DIGITAL FABRICATION FOR RETROREFLECTIVE CEILING TREATMENT

Reducing Speech Distraction in an Open Work Environment

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Abstract. This paper presents a case study for the production of retroreflective ceiling treatment in an open work environment. In this setting with multiple talkers, speech distraction can be a significant cause of dissatisfaction and loss of productivity. Ceiling treatment in open plan work environments can provide an important way of ameliorating distraction from unattended speech, and rather than absorbing the sound at the ceiling, this paper examines the possibility of reflecting sound back to the source. Computational design and digital fabrication are integrated in this research for a site-specific deployment of the ceiling treatment and physical testing of prototypes in an acoustics laboratory. The contemporary possibilities that open up with new technologies to understand and resurrect faceted geometries and potentially vary historical precedents via new manufacturing techniques are demonstrated in these novel acoustic reflective ceilings that reflect sound back to their original source.

Keywords. Acoustic Ceiling Treatment; Computational Design; Digital Fabrication; Faceted Geometries; Retroreflection.

1. Introduction

This paper outlines a digital workflow for the design, fabrication and testing of multiple ceiling arrangements and spatial conditions for a client to minimise speech distraction in an open workspace. A series of timber prototypes are tested for acoustic retroreflectivity as indicated by computer simulations and physical testing on modular clusters of regular and irregular forms arranged in cubic or triangular trihedral arrays of concave right-angle corners. A fluent information transfer sits at the core of the research, from computational design-to-generated code for CNC and multi-axis robotic milling which potentially streamlines the production of non-standard, complex geometries. A series of comparative analyses is conducted for acoustic testing in digital and physical scenarios, as well as between standard non-conditioned surfaces and acoustically conditioned
surfaces. This case study demonstrates that we can rely on computational design to explain variant complexities (Naboni, Paoletti, 2015, p. 154) for production and performative testing.

2. Background

2.1. SOUND REFLECTION: WHY RETROREFLECTION?

Very commonly, acoustic conditioning in multi-talker environments is achieved by ‘acoustic tiles’, which offer a high degree of sound absorption so as to minimise the sound reflected from the ceiling. Minimising ceiling reflections can increase the spatial decay rate of speech, thereby increasing privacy and reducing speech distraction and the build-up of noise. However, a side-effect of this is that the space becomes ‘dead’. The client of this research project desired a ‘live’ sound environment in an open workspace. Another common ceiling treatment (or lack thereof) is a hard flat ceiling, which produces mirror-like reflections, which can contribute to speech disturbance over distance. Alternatively, a sound-scattering ceiling produces reflections in all directions from everywhere. This is often beneficial in critical listening spaces, such as sound studios, rooms for music; and in other situations where echoes can be a problem in auditoria, and roadside noise barriers.

The concept of a retroreflective ceiling is that it returns the sound to where it came from. This has the potential to provide a feeling of acoustic support to a person who is speaking, which can make communication more comfortable, and lead to a more relaxed vocal effort (Brunskog et al., 2009). It also has the potential to reduce disturbance to others somewhat similarly to an absorptive ceiling by reducing disturbing reflections. However, as a retroreflective surface does not absorb much sound, it engenders a ‘live’ acoustic environment.

Extensive research on retroreflective forms for optics and radar has been implemented to various devices, e.g. trihedral corner reflectors (e.g., Eckhardt, 1971) and sheeting, but is lacking in architectural acoustics. Notable ceiling designs act as architectural precedents to this research, which could be retroreflective if their geometric systems were slightly altered. These include hexagonal prisms in the Harpa Foyer, Reykjavik, and non-right angled tetrahedral cavities in the Yale University Art Gallery & National Gallery of Australia, where had these systems been right-angled trihedra they would achieve acoustically retroreflective ceilings. However, there are some architectural precedents for acoustically retroreflective facades, most strikingly the Ports 1961 Flagship Store building (Shanghai) façade, which uses 300 mm glass cubes (Barr, 2016). However, acoustic retroreflectivity appears to be unintentional in that design. This research identifies a growing link between faceted geometries and architectural acoustics.

2.2. FACETED GEOMETRIES

To test base geometries for acoustic retroreflection, inspiration is drawn from the historic quad-subdivision of geometries in vaulted structures, notably found at the Alhambra Palace in Granada, c. 1200’s. The muqarnas shown in Figure 1,
a technique characterised for ornamental vaulting consisting of intricately-tiled structures (Castera, 2003), is not purely aesthetic but also structural. Ideally, the more ornate these 90-degree facets are, the more weight they can support (Schlager & Lauer, 2001), lending to the notion that function (as load-bearing support) and form (as ornament) are synonymous. Where ornament is intrinsically linked to structural performance in the Alhambra, the concept that faceted geometries drive functionality is paralleled in this research in the exploration of customised retroreflective surfaces for acoustic performance.

Figure 1. Muqarnas column and arch at the Patio de los Leones, Granada.

