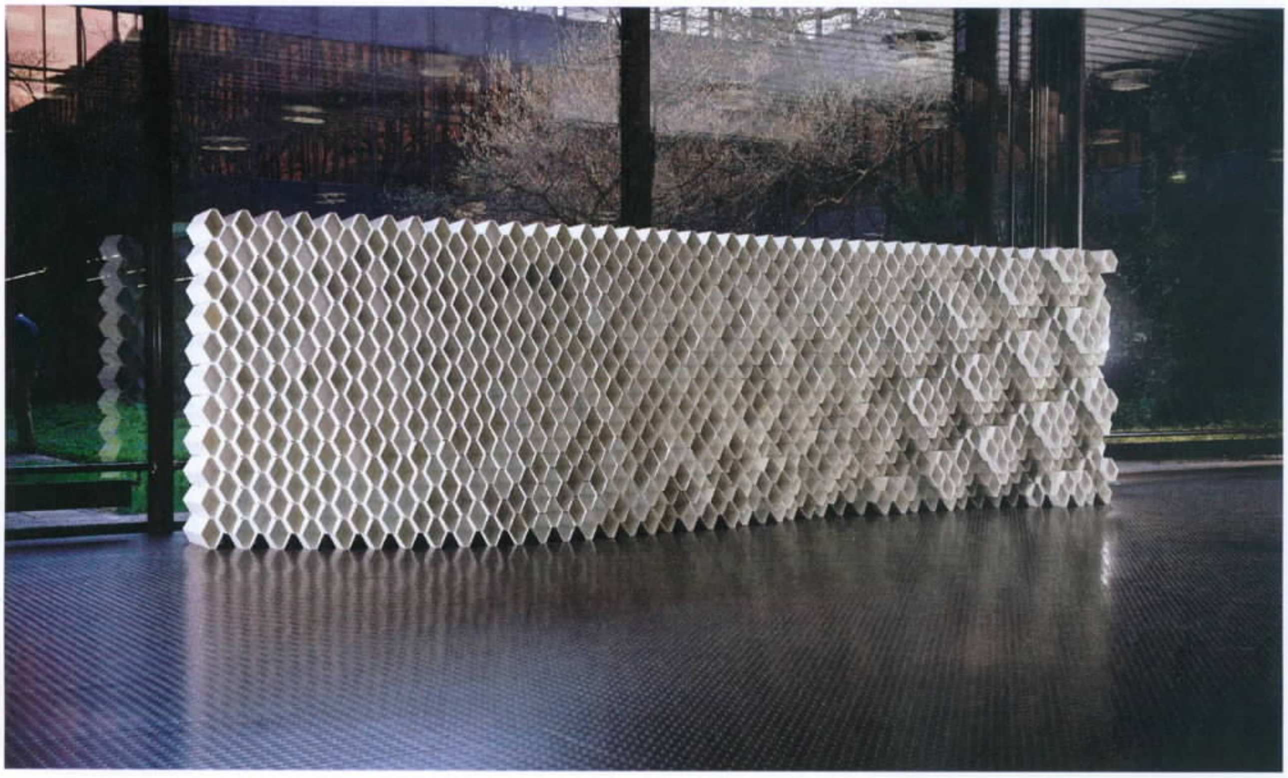
ROBOTIC FABRICATION OF ACOUSTIC BRICK WALLS

Maximilian Vomhof, Lauren Vasey,
Fabio Gramazio, Matthias Kohler ETH Zurich
Stefan Bräuer REHAU AG & Co.
Kurt Eggenschwiler USwiss Federal Laboratories for Materials Science and Technology (EMPA)
Jürgen Strauss Strauss Electroacoustics



1 Acoustic Brick Wall–digitally designed and fabricated by an industrial robot (Gramazio & Kohler, ETH Zurich, 2014)

ABSTRACT

The paper presents research on a robotically fabricated acoustic wall system, the so-called "Acoustic Brick Wall", which functions as an acoustic zoning element for office spaces. Two aims were embedded in this research. First, the investigation of alternate design and fabrication means of manipulating and enhancing the acoustic performance of office spaces through the fundamental implementation of a powerful but so far rarely recognized phenomenon: sound diffusion. Second, the development of a computational design and fabrication framework that would allow the production of individually adaptable walls in an industrial context. To verify the findings, the fabrication and related acoustic measures of 1:1 prototypes (Figure 1) are discussed.

INTRODUCTION

ROBOTS AND DIGITAL FABRICATION

Industrial robots have the power to alter standardized means of production in the discipline of architecture and construction (Gramazio and Kohler 2008). Not only can they lead to significant time and cost savings in fabrication, but their ability to connect digital design data directly to the fabrication process also enables the construction of very complex components at full-scale.

The production of full-scale elements raises the question of what materials to use and how to process them. Since 2005, the Chair of Architecture and Digital Fabrication at the Swiss Federal Institute of Technology and other institutions worldwide, have investigated several fabrication systems enabled through the use of robots, whose generic nature make them capable of handling a variety of customizable tasks. Of particular focus at The Chair for Architecture and Digital Fabrication has been the process of additive assembly. Rather than subtracting and therefore wasting material from a preset body, material can be assembled by robots in a straight forward manner. Through this process, material is only placed where it is needed, and system parameters, for example placement and orientation, can be manipulated or varied as desired.

