FABPOD: AN OPEN DESIGN-TO-FABRICATION SYSTEM

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Abstract. Digital workflows from the design to the production of buildings have received significant recent attention in architectural research. The need for both integrated systems for design collaboration (Boeykens and Neuckermans, 2006) and clear and flexible communication flows for non-standard fabrication outcomes have been identified as fundamental (Scheurer, 2010). This paper reports on the development of a digital “design system” for the design and prototyping of an acoustic enclosure for meetings in a large open work environment, the FabPod. The aim was to keep this system open for temporal flexibility in as many aspects of the finalisation of the design as possible. The system provides novel examples of both integrated collaboration and clear communication flow. (1) Acoustics is included as a design driver in early stages through the connection of digital simulation tools with design models. (2) Bi-directional information flows and clear modularisation of workflow underpins the system from design through to fabrication and assembly of the enclosure. Following the completion and evaluation of the FabPod prototype, the openness of the system will be tested through its application in subsequent design and prototyping iterations. Design development will respond to performance testing through user engagement methods and acoustic measurement.

Keywords. Digital workflow; prototyping; acoustic simulation; collaborative design.

1. Introduction

The FabPod is the second iteration in a progression of research exploring the acoustic properties of doubly ruled, specifically hyperboloid surfaces. The
research stems from a hypothesis, based on anecdotal evidence from Antoni Gaudí’s Sagrada Família church, that hyperboloids are effective diffusers of sound. This hypothesis was initially tested by constructing a prototype wall from hyperboloid shaped plaster bricks as part of the Responsive Acoustic Surfaces (RAS) cluster at SmartGeometry 2011 (Burry et al., 2011) (Figure 1, left). Building upon the promising outcomes of these experiments, in this iteration we explore whether hyperbolic surfaces can be employed to create a meeting room that satisfies auditory and acoustic criteria – the FabPod (Figure 1, right).

Both the collaborative nature of the project as well as the opportunity for an ongoing series of design iterations led to the conception of a generic “design system”. The system itself was prototyped as part of its development before application to the full-scale fabrication process. It was underpinned by a holistic conception of a workflow, from early schematic stages through to the complete fabrication of the prototype. A series of digital tools are central to the workflow, however it is also designed around manual assembly processes for quality of finish. In such contemporary projects engaging design processes, geometry and fabrication technologies which are non-standard, it has been well documented that digital workflows have significant impact on both the richness of design potential and quality of the built outcome (Marble, 2012).

2. Background

2.1. RESPONSIVE ACOUSTIC SURFACES

The Responsive Acoustic Surfaces (RAS) cluster at SmartGeometry 2011 demonstrated the potential for acoustically reflective surfaces to act as sound diffusors
when they have a hyperboloid shape (Burry et al., 2011). As part of this cluster a full scale wall prototype was developed from plaster hyperboloids supported by a plywood frame. The wall was semi-circular in plan, a shape known to be acoustically challenging since all the reflected sound is concentrated at a central focus point. However, the wall with this surface articulation had a perceptible impact on the diffusion of sound when compared to a smooth wall of the same overall curved geometry. The hyperboloids were distributed in a regular pattern across the wall in order to simplify both the acoustic measurements and the construction of the plywood frame (by standardising the brick shape). Even though the wall shape and hyperboloid distribution was relatively straightforward, the researchers still encountered challenges both in calculating the intersections of the hyperboloids and designing a satisfactory construction paradigm.

While the hyperboloid wall from the RAS cluster was ideal for demonstrating sound diffusion, research by Peters and Olesen (2010) suggests sound diffusion can be improved further in practice by minimising periodic tessellation of the surface pattern. This was tested through the 1:10 scale modelling in the workshop to test scattering coefficients.

