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The sound of space in 3 robotic prototypes: Introducing 6-axis robotic fabrication to shape macro- and micro-geometries for acoustic performance

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Abstract

Sound performance plays a significant role in the experience of space. Theatre and performance spaces provide a context where acoustic and spatiotemporal characteristics can be informed through the controlled robotic fabrication of macro- and micro-geometries, by using mathematical principles as a driver for design variations and machine code.

This essay discusses a short history of relationships between sound and geometry; from acoustic reflection methods (Kircher, 1673); to a theatre seating matrix (Saunders, 1790); to positioning of individual listeners and their specific acoustic environments (Russel 1883); to sound concentrations in spherical shapes (Cremer, 1982, Vercammen, 2012); to current strategies for acoustically performative scattering surfaces (Reinhardt, 2012, 2015).

The essay further introduces empirical research into robotic prototypes that test the acoustic effects of complex architectural geometries, with a focus on robotic fabrication of macro geometries that change the colouration of sound; and micro-geometric surfaces that can be applied to improve acoustic performance by scattering. It presents a 6-axis fabrication process for acoustic scale prototypes, based on a range of mathematical equations that regulate physical properties of spatial surfaces and pattern details. Here, generative tools and robotic tooling processes are linked to the angle and cavity depth in a surface medium. The essay concludes with a discussion and an outline of future strategies for the acoustic performance in multi-talker work environments or daily life scenarios.

Keywords
Robotic fabrication, Theatre, Acoustic performance, Scattering surfaces, Sound concentration, Micro-geometries, Speech intelligibility.

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1. Introduction

Sound is an immersive experience. We encounter it as in many different forms, as noise, melodies, voices or song. Our sense of sound is the oldest, most primal mechanism capable of establishing a culture through narration. The acoustic character of spaces feeds into our perception and experience. In fact, architecture 'echoes' or reverberates with sound, often without being explicitly designed to do so. All spaces deliver acoustic events by reflecting sound-waves projected within. This occurs relative to spatial characteristics; such as to geometry and shape, structure, materials, and surface finishes, but is also further dependent on the sound source, speaker and listener positions. Acoustic performance depends on the quality and character of sound propagation as a function of both overall spatial volume and surface properties, which combine to affect the spoken word or sound: through the overall shape (or macro-geometry) of space, and the character of its surface finishes (or micro-geometry). Depending on the desired effect, these can be shaped to decrease or increase sound performance, by absorption or by reflection. Furthermore, scattering can be controlled to change the direction of a sound, thus creating unique listening experiences.

In spaces for the Temporal Arts, such as theatres, concert halls or churches, the sound of space needs to be highly specified for performance (Figure 1). A general sonic character and specific aural qualities are intrinsically tied to choreographed activities and programs. And while most performances are amplified, theatres and concert halls tend to exhibit curved, spherical, ellipsoidal and often multiple intersecting complex geometries that support non-amplified performances by concentrating sound. These enforcing geometries are mirrored in the primary character of the space itself, or in secondary spatiotemporal characteristics such as seating arrangements or stage setting.

Simulating and forecasting sound is difficult because many parameters interplay and accurate computational predictions of sound propagation in space have relatively high (computational simulation) affordances. Hence, in architectural acoustics, scale models and prototypes are commonly used, which are preferable to virtual simulations since they monitor the physical acoustic phenomenon itself (Peters and Olesen, 2010). Alternatively, a variety of theoretical paradigms are available for modelling the behaviour of sound, including analytic, statistical and numerical methods; based on ray, wave, and particle propagation; in any or all of the domains of time, frequency, and space. A computational prediction of performance describes sound through mathematical models (such as Matlab equations as a point of departure), and acoustic simulations (Odeon or Ease) support optimization for performance through the negotiation of multiple criteria. Most significantly, common 3D modelling and scripting software (McNeel Rhino and GH Grasshopper) enable workflows and transitions between the different software environments.

To this extent, robotic fabrication can be deployed to bridge between design scope and desired acoustic performance, and the manufacturing of surface treatments or modules for spherical or vaulting architectural spaces. While traditional methods of producing scale model prototypes require high levels of manual craftsmanship, six-axis robotic fabrication protocols enable precise, fast, variable, detailed, and economic manufacturing of curved surfaces and surface patterns. Moreover, robotically cut 1:10 scale model prototypes can seamlessly integrate geometrical descriptions, and thus expand the spectrum of available acoustic options. In other words, geometry presents a mathematical source-code for the acoustic design of architecture, which can be simultaneously and variably linked to design, structural simulation, acoustic analysis, and fabrication protocols, and consequently supports the non-amplified acoustic performance of spaces.

In the following, this research introduces theatre spaces and derives strategies for shaping sound based on historical developments of relationships between ray/wave propagation