While robots in an industrial context, particularly in the manufacturing industry, are primarily used to iteratively repeat identical tasks, in architectural fabrication their application can be more specific to executing non-standard tasks (Willmann et al. 2012). Such ability makes possible the production of truly customizable and non-standardized architectural aggregations with specific aesthetic and functional performance (Bonwetsch, Gramazio, and Kohler 2012).

ACOUSTICS AND DIGITAL FABRICATION

The acoustic quality of a room is an important criterion for the perception of spaces (Handel 1989) and subsequently the sense of well-being of the people living, learning and working in it. However, most acoustic treatments happen after the initial space planning and design process. Additionally, there are only few existing design tools available that would allow architects to improve the acoustic performance of their designs through analysis or simulation (Peters 2009). Furthermore, existing products on the market primarily focus on shortening the reverberation time through absorbing sound energy, which is basically a damping of the acoustic environment. This damping reduces the noise but can also lead to a misperception– spaces may seem smaller. However, other forms of treating the sonic environment, for example, sound diffusers, rather enhance spatial perception.

Sound diffusing surfaces follow particular rules and exhibit highly irregular geometric characteristics. Because the granularity of the surface structure and its spatial depth is directly related to the frequency bandwidth of the sound that has to be scattered, it is possible to determine it precisely (Cox and D`Antonio 2009). With digital design methods available, this information can be applied in the design and creation of a range of geometrically unique and acoustically effective panels. The implementation of digital fabrication to realize such panels will expand the application of professional acoustic solutions to rooms such as office spaces.

Attempts to encode the underlying geometric rules of different acoustical phenomena and translating them into design scripts have been made (Peters 2009), but adding criteria of digital fabrication to the design process of such surfaces has only happened to a limited extent (Figure 2) (Bonwetsch, Baertschi and Oesterle 2008).

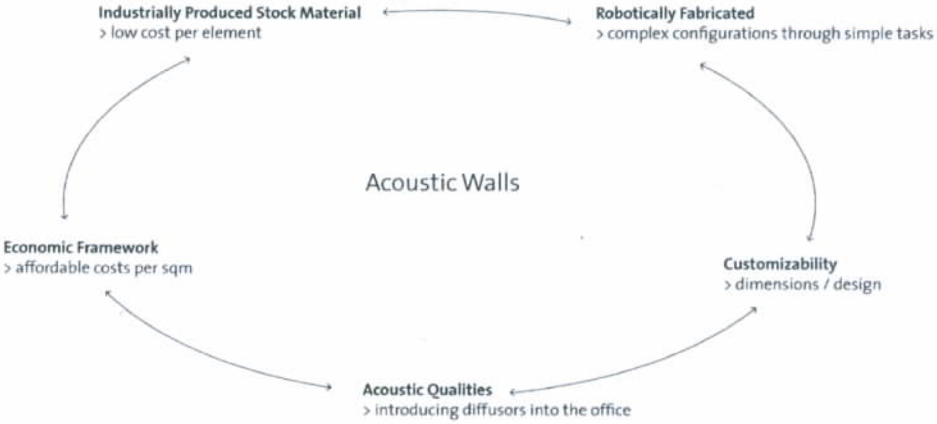
FIELDS OF RESEARCH

To continue the research done in this field, the specific aim of this research project is to develop industrially produced polymer elements whose size is determined by the necessary granularity for the diffuse reflection of 125Hz to 4000 Hz (typical frequency area of human speech) and to robotically assemble these elements to acoustically active and individually designed walls (Figure 3).

IMPORTANT ROOM ACOUSTIC PHENOMENA

In room acoustics, there are three main phenomena that shape our perception of the acoustic qualities of a space. Although we encounter each of these phenomena on a daily basis, their actual impact on our well-being is rarely taken into account in the architectural planning process. Whilst the effects of absorption and specular reflection are commonly known, the third significant phenomenon, the diffusion or scattering of a sound wave, needs further explanation.

2 Robotically produced foam diffusors (Gramazio & Kohler, ETH Zurich, 2010)



3 Characterization of the most important parameters that represent the framework for the development of the acoustic walls

This effect is strongly related to the geometric structure of a wall's surface rather than to its exact material composition. A wall with a high scattering coefficient does not reflect the mirror image of the initial wave as in the event of a specular reflection, but numerous small waves that are ideally reflected in a spatially non-uniform manner. Through diffusion, flutter echoes are avoided and the existing sound energy is equally distributed over the space.

While the implementation of so-called diffusors in concert halls, music studios, etc. is commonplace (Cox and D'Antonio 2009), their usage in other, less specifically dedicated rooms is very rare (Choy 2013). Reasons for this are the considerably high costs of existing diffusor typologies as well as their rigid nature–they are not adaptable to specific design intentions or situations. A more flexible design approach could allow the positive effects of diffusion, including enhanced speech intelligibility, minimization of flutter echoes, enhancement of sense of self in space (Strauss 2012), and enhancement of efficiency of existing absorbing surfaces, to be experienced in a variety of spatial conditions. Such attributes are incentives to further investigate this rarely used principle for application in office or living spaces.