2.2. THE FABPOD BRIEF

The physical context for the FabPod exercise is an open knowledge work environment within a new faculty building in the University. The architectural brief called for a space that could comfortably seat 8 people. Complete acoustic privacy within the enclosure was not required. Rather, the brief was to provide a significant barrier to sound transmission into and out of the meeting area and an internal acoustic that was conducive to small meetings. The research team proposed that a design that combined partial acoustic absorption with a degree of sound scattering would be an appropriate response to this brief. It should provide some sound reduction close to the source, good speech intelligibility without loud and quiet spots and a space that would remain bright and lively rather than suffering the deadening effect of excessive sound absorption (Bradley, 2009). By deploying absorbing materials and forms for sound scattering on the outside of the structure, it should improve the auditory experience of the surrounding workspace (Petersen, 2008).

Importantly, the brief was based on the understanding the project proposed a prototype, a structure that might be evaluated to extend the project to further briefs and similar structures. The brief was in some regards highly generic, situated within a common context. It was clear that a design system was required that was sufficiently flexible and open to be applied to range of scenarios, a system that could be used to design a series of unique but related structures in response to the research findings from the evaluation of the first.
3. Aims – Temporal Flexibility in Design

Common to standard architectural projects, the most fundamental requirement of the workflow is the clear and consistent flow of information in a ‘downstream’ direction (Williams et al., 2011). This follows a chronological project sequence from early design proposals, through to models with greater levels of detail and the further communication of the required information for fabrication.

Contrasting such a linear model, the FabPod project required temporal flexibility in order to address the acoustic design imperatives as well as facilitate the desired fabrication quality. The central aim was the ability to defer decisions where further research and testing would be of benefit, without halting the work on other aspects of the project. This was dependent on a workflow which would incorporate a very clear set of geometrical constraints as well as programmatic considerations, materiality, and fabrication and construction constraints. It was a requirement that information be communicated upstream in two broad forms: (1) as knowledge resulting from acoustic simulation fed back into early stage design and; (2) as a series of parameters and limits relating to the fabrication, in order that the design met a series of requirements consistent through the process (Figure 2).

While such a design system shapes a clear design space, it should allow significant design flexibility within this constraint system. For instance, while the final form was constrained to a given number of types, in this case comprised of intersecting segments of spheres, further detail of the room should be able to be deferred until the commencement of fabrication, as detailed custom components, assembly and fabrication design are already fully developed. Once identified, such constraints provided significant temporal flexibility. However, this also demanded the identification of constraints which were sufficiently broad enough so as not be overly deterministic both architecturally as well as in significant variation relating to performance criteria, here primarily acoustic.

![Diagram showing workflow elements and information flows required for the FabPod.](3A-135.png)

Figure 2. The broad workflow elements and information flows required for the FabPod.
The research did not seek to either propose or engage a holistic software environment in which all aspects of the design exercise could be integrated. While there has been widespread speculation on such integrated packages and so-called ‘collaborative platforms’ proposed (Boeykens and Neuckermans, 2006), a package suitable to the project’s drivers and providing adequate flexibility could not be identified. We aimed instead to connect the software packages and specialised tools of the involved collaborators within the workflow.

Underlying this was a strong consideration of how the workflow might be modularised. The aim was for a collection of components which could be easily adjusted, exchanged or even bypassed as required without disrupting broader project continuity. The conception of such a modular workflow requires the clear definition of appropriate interfaces defining inputs and outputs. These must be intelligently conceived so as not to be overly complex but to allow for a degree of flexibility, even if this involves maintaining a degree of redundancy (Williams et al., 2011). Further research has shown that the division of models into modular stages greatly improves the overall legibility of a project (Davis et al., 2011).

4. Methodology – The Design System

4.1. ACOUSTIC SIMULATION IN DESIGN

We developed a series of design tools for the early design stages. These comprised parametric models governed by the generic rules of the geometric system of intersecting spheres and hyperboloids. The models were organised according to a clear set of processes for an individual designer to address the overall form, surface patterning and distribution of surfacing materials across a given design geometry (Figure 3). They respond to a common structuring of acoustic simulation software in which building geometries are commonly presented as simplified geometries, to which coefficients are attached to represent the acoustic properties such as the reflection, absorption and scattering of sound.