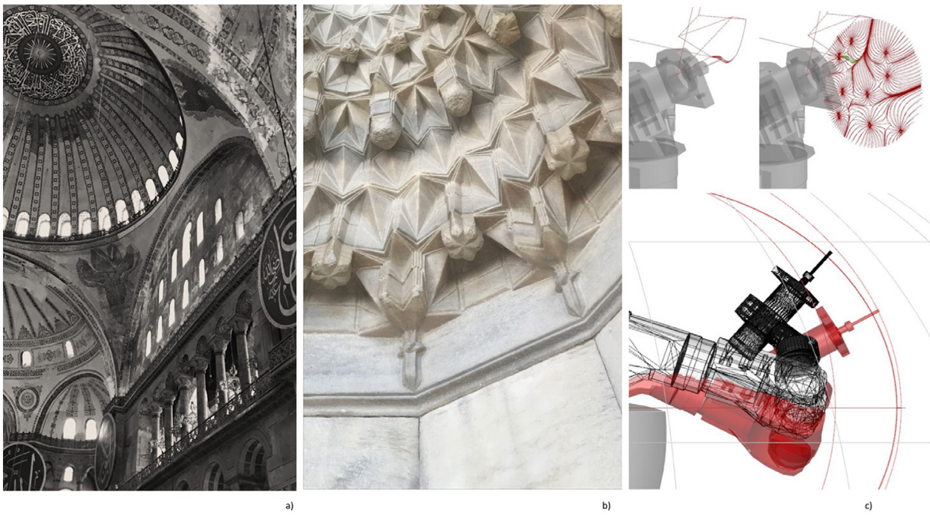

Figure 1. *Complex spherical geometries of domes and vaults in Hagia Sophia, Istanbul (a). Pattern sequences in the Blue Mosque, entrance detail, Istanbul (b). Robotic fabrication protocols for micro (c, top) and macro-geometries (c, bottom). Images and diagrams by author.*

and geometry. It presents the development of successive case studies that investigate robotic fabrication of micro- and macro-acoustic geometries and patterns. The research continues to discuss a framework in which robotic and computational design and analysis codes across different scales directly link to mathematical equations that determine acoustic behaviour. Hence, sonic events such as the directional reflection of sound, typical sound characters or 'sound colourations' becomes possible. The research concludes with a methodology and workflow proposition for future research to further support the design of acoustic performance of spaces beyond a context of the temporal arts.

2. Context of performance spaces and theatre acoustics

Theatre frames the choreography of human expressions and cultural practices in four-dimensional space. In this dynamic setting, performance can be considered two-fold, as a performance of actors within space, and of space itself. Performances deploy a multiplicity of factors, such as the choreography of bodies and movement; size and program organisation, seating, visual lines, machining, lighting, and most importantly the geometry of space.

Classical theatrical performances involve a seated audience in a directional visual line, a space split between audience and a centre stage framed by a proscenium arch (a picture frame). Its acoustic and visual operations are conditioned by a directional view, fixed seating, defined stage presentation. Usually, an amplified sound system with a centralised source distributes sound in space, as opposed to 'naturally' amplified sound through spatial conditions. In recent years, contemporary performances have shown a tendency to explore multi-directional spaces with potentially simultaneous presentations (Figure 1). In these events, a walking audience engages with performances from many different angles. In experimental theatres where 'choreography elicits action upon action' (Forsythe 2011), parallel events are proceeding simultaneously. The multiple sources, viewpoints and audience positions in such synchronous storytelling consequently require a different treatment of the environment and sound technology. If the strategy is not to bundle numerous sources into a centralised sound distribution and thus amplified performance, in which way can various discrete, local aural conditions be established?

2.1. Theatres

In theatre, the very nature of performance relates to a spectrum of acoustic events. The capacity of an actor to speak into space, and the ability of an audience to understand the words or lines delivered is essential to the 'soundscape' (Figure 2). Furthermore, actors

Figure 2. Temporal Arts in acoustic and visual performance: human voice and song (left: Eddie Perfect, Misanthropology), and choreographed dance movements (right: William Forsythe, Endless House).

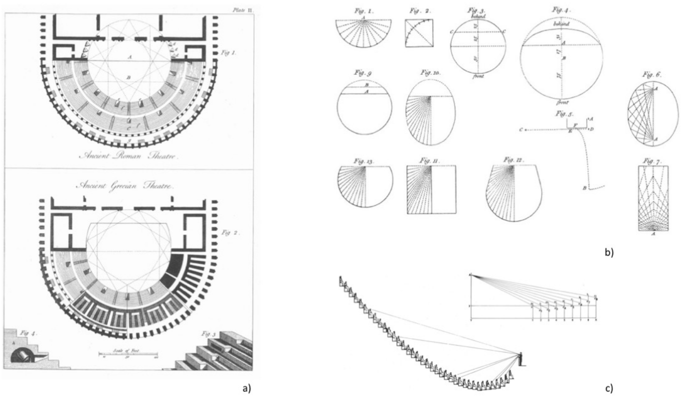

Figure 3. Geometrical relationships between acoustic and visual performance in the Temporal Arts: Common Shapes for Roman and Greek theatre spaces (a); G Saunders's diagrams of relationships between theatre geometries and sightlines (b), Saunders, Treatise on Theatre, 1790); and John Scott Russel's 'isacoustic curve' (c). Russel, Edinburgh New Philosophical Journal 27 (1838).

rely on the acoustics of space to listen to their voice reflected back (commonly referred to as speech intelligibility), and in fact continuously adapt their voice projecting into space. This vocal impact is based on a multiple-criteria set; such as the length and speed of sound waves; the surface characteristics they hit; the angle in which they arrive and thus exit as sound reflection, amongst many others. Acoustic performance is mostly conditioned relationships between the sound source, and different scales of geometry that inflects the sound.

Natural geometries that amplify sound can be found in Greek and Roman theatres and are the result of a curved geometry that frames the 'theatron' (θέατρον, Greek: a 'space for watching'), a technical term for an evenly rising area of audiences (Pelletier, 2006). The early Hellenistic theatres used negligible backdrops and a staging area so that optimal sightlines were given. A flat area for the chorus (orchestra) is extended by a raised area for actors, with seating arranged in a segment of a circle, or semi-circular or semi-oval layout around the stage. In this bowl-like arrangement, both steps and risers reflect the sound and so increase the performance capacities of an open-air space (Figure 3, a). Further developments in Roman theatres shifted the actors from the orchestra, and onto the stage. This included introducing an expanded back-of-house and adding a backdrop that also served sound reflective functions. Rendering the stage as an independent spatial or structural element inevitably led to a separation of actors-space and audience-space. Most significantly, this directionality resulted in directional sound relationships, effectively limiting a previous omnidirectional experience to a 90-degree acoustic and visual field.