3. Variable Geometries for Acoustic Retroreflection

A trihedral array is examined as the principle geometry for this alternative approach to ceiling treatment in Figure 2a. There are two simple solutions to tessellated trihedra, one with square faces (hexagonal tessellation) and the other with triangular faces (triangular tessellation). While the regularity of these is limiting from an architectural design perspective, intermediate solutions between these extremes allow for a variable geometric design. This research conducts iterations using computational design to make variations to the ‘square’ and ‘triangular’ trihedra: if not to their cluster arrangements then to their corners. Immediately, a 90-degree inversion to the convex corner of the ‘square’ is realised from the geometric principle of the ‘triangle’ for different lengths of folding in Figure 2b. The two shapes nevertheless share the same principle, only differing by the length of an inverted fold to the convex corner. The inversion of all convex corners which initially offer little by way of acoustic performance or aesthetic quality now double the number of retroreflective corners.
The parametric design of different types of triangles solves ceiling height constraints and aesthetic appeal where the folding of all convex corners push back the lengthy protrusions of a standard trihedral array. The variable geometry contributes to the trade-off between the size and number of retroreflective corners. Right-angled folds made to all convex corners can be shaped into equilateral, isosceles and scalene triangles, where equilateral is the most regular surface; an isosceles can point in the same direction for an informed or directional visual effect; and scalene is the most irregular given that all sides are unequal. An irregular scalene pattern would be the most effective for a live space in a work environment as the source angle of a speaker’s voice can come from any location in plan and/or elevated height. Grasshopper is used in Figure 3 for a mass deployment of 450 mm and 550 mm modular-sized iterations for comparison, and algorithmic adjustments to the secondary triangular folds and ‘culling’ of modules where suspended ceiling services and structure would not permit them.
4. Acoustic Rationale, Testing and Results

Acoustic design of a retroreflective ceiling treatment requires a balance between the size of each reflector and the number of reflectors per unit area. The best solution is likely to depend upon ceiling height: a lower ceiling will benefit from more densely packed smaller reflectors. Simply put, the energy of the retroreflection focus depends on the number of simultaneously visible concave corners (or full faces), but is highly frequency-dependent, with larger reflectors extending the effect to lower frequencies. To be effective for speech in a multi-talker environment, the aim of the treatment is to reduce intelligibility of others’ irrelevant speech (Virjonen et al, 2007). Fortunately, consonant phonemes, which often have distinctive features in the high frequency range, are much more important than vowel phonemes (which have main distinctive features in the mid-frequency range) for speech intelligibility. Therefore we aimed to provide retroreflection from 1 kHz and above through the ceiling treatment, which should substantially affect the most important part of the spectrum for intelligibility (and hence distraction). Hence wavelengths of around 344 mm and smaller should be retroreflected, which implies that the reflector appertures need to be at least this size, and preferably larger (Ichikawa, 2004).

Initial tests were done using regular arrays of 10 square and 9 triangular trihedra, with 300 mm edge lengths, made from timber. Measurements were made with the sample at the equator of a hemispherical (2.1 m radius) 196-loudspeaker array in a highly sound-absorptive environment, described by Cabrera et al. (2015). Figure 4 shows an example of the distribution of reflected sound energy in mid-to-high frequency octave bands. Retroreflectivity is summarized by the amount of reflected energy returned to the source ($L_{\text{retro}}$) and by the retroreflective directivity index (DI), which is the ratio of this to the average energy over the whole hemisphere, expressed in decibels.

![Figure 4. Spatial distribution of octave band reflected sound energy received at a normal incidence microphone from 196 loudspeakers distributed over a hemisphere, using a square trihedral array (top row) and triangular trihedral array (bottom row) with 300 mm edge lengths. Values are in decibels, normalised to the greatest value. Mesh intersections indicate loudspeaker positions (using stereographic projection of the hemisphere onto a plane).](image-url)
Results indicate that the 300 mm edge regular arrays are strongly retroreflective in the 4 kHz and 8 kHz octave bands, moderately so at 2 kHz, and weakly at 1 kHz. The triangular array reflects less sound because it is smaller, because it has 9 corners instead of 10, and because the corner reflectors have smaller effective apertures. Results suggest that larger retroreflective elements would be beneficial for controlling speech consonants, as intended. Doubling the edge lengths would transpose reflection patterns down by one octave, which would better achieve the desired effect. Following this, two irregular prototype samples were constructed, one with a base edge length of 550 mm (with 7 retroreflective corners), and the other 450 mm (with 4 retroreflective corners). Some results for the larger 7-corner prototype are presented in this paper.

The reinforcement of the sound of one’s own voice by an acoustic environment can be quantified in terms of the acoustic parameter ‘voice support’, STV. This is the ratio of reflected sound energy to direct sound energy transmitted from mouth to ears of a head and torso simulator (HATS), expressed in decibels (Pelegrín-García, 2011). Measurements of STV were made in an anechoic room, using a Brüel & Kjær 4128C HATS, oriented such that the reflector acted as either a ceiling or wall element (Figure 5), at 1 m intervals up to 4 m from the reflector.