The first of these models addressed the overall form of the enclosure. This utilised the geometric constraint of planar intersections between hyperboloids to identify a finite set of design spaces which might utilise either planar or spherical geometries to set out the overall form of an enclosure. The acoustic properties of planar surfaces, including those with highly articulated surface geometries, have been well researched and so we focused on spherical geometries.

The second model created the surface pattern. The distribution of hyperboloid surfaces was controlled by the distribution of a set of points, each corresponding with the position of centre point of the collar of the circular hyperboloid with the parent surface. The solution space for distributing the
pattern points was so discontinuous and in the end we used a UV mapping to wrap a two-dimensional distribution of points onto the surfaces. The pattern was then created with a spherical voronoi algorithm written specifically for this project (http://parametricmodel.com/SphericalVoronoi/67.html). The final model transforms the planar pattern into hyperboloid geometry. This involves both generating and trimming the hyperboloids to create a single undulating surface. In the RAS workshop it was found that intersection algorithms built into Rhino, CATIA, and OpenCascade would often take many minutes to trim the hyperboloids, which limited the speed of design iterations. In FabPod we instead derived a formula for finding the intersections of the hyperboloids with an averaged intersection plane. This was achieved by taking the formula for a hyperboloid:

\[
\frac{x^2}{a^2} + \frac{y^2}{b^2} - \frac{z^2}{c^2} = 1
\]

And the formula for a line:

\[
\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} i \\ m \\ p \end{bmatrix} + \begin{bmatrix} f \\ n \cdot t \\ q \end{bmatrix}
\]

And then eliminating $x, y, z$ and solving simultaneously for $t$:

\[
t = \frac{-2 \cdot (c^2 i^2 + c^2 m^2 - c^2 p^2) \pm \sqrt{(2c^2 i^2 + 2c^2 m^2 - 2c^2 p^2)^2 - 4 \cdot (c^2 i^2 + c^2 m^2 - c^2 p^2) \cdot (c^2 i^2 + c^2 m^2 - c^2 p^2) \cdot (p^2 + c^2) \cdot 1}}{2c^2 (p^2 + c^2) - 2c^2 p^2}
\]
4.2. FABRICATION WORKFLOW

Underpinning the fabrication of the Pod is the division of the system of ‘cells’, hybrid components which can be fabricated individually and subsequently assembled in place. This system is a direct extension of that utilised in the RAS workshop and considered a successful fabrication for its suitability to manufacturing from standard material sizes and which can be handled by a single person. Each cell comprises a timber frame with hyperboloid and planar faces on opposing sides (Figure 4). In the final assembly, these hyperbolic faces are the visible and are the acoustically designed surfaces of the pod. The frame, though hidden when complete, provides structure, geometric definition for ease of fabrication and assembly as well as acoustical separation through the provision of mass.

The final pod is comprised of a series of cells with simple bolted connections between frames. Allowances were needed for machining and fabrication tolerances between cells and these were included as ‘spacers’, the thickness of which could be adjusted up to 0.5 mm, a measure typically associated with furniture. In the final assembly these pieces are read as shadow lines.

It was vital to model the assembled components as a full digital prototype to check the outcome – the exact geometrical relationships are difficult to predict. This would also be used as the basis for extracting the fabrication and construction information for cutting and forming. To avoid burdening the design model with the large amounts of information needed for the detailed prototype, an independent model was developed in Dessault Systemes’ Digital Project. Design data was communicated from the design model to it through a neutral comma-separated within an agreed interface. This model was a key aspect of the larger modular workflow, however, further details are outside the scope of this paper.

Figure 4. The basic components for the fabrication of a ‘cell’.
Taking geometry from both this detailed model, as well as geometrically simple items from the design model, a modular workflow was created to extract information required for the fabrication and assembly of components.

5. Results

Broadly, the workflow has proved sufficiently open to meet project ambitions to this stage. A week-long workshop intensive engaging students and practitioners with researchers explored an expansive set of design possibilities. The following week, the fabrication of the full-scale prototype commenced. The enclosure was successfully fabricated and assembled within the proposed timeframe of four months.