Saunders was the first to present in 'Treatise on Theatre' a comprehensive pattern language for theatre layouts upon which a significant number would continue to be built (Saunders, 1790). Based on an actor as a central focus for both viewing and listening, he discussed oval, semicircle, quadrangle, to horseshoe geometries as potential space diagrams. Potential visual disruptions caused by geometry are indicated, such as distortion of images with an increase over 45 degrees in viewing angle. Amongst primarily visual dominated options, some diagrams also refer to sound travelling, reflected by wall surfaces in a box, as opposed to within ellipsoidal geometries (Figure 3, b 6-7). The latter is significant since it represents an acoustic phenomenon that is mostly ignored until much later.

Russell extended this two-dimensional catalogue of spatial and predominantly visual based options towards sound (Russell, 1838). His 'isacoustic curve' describes diagrammatically the way in which sound waves travel congruently with sightlines. Consequently, spectators should sit along the lines of equal sound intensity. By aligning head and shoulders of individual listeners according to distance and angle, a curve emerges whereby the steepness determines the optimum acoustic experience for everyone, with

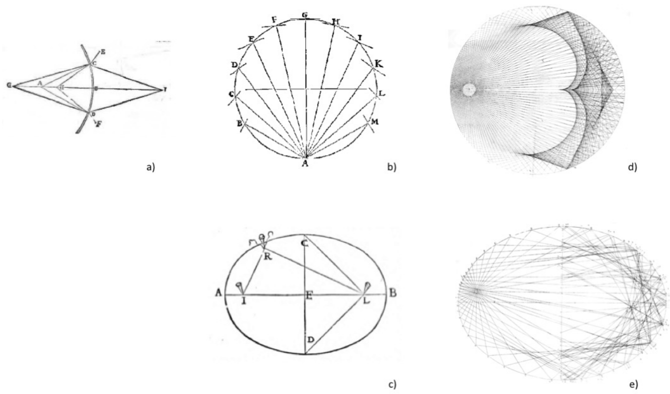

Figure 4. *Studies into relationships between shape and sound. Blancanus (1620) sets geometrical explanations of the focusing effect of reflections in concave/convex curved surfaces (a). Kircher (1673) distinguished ray reflections in circles and ellipsoids (b), Kircher, Phonurgia Nova. C Langhans (1810) describes successive sound wave-fronts in circular spaces (d, plate 45), and effects of directional sound reflection in elliptical spaces (e, plate 46, both in: Ueber Theater oder Bemerkungen ueber Katakustik in Beziehung auf Theater).*

a direct sound path (Forsyth, 1985). Significant is here that this establishes a three-dimensional sonic space, with an upward slope from front to back, virtually eliminating a broad back wall where reverberation could cause problems. Instead, each seat is a serial module that becomes part of a formation of sound reflectors and contributes to the overall dynamic in the area of performance. In short, geometries of space, stage setting, and acoustic and visual performance are intricately linked. The morphology and curvature of surfaces and the conditions within the surfaces themselves can generate widely diverse sound effects.

2.2. Sound as a function of space (macro-acoustics)

When sound encounters a surface it can be absorbed, reflected, diffracted or transmitted, and will, depending on the morphology of said surface, result in different acoustic responses regarding sound reflection. Blancanus discussed acoustic phenomena in relationship to curved geometries (Figure 4) in 'Sphaera Mundi - Echometria' (Blancanus, 1620). Kircher traced reflections that focus in and are amplified by concave and convex surfaces, and thus laid the foundation for a concept of geometrical acoustics. In his compelling study 'Phonurgia Nova,' Kircher extended this theory into applied geometries, particularly with principles that differentiate sound phenomena in arches, vault, and domes (Kircher, 1650). Detailed studies show sound rays in a circle that originates from one centre point are reflected by an opposite concave surface, and refocused within the same centre point, thereby creating 'white noise.' In contrast, ellipsoid geometries produce sound reflections that continue towards an opposite centre point along the same axis, and so avoid sound concentration. Huygens introduced his wave theory which explicitly models acoustic behaviour following principles of optical geometries (Huygens, 1690). Sound waves are treated similar to light rays, and so demonstrate wave propagation. The ray entrance angle reflecting from a surface determines an equal exit angle relative to the surface normal. Furthermore, the angle is naturally domesticated by the overall surface geometry of the wall. Consequently, geometry can be understood as a tool with which to model sound behaviour - as sound trajectory across space, or in an incremental development in volume/density.

Langhans detailed such incremental sound build-ups that form successive wavefronts through secondary sound reflections in his treatise on acoustics, 'Ueber Theater oder Bemerkungen über Katakustik in Beziehung auf Theater' (Langhans, 1810). In spaces with a circular ground plane (with a centre based sound source), sound rays meet the wall at the same time, are reflected, and a sound wave and subsequent wavelets that build up a wavefront, and will converge simultaneously upon the source position. Reflections of second order that render audio concentration in the audience area that negatively impacts on the speech quality. Langhans proposed secondary sound measurements to overcome these unwanted echoes such as the use of ellipsoids. When sound traverses a surface, it potentially enables private conversations between two parties. Surfaces curved in two directions such as ellipsoids result in a redirection in the opposite centre, as a result of this deflecting sound concentration.