Overall STV values for the ceiling configuration are -13.3, -18.7, -21.3, and -23.8 dB at distances of 1, 2, 3 and 4 m from the reflector respectively. For the wall configuration, values are between 3 and 5 dB greater (-8.2, -15.3, -18.3 and -19.9 dB), this increase mostly due to the directivity of the mouth. Considering that these measurements were made in an anechoic room with one reflective surface, the values are quite high - by way of comparison Pelegrín-García (2011) reports values ranging between -14.9 to -9.8 dB for various non-anechoic rooms. If the surface was extended to a larger array of retroreflectors (e.g. a whole ceiling or wall), STV values would likely increase considerably, especially for more distant positions. As a first approximation, if constant aperture and incoherent summation are assumed, each doubling of visible corner cubes in a retroreflective surface should increase STV by 3 dB. In a real room STV would be supplemented by reflections from other surfaces (e.g., floor, furniture, walls, and general reverberation).
The aforementioned STV values are averages of the 125 Hz - 4 kHz octave band values (Brunskog et al. 2009), and so are not influenced by the very high frequency range. However, for this retroreflective surface, voice support values are particularly interesting as a function of frequency. Figure 6 shows a steep increase in octave band voice support over 1-8 kHz for both ceiling and wall spatial configurations. An increase in voice support peaking at 8 kHz is usual in room measurements, because of the increasing voice directivity at high frequencies, but the increase in these results is about 5 dB greater than typical.

In cases where the value exceeds 0 dB, this means that the energy in the reflected sound is greater than that of the direct airborne sound from mouth to ear (even though the reflected sound has travelled some metres).

Figure 6. Octave band voice support, measured at four distances from the 550 mm timber physical model: as a ceiling element (left) or wall element (right).

5. Discussion

The adoption of digital workflows for variable control of the same fabrication process can effortlessly produce different outcomes for design variations, keeping costs and production times low to achieve a non-standard architecture (Carpo, 2011, p. 97). This research will continue to investigate different work and spatial conditions from mid- to high-ceiling spaces, and their relationships to retroreflective elements, as well as the possibility to hybridise the geometries discussed in this paper with acoustic absorption, and other non-physical factors, such as light scattering. Cost-effective digital production processes are shown to make cross-disciplinary outcomes and mass customisation efforts easier to achieve, while further applications to this research can involve climatic zoning for room transitions (Willmert, 2011, p. 159) and light conditions, reminiscing traditional stone architectures. Digital fabrication can afford an efficient, rapid and precise contemporary approach to the realisation of complex, structural and ornamental surfaces such as those found at the Alhambra; albeit considering the context of today’s labour market. Their complex carved geometries inspire a continuous workflow of geometrical rules, acoustic simulation, and digital fabrication and the assembly of components in this research.
5.1. FURTHER WORKS

The faceted prototypes in this paper were developed with plywood as full-scale prototypes for physical testing. Generated code will later be translated into multiple toolpaths using KUKA PRC for multi-axis milling and hot wire cutting of these modules. Recently, the significance of cost-effective robotic foam cutting for rapid prototyping has been recognised (Brooks & Aitchison, 2010, p. 318) particularly for full-scale physical representations prior to the final production of stone. The extra degrees of freedom of a multi-axis robot achieves larger architectural volumes when compared to traditional CNC machines. While both processes are subtractive, the time factor is significantly minimised when replacing CNC milling or cutting (Naboni & Paoletti, 2015, p. 51), and robotic hot wire cutting deposits reusable volumetric offcuts as opposed to degraded foam. Figure 7 demonstrates the testing of a hot wire cutter, mounted to a KUKA 120HA, with a 1 metre long wire and 600 mm deep frame for shaping large volumes of foam. The base of the six-axis robot traverses across an external rail, or seventh axis, hinting to multiple cutting operations in the future. The integrated workflow of computational design and digital fabrication technologies not only establishes a potential to deduce key design decisions prior to fabricating permanent materials but also allows for the customised and programmable conditioning of spaces based on acoustic performance (Reinhardt & Cabrera, 2017).

6. Conclusion

This paper demonstrates a comprehensive design-to-production framework that permits a renewed engagement between presently compartmentalised domains of design, fabrication and acoustic performance for new opportunities to arise via the inclusions of an enlarged number of influences at the moment of a project’s conceptualisation. This research provides acoustic support for human speech comfort and work productivity, encouraging a more relaxed vocal effort with reduced distractions from sound sources in intermediate distances (Yadav et al, 2017), while the ceiling does not act as a sound absorber maintaining a ‘live’
room sound in an open plan work environment. Computational design and digital fabrication will assist in the future installation of these acoustic reflective ceilings for dynamic architectures that result in dramatic transitions in acoustic environments from retroreflective to flat, scattering, or absorptive.

Acknowledgements
The authors of this paper would like to acknowledge the support given for fabrication from the Design, Modelling and Fabrication Lab (DMaF) and for testing and results by Manuj Yadav and Jonothan Holmes from the Audio and Acoustics Lab in the University of Sydney School of Architecture, Design and Planning. This study was partly funded through the Australian Research Council’s Discovery Projects scheme (project DP160103978), in addition to a primary funding source through BVN Architecture for an ongoing research project.

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