic super-computer; and the University began to develop an interdepartmental "Advanced Visualization Laboratory" which came to include an Ardent Titan, several Apollos, and an assortment of other graphic work stations, video recorders, and printers. Shortly after the Ardent was acquired by the University, Harold Borkin installed the experimental version of our solid modeler that he had developed during his sabbatical. Some time later, when Scott and Eric had nearly completed their model, it was ported to the Ardent for "advanced visualization" in the Doré environment, which provides high-resolution, true-color, real-time rendering with multiple light sources and perspective views controllable from a dial box. Ultimately, the APRL acquired its own Ardent computer through an independent research and development arrangement with the manufacturer.

DEVELOPMENT OF THE ACOUSTIC SIMULATION

The algorithms, mathematics, and measurements used in this simulation follow closely to those presented in the SIGGRAPH '89 paper by Adam Stettner and Donald Greenberg titled, "Computer Graphics Visualization For Acoustic Simulation" (Stettner and Greenberg, 1989). It is not the goal of this paper to re-invent; instead, we are presenting an application of theoretical research to a real design problem. Our contribution is in the integration of state-of-the-art acoustical simulation algorithms with an existing geometric modeling and computer graphics system, and in a demonstration of cooperation between research, practice and education.

Norm Barnett had analyzed the acoustics of previous structures by Kent L. Hubbell Architects (and others) through the use of scale models and laser beams. Since no scale model existed for this project, but an accurate and fairly complete computer model did exist, it was proposed that a computer program be developed to analyze the geometric model, using ray-tracing techniques derived from image synthesis, and lighting and thermal simulation.

Instead of developing software specifically for this application, we decided to write a general ray-tracing program based on two sets of GEDIT geometries: those which act as reflecting surfaces, and those which act as receiving, or destination surfaces. This decision allowed us to use the same models for both visualization and acoustical analysis, and allowed us to make quick changes using the modeling tools of GEDIT. And although two applications using the same model is not quite an integrated data base, there are advantages in data consistency and reduction in modeling time.

GEDIT supports surfaces as sets of 2-d and 3-d polygons, and supports solid models as polyhedrons. For this application the polygons of the roof fabric, stage, and backdrop were used directly as the reflecting surfaces, and simplified polygons resembling the seats were created as the destination surfaces. (A more detailed solid model of the seats was used for visualization.)

The "ray" in this application is used to model a small "packet" of sound, or a small portion of a wave front leaving the stage and eventually landing in the seats. A large quantity of rays leaving the stage at uniformly random directions is used to simulate an instantaneous "blast" of sound. (Many arguments for using a ray, or straight line, as a geometric approximation of a sound wave can be found in the literature.) The quantity and quality of rays terminating at the destination surfaces can be helpful in understanding the impact of the shape, location, and material of the reflecting surfaces, the location and orientation of the destination surfaces, and of the location and direction of the sound sources. From a programming perspective, the mathematical formulation of a line allows it to be easily stored, transformed, reflected, and intersected with other lines and polygons.

For this simulation it was decided that the reflecting surfaces would do nothing more than redirect a ray with the angle of incidence equal to the angle of reflection. This assumption removed all possible diffraction, diffusion, and absorption due to the quality of the reflecting surface. We also decided to eliminate attenuation, and to ignore possible ray interference and differences in reflection related to frequencies. A future version may simulate these characteristics.