REFERENCES AND THE DEDUCTION OF DESIGN RULES

Studying existing diffusor typologies (Figure 4) and the insights given by Cox and D'Antonio (Cox and D'Antonio 2009) closely, one can derive the following basic rules for constructing a surface that effectively scatters sound in the defined frequency range of 125 Hz to 4000 Hz (Figure 5).

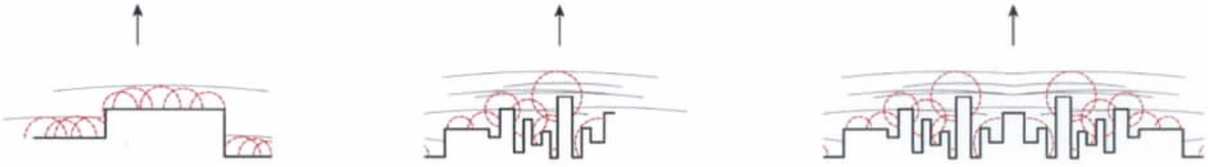
1. For the diffuse reflection of lower frequencies, the surface needs a depth of 20 cm. This value is derived from a fourth of the wavelength of the lowest frequency.


Skyline Diffusor


Harmonix K


Binary Amplitude Diffusor

4 In the 1970s, Manfred Schroeder created a number-theoretic formula that would allow the construction of a diffusor based on its center frequency utilizing only a limited number of different pieces. The 1D/2D Schroeder-Diffuser or the Skyline Diffuser are examples for these mathematically describable diffusors. Other examples for diffusors are the Harmonix K from RPG.Inc, which tries to break up the rigidity of the Schroeder-Diffusor through the use of curved surfaces. The Binary Amplitude Diffusor, also produced by RPG Inc, achieves diffuse reflection through a specific 2D pattern of either absorptive or reflective surfaces.



1. division in depth

2. division in width

3. aperiodic repetition

5 Three rules for sound scattering surfaces: 1.Importance of division in depth, 2.Importance of division in width and 3. Avoidance of periodic repetition

2. For the diffuse reflection of higher frequencies, the surface needs to be discretized in width with a maximum step size of 10 cm. This step size correlates with half of the wavelength of the highest frequency.

3. Additionally, the described discretization pattern should not be periodically repetitive for effective scattering of reflected sound waves.

FABRICATION

The most important criteria for the choice of an appropriate fabrication procedure were the demand for a high degree of automation, the use of a mass producible base unit, and the criterion of mass customizability. Therefore, it was of particular importance that the process would be as autonomous, fast and robust as possible, with minimal human intervention. In this context, the decision for bespoke additive assembly as a mode of fabrication was taken at an early stage in the project. Robotically driven assembly has proven to adapt to the needs of the industrialized non-standard production of architectural elements very well.

MATERIAL SYSTEMS

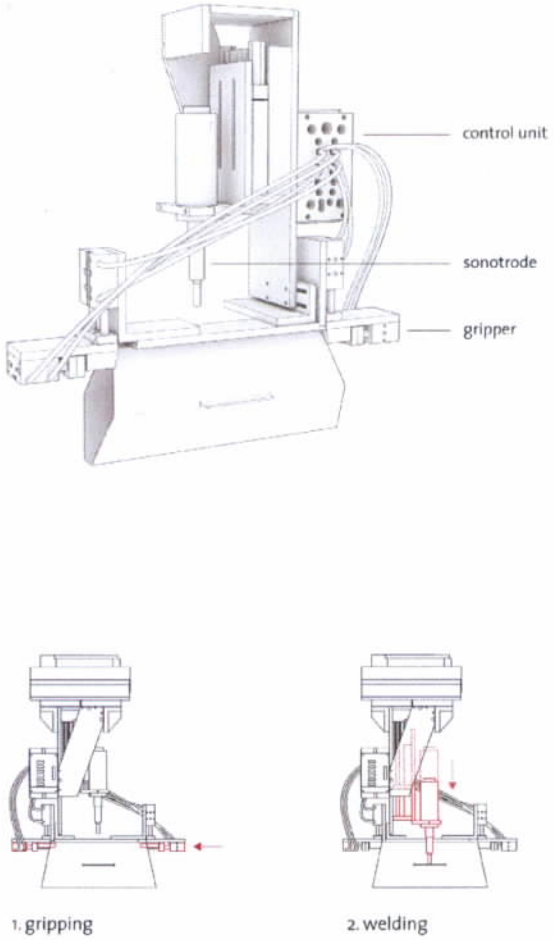
The expertise in processing polymers, which the industrial partner REHAU brought into the project, made the decision for a material fairly straightforward. Still, several options in terms of processing technology and type of plastic were tested and considered. Ultimately, Acrylonitrile butadiene styrene (ABS), one of the most common plastics used in the production of furniture elements, was selected for its vast color palette and it's excellent processability.