These significant observations, unfortunately, remained as such for a long time. As the research argues, these historical precedents can be strategically

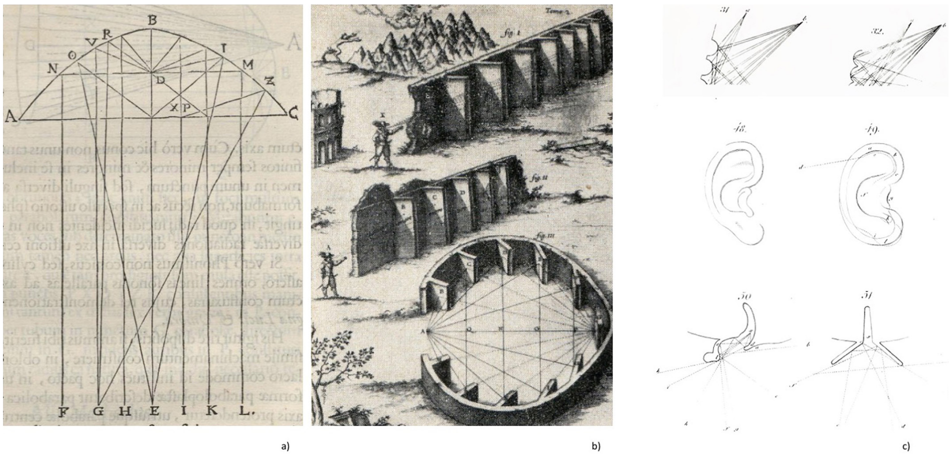

Figure 5. *Kircher (1673) introduces entrance-exit angle relations in ray reflections for concave surfaces (a), and a series of tectonic plates that direct sound pathways (b), Kircher, Phonurgia Nova. C Langhans (1810) further describes a patterning strategy for surfaces describes to produce scattering effects (breaking successive sound wave-fronts in circular spaces (c, top, plate 31,32); sound pathways in a human ear (c, bottom, plate 50,51, both in: Ueber Theater oder Bemerkungen ueber Katakustik in Beziehung auf Theater).*

employed to shape relationships between sound and space. By informing the macro-structure of space, its circular and ellipsoidal geometries, sound reflections can be intensified. This presents the first strategy for 'analog' amplification whereby the geometry has a direct impact on the behaviour of the overall 'soundscape'.

2.3. Sound as a function of surfaces (micro-acoustics)

An overall geometry of space can inform sound behaviour, but so can micro characteristics, patterns and surface conditions. The scattering of sound, when reflected by a surface, can be a desirable characteristic in the acoustic treatment of spaces, and is achieved through patterns (Cox and D'Antonio, 2009). Kircher's early descriptions of speculative acoustic experiments present such a spatial positioning of planar sound reflectors (Kircher, 1673). Some angled panels modify the properties of the space; instead of traversing the concave wall, the sound is scattered by the incidence angle and reflected back to the source origin that coincides with the audience position (Figure 5,b). The reflections decrease into a series of syllables (Latin.; clamore-amore-more-ore-re), that successively changes the meaning. This demonstrates a compelling variation to the common sound phenomenon of wide reflections of sound (scattering), which represents one of several major acoustic strategies (amongst sound absorption, reflection, diffraction). As Langhans also documented in 'Ueber Theater', scattering principles work across different scales (note here the scale-shift from wall geometry to passage into a human ear). This can be achieved through a variety of acoustic patterning strategies for surfaces that produce scattering effects, both through concave and convex subtractions, whereby sound is reflected irregularly over a wide range of directions (Langhans, 1810, Figure 5, c). Consequently, geometry can be understood as a tool with which to model sound behaviour as implemented through discrete or localised pattern topographies.

Whereas architecture seldom implements considerations of sound relative to spatial form or shape, in the field of audio-acoustics these observations are fundamental. In general, terms, scattering results from variation in the physical surface such as curvature, relief forms or textures, and changes in contrasts in material acoustic properties (Sabine 1964). Specifically, varying the angles and depths of a surface with relatively shallow surface modulation achieves scattering at high frequencies, such as the spoken word (Reinhardt et al., 2014, 2016, 2017). For high-frequency scattering, aperiodic patterns are preferred so as not to reduce the complexity of the reflected sound field (Bonwetsch et al., 2008). Additionally, a known factor is that surface roughness increases sound absorption. And although scattering performance is relatively hard to predict, incremental variations in of pattern geometries can be computationally controlled via depth and width.

Consequently, a second strategy for shaping sound can be derived: the micro-structure of surfaces, its rhythms, densities and depths, impacts on sound reflections. This presents another potential for 'analog' amplification whereby the geometry has a direct impact on local modulations of sound effects.

We defined these strategies as a potential for the development of sound prototypes, with accurate propositions for an explicit listening experience. For the geometrical, physical and mathematical modelling of the sound field of a source in space, we used mathematical models as source code (a DNA), and reverse engineered it for generations of prototypes.

3. Robotic prototypes for shaping sound

Based on the two strategies for micro- and macro acoustic sound shaping, the research explored a series of robotic case studies that extend scripted codes or codes derived from signal processing software directly to the 6axis robotic manufacturing for non-standard spaces and non-periodic patterns (Reinhardt et al., 2017). Previous robotic research developed between 2013-2017 is presented here in a comprehensive discussion for the first time. We discuss development of sound performance - from the robotic fabrication of macro geometries that change the colouration of sound to micro-geometric surfaces that can be applied to improve acoustic performance by scattering. Several 6-axis fabrication processes for acoustic scale prototypes are discussed, based on a range of mathematical equations that regulate physical properties of spatial surfaces and pattern details. This approach thus expands the scope of geometric surfaces by integrating scripting logic, surface angles and depth, and toolpath, thus enabling successive acoustic design variations that were tested for proficiency. This is undertaken to identify a framework and pathways for architecture and acoustics towards shaping non-amplified acoustic performances of spaces, towards applications in multi-talker work environments or daily life scenarios.