A "ray source" file format and matching data structure was developed to allow for the definition of single or multiple rays. Currently, a source can radiate rays only in a spherical pattern from a specified X,Y,Z location. Future versions will allow cylindrical, and conical patterns. Ray directions are limited by latitude and longitude values, and can be generated in a random or uniform pattern. The number of rays emanating from each source is also specified.

```
SPHERE              (Ray source type)
RANDOM
   0.,  7.,  14.,   (origin of source)
   0., 360.,        (longitude begin and end angle)
  15., 135.,        (latitude  begin and end angle)
  10000,            (number of rays)
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<u>Figure 5</u>
Ray Source File

This pattern was repeated in the file, with different origins, to generated rays from multiple ray sources.

RAY TRACE ALGORITHM

The algorithm proceeds as follows:

1. Each reflecting surface is "triangulated" and stored. Currently this includes the fabric roof, the stage platform and the backdrop. A triangle is used because it requires only a simple

internal data structure and because it is convenient to manipulate (algorithmically easy to search for, mathematically easy to bounce rays off).

Figure 6.
Triangulated Reflecting Surface
(Fabric Roof)

2. Each destination surface is triangulated and stored. Currently this is only the seating area. Triangles are used for the destination surfaces because: it is simple to divide any arbitrary shape into a set of almost equal sized triangles; and it is desirable to collect data by uniform area. The destination surfaces accumulate the acoustical data and terminate the rays.

Figure 7
Destination Polygons before Triangulation
(Equal Sized Seating)

3. Individual rays are projected within the specified latitude and longitude limits. The sound rays are actually straight lines at a fixed (but randomly determined) orientation. The lines are infinitely long and only terminate when they reach a destination or disappear.

Figure 8.
Sample Random Ray Pattern

Figure 9.
Random Rays with Roof, Seating and Stage

4. A ray either: a) immediately reaches a destination triangle; b) reflects off one or more reflecting triangles, and then reaches a destination triangle; c) reflects off one or more reflecting triangles, and disappears; d) or, immediately disappears.

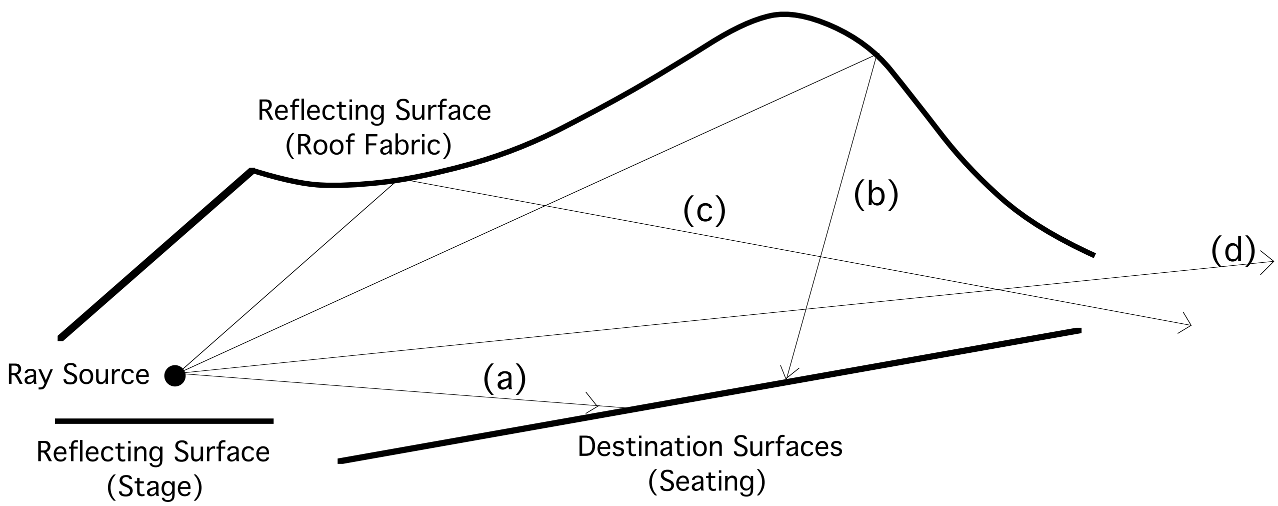

Figure 10.
Ray Classification

CURRENT SIMULATION

The Chene Park simulation consisted of 14 spherical ray sources placed two feet apart, across center stage, with each ray source generating 5,000 rays. A second simulation using a single spherical ray source generating 100,000 rays produced similar results.

Currently, the data collected and displayed for each destination triangle is:

1. The time of the earliest direct ray (D_{time}). The direct, non-reflected distance from the centroid of each destination triangle to the nearest source is found.
2. The time of the earliest reflected ray (R_{time}). For a typical simulation of this type, many reflected rays hit each destination triangle. Most reflected rays arrive at the destination at different times. It was decided that the time of the arrival of the earliest reflected ray had the most acoustical significance. (The pattern, duration, degradation, and direction of all reflected rays are also important, and will be accumulated and displayed in future versions.)

3. The time interval between the earliest reflected ray and the earliest direct ray ($GAP_{time} = R_{time} - D_{time}$) is an indicator of sound clarity.
4. The sound strength. As an estimate of sound strength, the quantity ($1/distance^{2}$) is accumulated for the earliest direct and all reflected rays hitting each destination triangle. Because sound strength, as it relates to sound quality, must be quantified relative to time, future versions will collect sound strength by time intervals.