This material choice also enabled the use of ultrasonic welding as a very fast, material-specific, economically viable and ecologically sustainable joining technology. Ultrasonic welding is an industrial process by which two plastic parts are melted together through the application of high frequency vibrations. The welding type used in this project, the so-called rivet welding, allows for welding material with a thickness of 2.5mm through the application of 1.8 bar of pressure and a vibration frequency of 20.000 Hz in only half a second, achieving a very strong connection. In this process, a cylindrical aluminum bar, the *Sonotrode*, is pressed on the material and made to oscillate by a so-called booster. Through the vibration, the plastic melts locally and the *Sonotrode* can pierce the material and rivet the two plastic parts together. This technology enables the whole wall assembly to be constructed of a single material and to be therefore fully recyclable. Such a characteristic would not have been possible if glue would have been employed.

EXPERIMENTAL SETUP

The fabrication workflow was developed in the robotic cell of the Chair of Architecture and Digital Fabrication at ETH Zurich. Equipped with a KUKA KR 150 on an 8m long external axis and a large working platform, this environment served the purpose of demonstrating the adaptability of the developed workflow to implementation at full architectural scale.

6 Robotic cell, including custom made jigs and end effector (Gramazio & Kohler, ETH Zurich, 2014)



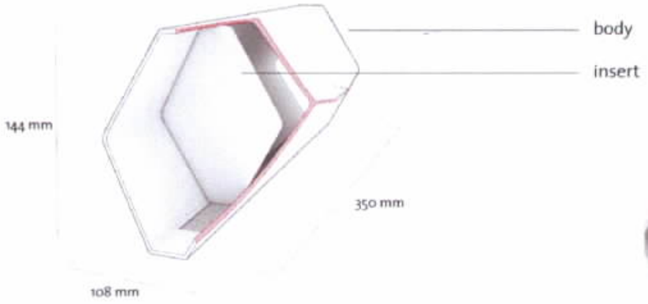
7 The robotic end effector is essentially composed of a gripping module, the ultrasonic welding head and a control unit

Two main measures were applied to this setup to adapt it to the needs of the project. First, two custom-made jigs were placed on the platform (Figure 6). Second, a customized end effector was developed in cooperation with REHAU, the industrial partner of the project, and attached to the robot. This end effector contained multiple features: a pneumatic gripper that would hold the element, a *Sonotrode* that would weld the pieces together, a pneumatic cylinder that would lower and lift the *Sonotrode* once in place, a valve that would allow to set the amount of pressure applied to the *Sonotrode* while welding and a control unit, that would control the switching of the necessary valves (Figure 7). A generator supplies the power to the ultrasonic welder, and connects to the system through the I/O bus of the robot.

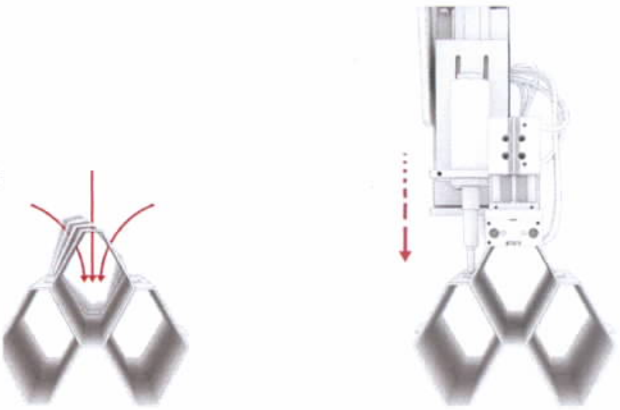
PROJECT: THE ACOUSTIC BRICK

The choice of injection molding as manufacturing process for the acoustic elements enabled the design of a specific unit, the so-called "Acoustic Brick" (Gramazio, Kohler and Willmann 2014). This brick is composed of a main body and a secondary insert. The dimensions of the body were derived from the earlier defined design rules. Ridges on the interior of the cavity of the main body allow the insert piece to be uniquely placed by robot along the axis of the part (Figure 8).

The specific diamond form of the part was derived from fabrication constraints active in ultrasonic welding as well as from measures for tolerance handling. In aggregation, the wing of a single element directly connects to the top of an adjacent part. The aggregation is such that despite the vibration and pressure occurring during the weld process, lateral movement was prevented by the previous row of elements. Translational movement along the axis of the part is prevented by the retractable gripper, whose beveled edges maintain connection to the part while allowing the piece itself to settle into position between two adjacent pieces.



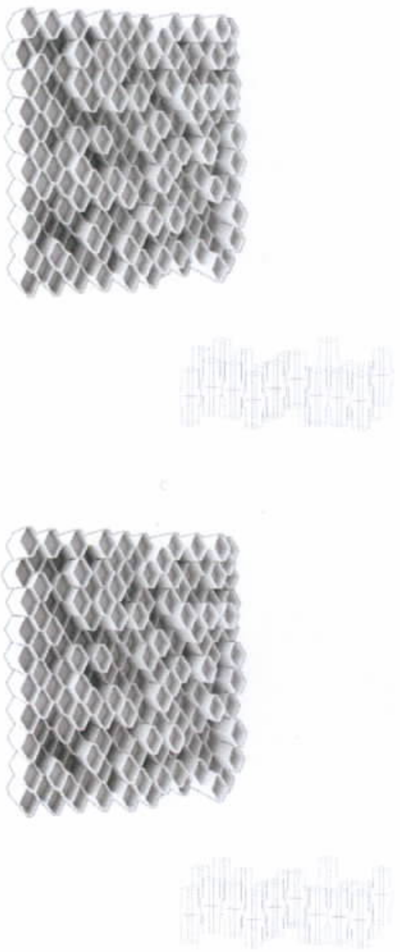
8 Geometry and functionality of the acoustic brick