In the following, the empirical research studies share the interfacing of parametric design, structural analysis, acoustic analysis and the potential of robotic fabrication. For all case studies, the following segments were shared to derive threshold criteria:

- specification of the architectural design parameters in conjunction with acoustic aims (e.g., colouration or scattering coefficient spectrum);
- scripting codes or mathematical sequence for specific geometries, by computational modelling and scripting software (McNeel Rhino, GH Grasshopper, Matlab);
- evaluation in acoustic simulation (ODEON, Ease);
- simulated for robotic fabrication (KUKA|prc), and fabrication of physical scale model test samples (scaled prototypes or discs);
- and acoustic measurement and analysis of sample or prototype performance; and
- further design iteration and refinement.

The complexity of acoustic reflections required a workflow rationale, and hence this stream allowed extending from scripting surfaces towards the physical measurement of scale prototypes as an essential part of the design and validation process.

3.1. TriVoc | Robotic subtractive cutting of macro-geometries for a harmonic trichord

In the first prototype 'TriVoc', the research investigated in which way acoustic parameters that inform or consolidate complex geometries could be embedded. This required operations between different computational packages of simulation software (Comsol Multiphysics), plugin (McNeel Rhino/Pachyderm), and mathematical equations (Matlab). Specifically, the generic shape (ellipsoidal, spherical or dome structures) were altered by adapting the height, dimension and centre point. The robotic case study 'TriVoc' (Reinhardt et al. 2013, 2014) uses this

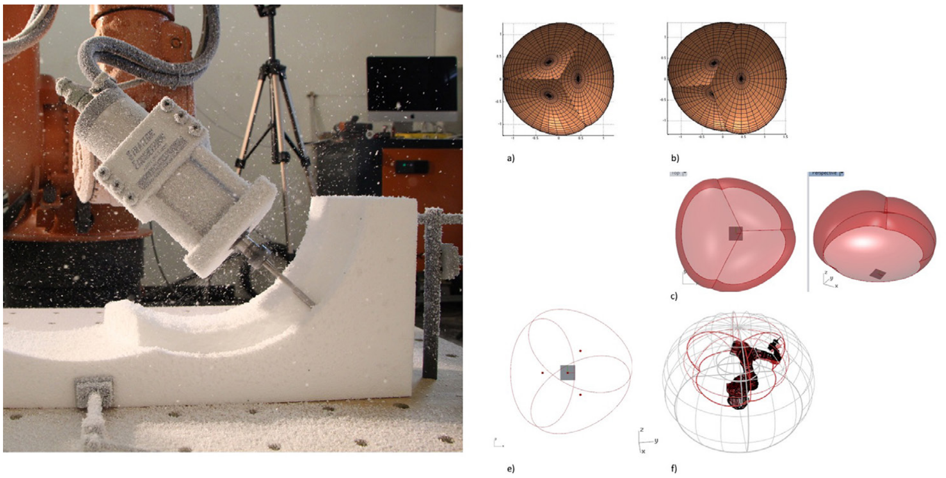

***Figure 6.** Shaping macro-geometries through robotic fabrication. Robotic acoustic prototype 1:4 scale model (left). Concept development (right): Generating Matlab function for primary geometry between homogenous 500-500-500 Hz space (as) and tuned ellipsoids as harmonic 400- 500-600Hz space(b) for ellipsoids; RhinoPython Code (c) and mapping producible space dimensions with constraints of robotic work envelope (f). Diagrams by author.*

to explore the harmonic inflexion of human voices through customised curved macro-geometries of spatial surfaces (Figure 6). The basic geometric/mathematical prompt was derived from Matlab (a computational and signal processing environment widely used in acoustics) which generates x/y/z coordinates for the ellipsoids. Based on the input parameters of distance between foci, and the respective tuning frequencies of each ellipsoid, this function was deployed towards two scenarios: three identical intersecting ellipsoids, and the more complex scenario of different three intersecting ellipsoids. By tuning the physical geometry of each ellipsoid, such as varying the distance between foci, the three intersecting ellipsoids were 'tuned' (in Hz). Thus, some geometrical solutions could be derived that look and sound very different to each other. This produces a three-person conversation space changes the tonal character or 'coloration' of voices and produces a 'triad,' or three-pitch chord.

These base conditions were then integrated into machine code (RhinoPython/GH), and mapped onto robotic manufacturing codes (kuka|prc) so that the design immediately responds to fabrication constraints, and a capacity of actual (acoustic) performance (Comsol Multiphysics). A functioning (acoustically proficient) prototype was produced at 1:4 scale through robotic milling, which required scaling in shape, and impacted on sound, but fundamentally maintained the most critical parameters of control over robotic toolpath: control over curvature and availability of resulting pitch for physical analysis. The intersection between Matlab, RhinoPython/ GH enabled control over the sound pitch and spatial design, to adapt the desired 'soundspace' continuously and repeatedly.