5.1. ACOUSTIC SIMULATION DRIVING DESIGN

The design workflow, bringing together a series of parametric models with several acoustic software packages including Pachyderm, a plugin for McNeel Rhinoceros and Odeon, a commercial room acoustics package. This provided an accessible and rapid generation of proposals at varying levels of detail and the testing of acoustic implications. As the models were parametric, the feedback at each stage could be rapidly incorporated allowing the model to be iteratively developed towards acoustic performance criteria, including targets for reverberation time and surface scattering coefficients. Alternatively, if acoustic simulation showed the design had limited functional characteristics, the divisions between stages made it easy to revert back to a prior design state and revisit the underlying causes. This ability to push the design backwards and forward between stages of development meant that the design team had the best knowledge and feedback to make these decisions.

Further, since each model functioned independently with well-defined interfaces, an instance could be easily replaced without disrupting the downstream or upstream models (provided the replacement model accepted and produced the prescribed geometry). As a key example, we experimented with a range of techniques for distributing the points that generated the patterned surface. We tried everything from dynamic relaxation, to circle packing, to swarming algorithms. Each time we tested a technique we swapped it into the overall design chain, which was simply a matter of importing the required geometry from the previous stage and creating the prerequisite geometry of the subsequent stage. If a monolithic model had been used, making such major changes to very fundamental aspects of how the design was created would have required significant modification of the model.

The focus on developing sophisticated and computationally cheap algorithms for key problems allowed for the design and feedback loop to occur within an acceptable timeframe. A maturing of this system could provide for the further
automation of key measurements to reduce this time. A level of this automation could conceivably be achieved without compromising the temporal flexibility of decision making, for instance a chain automating the calculation of sound reverberation times at given locations.

5.2. PROTOTYPING FLEXIBILITY

We have been able to apply the workflow to complete the prototype despite shifting logistical requirements and prototyping decisions made late in the process (Figure 5). We achieved the desired tolerances of less than 0.5mm and the material qualities and finishes are to a satisfactory level for the project leaders.

Significantly, the modular workflow allowed for the deferral of key decisions to accommodate for both the testing of component detailing and open logistics in the final delivery. The former of these is demonstrated by the development of assembly details for the timber frames. Holes in the central plate of the frame, found to be needed for access for assembly and fixing in construction, required additional laboratory transmission testing to clarify their impact on acoustic transmission. Details of the frame were left open to allow for testing of the machining tolerances and the assembly of parts within acceptable tolerances.

An example of the latter aspect, open logistics, was the final selection of a machine capable of achieving 5-axis cuttings at varying angles. While several machines had been identified, their availability and ability to handle the technical requirements could not be confirmed until well into the prototyping process. It has been well noted that CNC machines from different vendors require different G-code formats (Scheurer, 2010). As the machine was not selected until late in the process, tool paths were encapsulated in the generic APT file format which could be post-processed for a specific machine.

Figure 5. Images of the completed FabPod prototype.
6. Conclusion

This paper presents a modular workflow for a design system that is open in providing for temporal flexibility in as many aspects of the project as possible within a given constraint system. Most significantly, the workflow allows for the integration of acoustics as a design driver and the deferred finalisation of overall form and surface patterning to allow for as much acoustic testing and understanding of acoustics as possible. Testing and trials for the physical detailing of the FabPod also involved a high degree flexibility to allow for a refinement and development of fabrication strategies. The modular workflow allowed for aspects to be altered or exchanged without compromising the overall outcome of a full-scale prototype. This workflow will be further evaluated in application to future Pod design development and prototyping. The design will be developed in response to auditory and ethnographic testing through interaction with users and acoustic measurements on site.

Acknowledgements

John Cherrey contributed significant expertise to the project outside the scope of this paper. Further, a group of 16 students and 4 practitioners were engaged in a five-day intensive workshop and subsequently in fabricating the prototype. The project received funding from The Property Service Group and The Design Research Institute at RMIT University as well as The Australian Research Council through its support of the ARC Discovery Grant Challenging the Inflexibility of the Flexible Digital Model.

References