9 Embedded measures of tolerance handling

This low-tech yet self-correcting "fall in place" mechanism avoids horizontal misplacement automatically. The handling of possible vertical tolerances happens through a sensitive placement of the *Sonotrode*. To initialize the welding procedure, the *Sonotrode* is lowered to the piece without pressure. Once contact is established, additional pressure of 1.8 bar is applied, whether the *Sonotrode* has already achieved the programmed final position or not. This way, tolerances of up to 5mm can be handled without a loss in weld quality (Figure 9).

The implementation of the secondary insert was a key to the design flexibility of the overall system because the relative positioning of the insert has a strong influence on the acoustic function. This functional separation allows more formal design possibilities: a flat wall could still achieve a variety of the necessary acoustic depths (see 2.2. Design Rules), and thus be very acoustically performative (Figure 10).



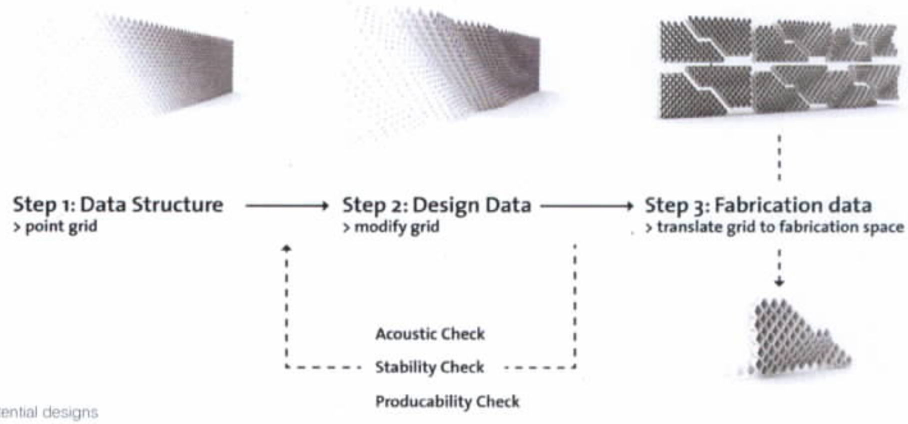
10 Acoustic functionality with insert piece at fixed position (*top*), which limits the design space dramatically compared to individually positioned insert pieces (*bottom*)

ASSEMBLY PROCESS

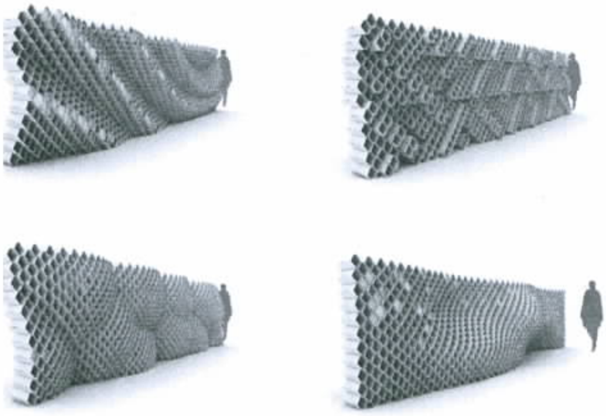
The essential fabrication workflow is based on a standard pick and place process. The robot picks an element out of a matrix of pick stations utilized to store every unique element: regular pieces with translucent inserts, regular pieces with opaque inserts, edge pieces with translucent inserts and edge pieces with opaque inserts. It then moves along a parallel path, allowing a fixed rod to push the insert into the correct position. Hereafter, it positions the element at its destined position in the aggregation and initiates the weld process, connecting the element with two welds each to its neighbors (Figure 11).

Throughout this process, digital inputs provide system feedback, ensuring that the *Sonotrode* does not overheat, and that the welder and generator are ready before continuing the fabrication process. Such feedback ensures weld quality and thus the structural quality of the overall system. With a production time of forty seconds per

11 Assembly procedure including positioning of insert and welding (Gramazio & Kohler, ETH Zurich, 2014)



13 Catalogue of potential designs



12 Functionality of underlying software development

piece (on average), it was possible to build two final prototypes with 893 pieces each and resulting dimensions of 5.6 x 1.6 x .35 to 1m (ca. 9 sqm each) in just four days.

DESIGN SOFTWARE

The algorithmic design scripts served to demonstrate the functionality of an eventual design software package and design process. The objective of this script library was to achieve a variety of formal and experiential design possibilities (Figure 12) through a limited number of functions and tools, while maintaining analytic measures to guarantee the structural, functional, and fabrication viability of each schematic design (Figure 13).