3.2. RoboFlowl | Robotic milling of micro-geometries for isocurves

As opposed to the previously described study, the second, 'RoboFlowl', focused on the surface condition of micro-patterns to inform acoustic performance (Reinhardt, 2014). As scripted geometry base, two variations were generated in GH Grasshopper (a plug-into McNeel Rhino/visual scripting environment); with a hexagonal periodic and hexagonal deformed pattern; and a vector-based pattern adopting a customized script 'Flowl' (Figure 7). Both developed zones of highly differentiated depth across the surface, with individual facets varying in depth, height, directionality, resulting in sound diffusive properties of test discs that acted as acoustic pattern prototypes. These 1:10 scale model discs were tested by random incidence measurement in a scale-model reverberant room, placed on a turntable, and synchronously averaged impulse responses are obtained for different source and receiver positions from

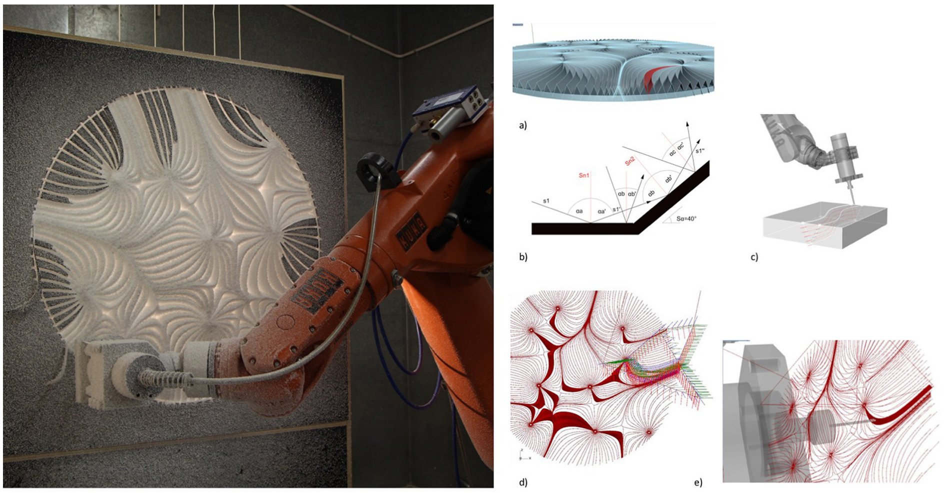

Figure 7. *Micropatterns. Shaping micro-geometries through robotic fabrication. Robotic acoustic prototype 1:1 scale model (left). Concept development (right): GH protocols for change of reflective area in scattering disc building zones around attractor points and changes in vortex field (a); specular reflections with sound rays reflected by an angled surface (b). Robotic fabrication syncing toolpath and angle of effective surface (c); and 364 facets that produce a soundfield (d, e). Images and diagrams by author.*

the material sample. From these, the scattering coefficient was calculated (the ratio of acoustic energy reflected in a non-specular manner to the total reflected acoustic energy). Significant results were yielded for scattering at frequencies above 1 kHz from the 'Flowl' surface, due to depth and number of ridges/valley volumes, which thus proofed an effective strategy for scattering surfaces on a micro-basis for human speech performances.

The robotic fabrication for the RoboFlowl prototype used the advantage of a relatively simple geometrical rule for deforming a collection of individual lines relative to one attractor and its adjacent neighbours. Every single line is a spline, but can be directly linked to the robotic toolpath, with the angle of the milling tool predefined and variable along the curve, resulting in the depth of valley that must be achieved to provide scattering. Instead of a workflow with multiple passes along splines, a pair can produce the surface void, and thus produces the acoustic scattering effect. This rule set interfaces directly with the robotic parameters, which include here toolpath and defined an angle of the milling tool; multiple passes along isocurve; the distance of the robotic end-effector to a material surface, and depth and surface angles of voids as a variable along the isocurve. In this manner, the approach concatenates computational design, acoustic analysis and robotic fabrication, which expands the potential scope of micro-geometric surfaces by integrating scripting logic, surface angles, and depth, and toolpath, thus enabling successive acoustic design variations that can be tested for proficiency. Limitations resulted from the fact that out of over 300 some 34 still had to be manually adjusted. However, the 1:10 prototypes could be scaled up to 1:4 to develop acoustic 'regions' within the geometrical envelope, and so act as proof of concept.

3.3. PRotoDNA | Sequenced Milling of Micro-geometries

In the third study series, single robotic test samples were limited to fabrication and required manual adaptation of original design script and robotic manufacturing process. Consequently, transfers between pattern scripting and flexible robotic fabrication for acoustic scattering needed to be significantly expanded to arrive at an efficient production of multiple series of 1:10 scale model prototypes, so that statistical information on relations between surface area and mean depth for the scattering of high frequencies could be derived (Reinhardt 2017). Hence, the basic premise for 'PRotoDN,' are continued developments as direct robotic manipulations of micro-acoustic patterns

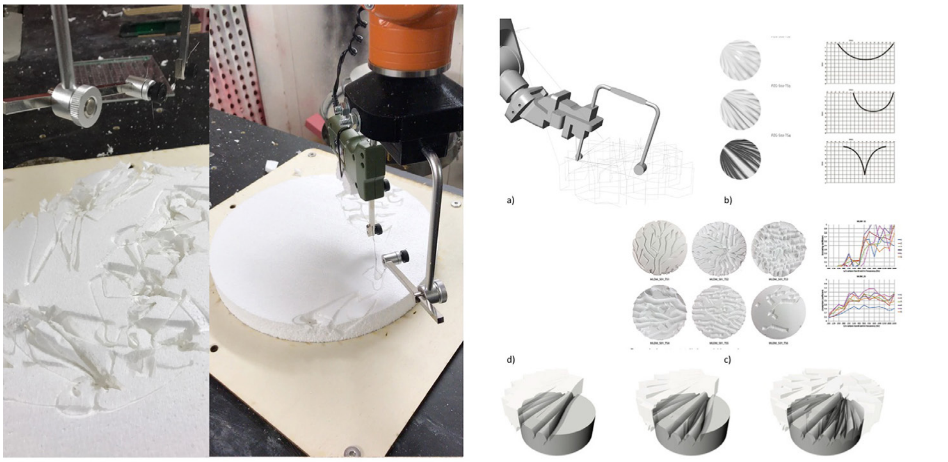

Figure 8. *Micropatterns as DNA of pattern script for robotic fabrication. Flocking based script for robotic fabrication (left). KUKA\prc simulation with hotwire endeffector (a), sound discs relative to cutting profile changes (b) ; acoustic profiles for scattering and absorption performance (c), and reverse-engineering a mathematical relation between valley total, density and pattern depth. Images and diagrams by author.*

(Figure 8). Since scattering is not the only acoustic surface characteristic that can benefit from high degrees of freedom digital fabrication, the research continued into developing a spectrum of micro-design of special patterns of reflection, highly tuned absorption, and potentially other unconventional acoustic surface behaviours. Robotic fabrication extends here randomness (or non-periodicity) through motion control, tool-path angle and shape of end-effector (wire element).