The software was developed and tested on an Apollo DN 4000. The initial test case was of a single ray source at center stage generating 10,000 rays. The program generated approximately 1,000 rays per hour. The code, GEDIT geometries, and ray source file were finally ported to an Ardent Titan computer where approximately 8,000 rays per hour were generated.

DISPLAY OF RESULTS

The results of the simulation are in a form compatible with a GEDIT assembly (of geometries) construct called an INSTANCE TABLE and, therefore, can be displayed through the graphic output capabilities of GEDIT. Each destination triangle is drawn and shaded according to the value of the displayed variable (earliest direct time, earliest reflected time, gap time, power). The results are shown in plan view but any parallel or perspective view can be displayed (as in Figure 13). The title and legend are generated automatically. A view of the fabric model has been added to aid interpretation.

<u>Figure 11.</u>
Time of Earliest Direct Ray

As we expected, because of the conical-like arrangement of the seating, the pattern of earliest direct ray times is uniform showing an increase in time as the distance from the stage increases. The legend shows a range of times between 18 and 180 msec.

<u>Figure 12.</u>
Time of Earliest Reflected Ray

The time of the earliest reflected rays follows a similar pattern with subtle variations due to the geometry (peaks and valleys) of the roof fabric. The legend shows a range of times between 88 and 240 msec. The blank and dark triangles at the far edges and back center of the seating suggest that few or no rays hit because of the shape of the roof fabric (or the fact that no fabric overhangs the seats). The dark triangles indicate that a reflected ray did hit but was very long, perhaps traveling through a protracted path, bouncing from surface to surface.

We assumed (at least some of us did) that the dark triangle near the back left edge of the seating was an anomaly — just a random orphan who collected few reflected rays. We will look into this as a possible ray tracing error as soon as time permits.

Figure 13.
Time Interval Between Earliest Direct and Earliest Reflected
Isometric View

The legend shows a range of interval times between 4 and 87 msec. Because the seats to the far right and far left are furthest from the stage, the time interval is small – it takes a long time for both earliest sound rays to reach them. The seats closest to the stage have the largest interval because the direct rays arrive so quickly and the roof is sloping upwards at a fast rate and not reflecting sound downwards.

Figure 14.
Sound Strength

We have not yet provided units for sound strength and are therefore using it as strictly a qualitative measure. There are patterns there but we currently don't know how to interpret them. They may coincide with the valleys in the roof fabric.

VALIDATION

This project is still active in that we are still writing code in response to Norm Barnett's advice. We validated the ray generation and reflectance algorithm and mathematics, but had time for only "seat-of-the-pants" validation of the results. A more formal validation will be performed when real measurements can be made after completion of the project this spring.

CONCLUSION

Like many real architectural projects Chene Park has suffered from administrative and funding problems. The APRL learned in June that the City of Detroit would not fund further acoustical analysis. This meant that the final debugging (fine-tuning) of the program and the final analysis would have to wait. In the meantime, to validate the program, we will model an existing local performance hall, perform our acoustical simulation and test the results against real measurements. We will also include an acoustical simulation assignment using this software as part of our CAD Fundamentals class.

REFERENCES

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