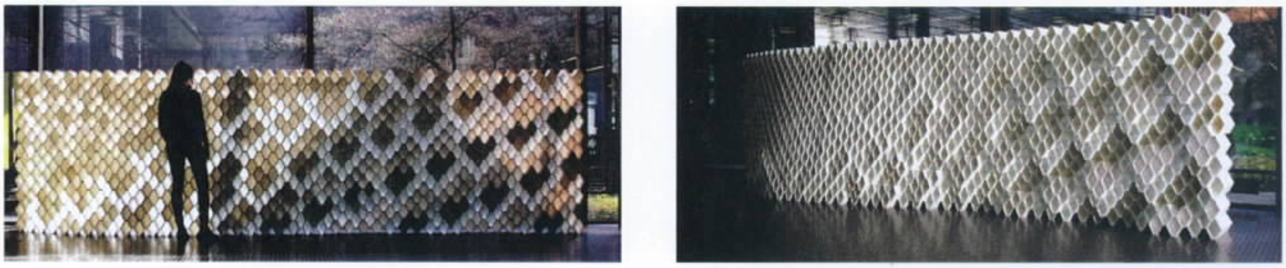
The script library was developed utilizing *Grasshopper* for *Rhino 5*, particularly for its ability to preview design geometry with minimal processing time. Color rendering functionality was developed utilizing the native Windows System. Drawing namespace as well as Rhino Common, with supplementary libraries written in iron-python and enabled through the *Grasshopper* plug-in for python. This setup allowed KRL robot files to be sent directly to a server connected to the robot, uniting the design and production environments.

An important achievement in the development of the computational design tools was to utilize known acoustic rules to predict the relative acoustic performance of the prototypes. This is accomplished through iterative re-sampling–a process which measures the acoustic depth of any sample, where the acoustic depth is defined as the difference in depth between the deepest and the shallowest insert along the axis of shift. This acoustic depth was benchmarked against the known depth of 20 cm, the target depth range defined by the acoustic design guidelines. Such a strategy was successful in producing live visual feedback, indicating the areas that would benefit from increased depth or randomization (Figure 14). Additional computational checks were implemented to ensure overall wall stability and a secondary weld overlap check ensured that the shift between a part and each of its neighbors was below a threshold.

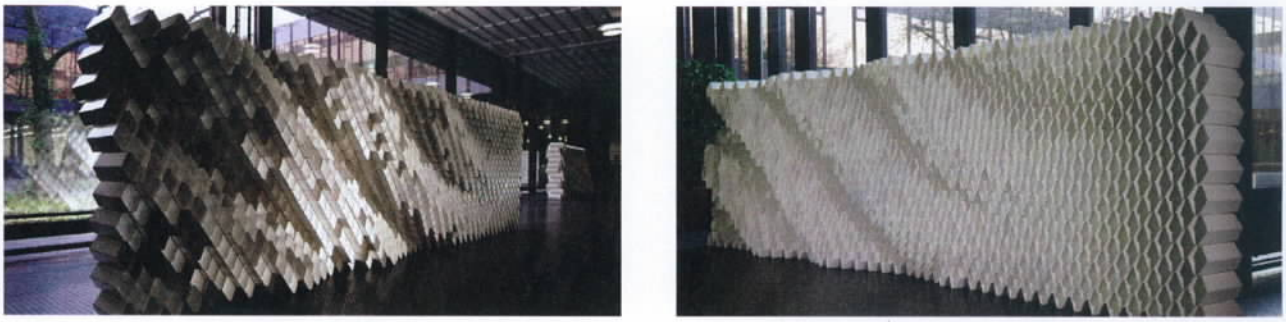
EXPERIMENTAL RESULTS: VALIDATION OF THE FABRICATION SYSTEM AND DESIGN POTENTIALS

With the physical production of two prototypes, the acoustic functionality and design space of the developed fabrication system could be demonstrated. The two prototypes achieved a variety of formal conditions by transitioning from smooth to accentuated and from flat to curved, indicating the experiential and spatial qualities that such a system can provide (Figure 15, Figure 16 and Figure 17). Of particularly phenomenological interest are the expressive and light qualities of the system, uniting spaces through diffused transparency. Also remarkable is the possible "softness" of a surface and the play with actual and perceived depth, all created through a systematic placement of one identical object and its insert.

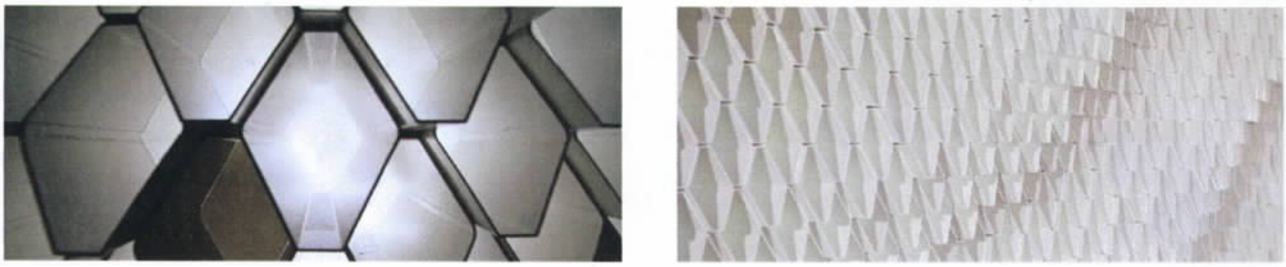
14 Visual feedback indicating the estimated acoustic performance of a design during the design process (white indicating a minimal local surface depth and red indicated the target depth of 200 mm). The graph shows the overall distribution of the depth, which should optimally be as equal as possible.