Current computational design approaches apply chaotic or unpredictable surface patterns to derive ranges of aesthetic solutions based on similar premises. As a concept of variation, randomness can be part of a highly controlled design process, which can be of particular significance in the context of acoustic performance in architecture. Surfaces deliver better acoustic scattering performance when based on aperiodicity. Hence, randomness can contribute to a broader range of diversity in the architectural envelope, when acoustic performance is understood statistically. The introduction of a degree of random variation in the surface has the potential to increase the frequency range of useful scattering, or absorption of sound – depending on the depth of valleys, and diversity of the pattern. As an empirical study of the relationship between bespoke fabricated surfaces and acoustic scattering tested degrees of variation in 1:10 scale model prototypes. Based on a single script, the robotic subtractive process was interrupted or partial lines of code in fabrication, executed. This enabled us to develop a pattern range, to derive statistical data on acoustic properties of these surfaces, and to deduce design rules.

The robotic patterns resulted from variations in robotic trajectory, depth, and sequence were random, non-periodic and non-directional. Each 1:10 scale model was assessed with detailed measuring scattering coefficients and random incidence absorption coefficients of the discs, using a scale model reverberant room. As a result, robotic manufacturing through spline curves offered a much more significant scope for variability in the production of sound discs, due to an easily accessible transfer of GH code to robotic machine code; maximum depth of valley could be continuously achieved across the surface. Acoustic testing further confirmed that similar densities of valley patterns cause similar acoustic behaviour, with simple robotic deposition of patterns on the surfaces, with a periodic spatial design of surfaces produces a periodic scattering spectrum with regular, visible peaks. These results enable differentiation of ratio between surface area, depth of cut and pattern frequency. The research found that measurement and integration of surface area of the disc could be expressed as a ratio to the flat disc before cutting. The research also found that descriptors for the root-mean-square (RMS) depth of the surface (subtracting mean depth) and the circular FFT power spectrum around the surface (at various radii) could be derived. In this manner, from the same code but with a change of tool, both scattering and absorption highly efficient surface could be produced through very few robotic tooling lines, and with a wire profile that generated an undercut. This research then results in an archive of different acoustic behaviours that can be engineered and orchestrated over a larger field, and thus deliver statistical data on surface effects for absorption, directional reflection, and scattering.

4. Discussion

In these studies, the interdisciplinary relationships, exchange, and collaboration between previously separate disciplinary areas contribute to a multi-criteria performance (Figure 9). Across the three robotic prototypes, the research has explored several acoustic concepts and case studies for non-amplified space. As a result:

The prototype series 'TriVoc' (2013/14) produced research into the macro-geometry of three intersecting ellipsoids, with the aim to produce a space that resonates with harmonic tonal effects. While this initial study proved effective, the research considered a larger setup of spatial geometries expansive due to milling toolpath, and so pursued further the original concept of further refining the overall space.

The prototype series 'RoboFlowl' (2015/16) investigated initial research into general trends for robotic fabrication of micro-acoustic patterns, such as the relationship between the depth range of the relief in the surface pattern and the frequency range for high scattering values. This aimed at generating a first fundamental understanding of pattern tendencies between planes and splines, and testing potential of robotic fabrication. As a result, general trends were determined for acoustic proficiency, here relative to the direct and implicit connection between guiding the robotic toolpath angle (through milling), and the resulting effectiveness in sound reflection angle.

Prototype series 'PRotoDNA-1' (2016/17) further explored the toolpath as a direct prompt for acoustic effectiveness and further explored the potential of gradient patterns. While the aim of this first series had been to find an empirical relationship between a physical parameter and acoustic result, the research generated here algorithmically differentiated patterns that were further intuitively changed. This was achieved through variability in toolpath and the defined angle of the subtractive tool, through multiple passes along isocurve, a distance of end-effector to a material surface, and the depth and surface angles of valleys variable along the curve.

Across 38 sample prototypes, the research manipulated a range of machine code by an interruption, recursion, or shift to another surface, so that parts of patterns in different locations were generated. As a result, the pattern generations within multiple criteria (parametric modelling to scale model production to physical simulation) expanded the archive or acoustically active surface patterns drastically. This enabled us to derive tendencies that needed to be further investigated.

Prototype series 'PRotoDNA-2' (2016/17) thus reverse engineered the previous study, as it derived mathematical equations and a working protocol for gradients of pattern densities across a surface, resulting in a specific acoustic performance. This further approach was geared towards including a differentiation ratio between surface area, depth of cut and pattern frequency; through measurement and integration of the of surface area of the disc, which can be expressed as a ratio to the flat disc prior to cutting; the root-mean-square (RMS) depth of the surface (subtracting mean depth); and the circular FFT power spectrum around the surface (at various radii) as the most detailed approach. As a result, a controlled and large spectrum of scattering-effective acoustic micro-patterns could be achieved for robotic subtractive processes, so that new design strategies for an acoustic performance in the built environment can now be applied.

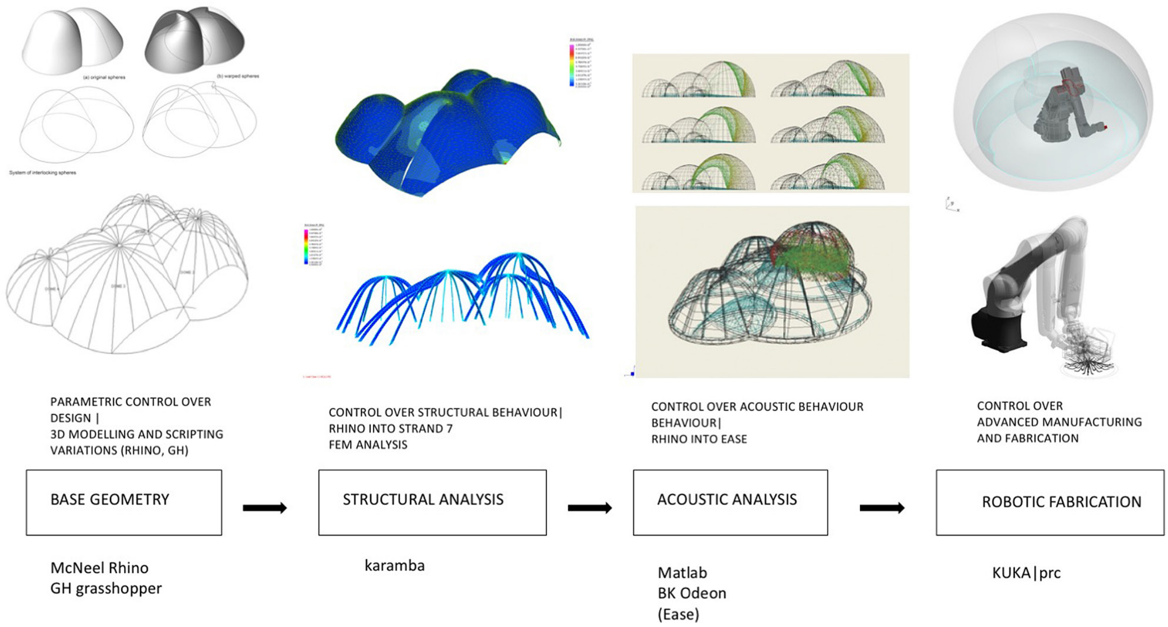

Figure 9. *Workflow and range of variable parameter. Development of base geometries for spaces and intersections, principle testing of structural performance principle analysis of acoustic behavior of macro – and micro-geometries, application of robotic manufacturing protocols for modules or components, and surface patterns. Note that this is not a linear process, but recursive. Diagrams by author.*

A typical protocol would need to expand from small-scale acoustic optimisations to the integrated structural performance within complex geometries on a scale of buildings (Figure 9). A workflow consequently could be initiated, to:

- identify and establish primary geometries (a) in 3D modelling software (McNeelRhino) or acoustic geometries (Matlab),
- Produce initial acoustic analysis to determine position of sound source in (b) significant volumes, or in micro-pattern sequences (c) (BK Odeon, EASE),
- if using spatial volumes, establishing parametrization (Grasshopper GH) of structural system (d) rigid shell system or (e) structural beams to morph geometry (f) height, (g) diameter, and (h) shift of central sphere point (abstraction of spheres), and test structural capacities and performance (karamba)
- apply a second acoustic analysis based on macro parametric variations comparing (i) ideal and (j) deflected centre points
- apply third acoustic analysis based on micro parametric modifications, relative to audible effect (k) reflective, or (l) absorbent, or (m) scattering distributed across the surface
- simulate robotic fabrication of modules or components in KUKA|prc, relative to work envelope (n) and acoustic pattern generation (o)
- produce robotic fabrication of modules for an envelope, or patterns (p), and
- extend robotic fabrication under the support of sensing technology and head-torso simulation to further enhance or change acoustic performance (q). To be continued.

Such a workflow would enable the strategic development capable of interfacing between disciplinary areas, and a framework for collaborations that prototype a spectrum of acoustic performance for real spaces, and future spatial simulations.

5. Conclusion

Robotic fabrication presents a huge potential for fine-tuning accentuated patterns relative to high frequencies for a person or an audience situated at any point in (a performance) space. As the research has discussed, sound propagation can be engineered as a function of spatial volume and surface properties. By interfacing computational scripts, mathematical source codes, and structural analysis and acoustic analysis, and then fine-tuning parameter (of dimension, distance, height, curvature, focus point, sound source and audience position), sonic events can be generated, controlled, fabricated, and further evaluated and continued. Consequently, a compelling and distinctive topography of multiple scales and dimensional geometries can be produced. A diversity of spaces that enhance acoustic performances/experiences by delivering a combination of beauty and sound reflection: sequential and multi-dimensional choreographed and differentiated soundscapes. Most significantly, this can be done without being dependent on the enclosing envelope, and through precise and controlled approach with local contexts.

Future research will need to be undertaken for the application in multi-talker multi-speaker environments, where different and contrasting acoustic protocols are choreographed. This can then extend criteria, conceptual framework, and robotic fabrication processes to the acoustic surface treatment of existing surface geometries, or to the conditioning of complex curved surfaces that can be sound-active on a larger scale in architectural space(s). This will enable fundamental research into other areas where unamplified speech or performance takes place (such as multi-talker workspaces, community halls, commercial open zones, or public transport infrastructures). In that manner, and building upon the discussed strategies, sound amplification for audiences, and retro-reflection for open workspace scenarios, and sound scattering for audio ambience can improve acoustic performance across a broad spectrum of everyday spaces.

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