15 First prototype (Gramazio & Kohler, ETH Zurich, 2014)



16 Second prototype (Gramazio & Kohler, ETH Zurich, 2014)



17 Details of the 1:1 prototypes (Gramazio & Kohler, ETH Zurich, 2014)

18 Measurement setup (Eggenschwiler, EMPA, 2014)

VALIDATION OF THE ACOUSTIC PERFORMANCE

The physical realization of prototypes validated the acoustic performance both qualitatively, through personal experience, but also quantitatively, through evaluative metrics. Fifteen test subjects were asked to perform a small test to experience the effects of a diffuse sound field themselves. Because this experiential test works best through active speaking and passive listening, they were asked to read and listen to a poem in front of the walls. The feedback derived from these tests was significant, because the subjects reported similar experiences; for example, higher self-confidence when speaking and a remarkable ease in focusing on what has been said. Another common remark was that the diffusors effectively influenced the perception of space: the surrounding seemed to be larger than it was which was reported as a surprising but very comfortable experience.

The quantifiable measures were done in a stereotypical office environment. This evaluation happened in a 5.8 x 6.8 x 3.0m large room with flat walls furnished with tables and chairs and equipped with an absorbing ceiling. The tests were conducted using the DIRAC measurement system by Empa (Figure 18). Without an acoustic treatment, unpleasant flutter echoes generally characterize the room acoustically.

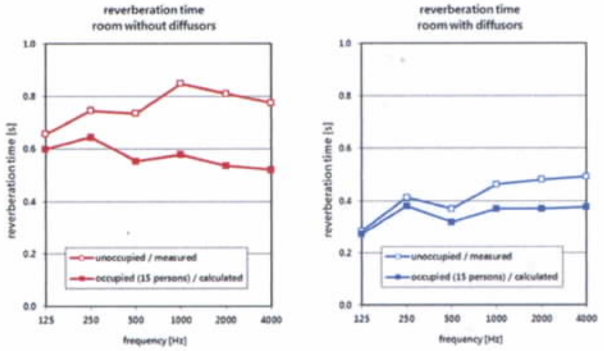
The results of this analysis were promising, because a clear reduction of the reverberation time became visible. This reduction is an indirect proof of the efficient scattering. The sound waves are scattered and also directed to the absorbent ceiling. The reduction of the reverberation time cannot be explained alone by the inevitable absorption of the diffusers. In addition, a maximal improvement of the speech intelligibility index STI of 0.11 (from 0.69 without to 0.80 with diffusors) could be registered. Flutter echoes were no longeraudible, which was also clearly visible when comparing the room impulse responses without and with diffusors (Figure 19).

CHALLENGES

The projects primary goal of transforming existing diffusor typologies into a customizable design object, producible under industrial conditions, was achieved. However, the project initiates new questions for further research and development. Several of the important challenges and future areas of development include:

1. Clear guidelines for possible deployment scenarios will have to be developed to simplify the integration into prototypical architectural design processes.

2. Digital acoustic simulation and advanced geometry processing is critical to validate the existing rule based strategy by demonstrating that the generated acoustic diffusors empirically validate their estimated diffusive capacity.



19 Measurement results

3. The computational accessibility of the fabrication process (digital interfaces, process adaptability, etc.) is a critical part of the further development.

4. Development and fabrication of further acoustic brick variations is valuable to the continuation of the research and eventual market success of the project.

CONCLUSIONS

This project demonstrated the viability of using robotic fabrication in the production of highly versatile acoustically performative walls. Due to the formal parameters which significantly impact the acoustics of a space through diffusion, in particular differentiated and aperiodic surface depth, a system was developed based on a simple translational degree of freedom of a unit and a secondary insert. Such a maneuver when enabled with the unique placement implicit in a robotically controlled additive assembly fabrication workflow has wide ranging design and architectural possibilities.

The underlying collaborative model which supported this project offers many opportunities that differ from the typical framework of an either purely academic or purely industrial project. Ultimately, the project makes a case for new research models, combining the experimental and research orientated approach in an academic setting with the market driven interests and industrial material and technology expertise. Such a model can ultimately generate new forms of design knowledge, both validating existing hypotheses and eliciting new research and market opportunities.

ACKNOWLEDGEMENTS

The research presented here was conducted in a collaborative model between three partners, led by the Chair of Architecture and Digital Fabrication, Prof. Gramazio, Prof. Kohler, ETH Zurich, supported by the Laboratory for Acoustics/Noise Control of Empa, Swiss Federal Laboratories for Materials Science and Technology and REHAU Vertriebs AG, a company specialized in the production and processing of polymer products. Necessary and substantial insights into the principle of diffusion were given throughout the entire project by Jürgen Strauss.Financially, this work was supported by the Swiss Innovation Promotion Agency (CTI) (grant number 12043.3 PFES-ES). Further, the authors want to thank Rainer Bollhorst, Guilherme da Silva Carvalho, Luis Gisler, Volker Helm, Dr. Kurt Heutschi, David Jenny, Clemens Klein, Pyoung Jik Lee, Luka Piskorec, Stefan Plüss, Silvio Rödel, Dr. Jan Willmann and Thorsten Zwenzner for their individual contributions to make this work possible.

REFERENCES

Bonwetsch, T., F. Gramazio, and M. Kohler. 2012. R-O-B: Towards a Bespoke Building Process. In Manufacturing the Bespoke: Making and Prototyping Architecture (AD Reader), ed. Bob Sheil, 78-87. London: John Wiley & Sons.

Bonwetsch, T., R. Baertschi, and S. Oesterle. 2008. Adding performance criteria to digital fabrication–room acoustical information of diffuse respondent panels. In Silicon + Skin_Biological processes and computation, proceedings of the 28th annual conference of the association for computer aided design in architecture (ACADIA), 364-369. ACADIA. Minneapolis, Minnesota.

Brady, P. 2009. Parametric Acoustic Surfaces. In reForm, Proceedings of the 29th annual conference of the association for computer aided design in architecture (ACADIA), 174-181. ACADIA. Chicago, Illinois: The School of the Art Institute of Chicago, 2009.

Choi, Y.-J.. 2013. Effects of periodic type diffusers on classroom acoustics. Y.-J. Choi. Applied Acoustics 74 (2013) 694–707 London: Elsevier.

Cox, T., and P. D'Antonio. 2009. Acoustic Absorbers and Diffusers: Theory, Design and Application. London: Taylor & Francis.

Gramazio, F., M. Kohler, and J. Willmann. 2014. The Robotic Touch: How Robots Change Architecture. Zurich: Park Books.

Gramazio, F., and M. Kohler. 2008. Digital Materiality in Architecture. Baden: Lars Mueller Publishers.

Handel, S. 1989. Listening: An Introduction to the Perception of Auditory Events. Cambridge: The MIT Press.

Strauss, J. 2012. Acoustic perception of space. In tec21(36/2012), 22-25. Zurich: espazium.

Willman, J., F.Gramazio, M. Kohler, and S. Langenberg. 2013. Digital by Material. In Rob Arch 2012: Robotic Fabrication in Architecture, Art, and Design. Wien: Springer Vienna.

IMAGE CREDITS

Figure 1. Gramazio & Kohler, ETH Zurich (2014), Acoustic Brick Wall.

Figure 2. Gramazio & Kohler, ETH Zurich (2010), Foam diffusors.

Figure 4. RPG.Inc (2014), http://www.rpginc.com/.

Figure 6, 11, 15-17. Gramazio & Kohler, ETH Zurich (2014).

Figure 18. Eggenschwiler, Kurt, EMPA Dübendorf (2014), Measurement Setup.

All Diagrams: Gramazio & Kohler, ETH Zurich (2014).

MAX VOMHO received his Diploma in Architecture with distinction from Stuttgart University. His professional experience spans from work at Herzog & de Meuron to his works as computational design consultant and covers many scales, from furniture to full scale concert halls. In 2012 he joined ETH Zurich to lead an interdisciplinary research project that focusses on the robotic fabrication of acoustic walls.

LAUREN VASEY received a Bachelor of Science in Engineering from Tufts University, cum laude, and a Masters of Architecture from the University of Michigan, with distinction. Currently she is a Doctoral Candidate and a Research Associate at the Institute for Computational Design (ICD) at the University of Stuttgart where her research focuses on materially driven computational methodologies.

STEFAN BRAUER studied mechanical engineering and polymer processing at the RWTH University of Aachen. In 1997 he joined REHAU AG&Co, where he is in charge as a technical director for furniture systems and products. During that time he was also responsible for the development of several acoustic products for the furniture industry.

KURT EGGENSCHWILER studied electrical engineering at the Swiss Federal Institute of Technology (ETH) in Zurich. Since 1985 he has been with the Laboratory of Acoustics at Empa Materials Science and Technology, Duebendorf, Switzerland, and is presently the head of the laboratory. His main interests are room acoustics and environmental acoustics in research, development, and consulting.

FABIO GRAMAZIO is professor for Architecture and Digital Fabrication at the Department of Architecture at ETH Zurich. In 2000, he founded the architecture practice Gramazio & Kohler, which has realizedw numerous award-winning projects. Opening also the world's first architectural robotic laboratory at ETH Zurich in 2005, Gramazio & Kohler's research has been formative in the field of digital architecture, creating a new research field merging advanced architectural design and additive fabrication processes through the customized use of industrial robots.

MATTHIAS KOHLER is professor for Architecture and Digital Fabrication at the Department of Architecture at ETH Zurich. In 2000 he founded the architecture practice Gramazio & Kohler, which has realized numerous award-winning projects. Since 2014 he leads the new National Centre of Competence in Research (NCCR) in Digital Fabrication supported by the Swiss National Science Foundation (SNSF).

JURGEN STRAUSS completed his training to become a physics laboratory technician at Landis & Gyr / Zug. He specializes within the electroacoustic field on the development and production of loudspeakers and public address systems for studios, concert halls, churches, museums and cinemas. Through the combination of electro and room acoustics, his sphere of activities expanded into architecture and sound engineering.