DESIGN STRATEGIES FOR A 3D PRINTED ACOUSTIC MIRROR

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Abstract. Large scale binder-jetting additive manufacturing has been available since almost a decade. While it offers great opportunities for the fabrication of complex ornate forms, so far, the potential of this printing method is not fully explored. Moreover, binder-jetted objects have never been tested for outdoor use and performance, because of the weak bond of the printed parts. This paper presents a design strategy that makes possible the fabrication of large, outdoor installations, with such a fragile material as printed sandstone. The presented process was developed for a full-scale installation of acoustic mirrors that was designed, manufactured and post processed in only a few steps. In the larger picture, this paper discusses how 3D printing can allow for design optimisation and reduction of material, while it proposes post-processing methods that strengthen and seal the printed objects for exterior use.

Keywords. 3D printing; acoustic mirror; topology optimization.

1. Introduction
With its performative form, engineered to create a spatial acoustic effect whilst being structurally optimised for efficient material use, the installation “Acoustic Mirrors” showcases the potential of computational design and large scale 3D printing for construction (see Figure 1).

New fabrication technologies have allowed architects and designers to explore the possibilities of design space within this new domain. This paper discusses the potential of 3D printing sandstone in the aspects of design opportunities and challenges the arise from the fabrication of a large-scale, sonic installation, following a publication of the same project discussing in depth the fabrication and post-processing strategies (Kladeftira et al. 2018, pp. 328-335). How can AM inform our approach to design, how can we rethink the way we envision the appearance of things we already know by investing in new production methods?

Additive manufacturing (AM) has been long used for fabrication in other fields, such as the automotive industry, but the fabrication of parts for the build environment is still a challenge, especially for large components of exterior use. The question of how AM informs our design still remains open. In the
chapters to follow, this question is addressed with an insight on a customised computational process that bridges the structural form-finding of a brittle material and construction detailing with design aesthetics and fabrication.

![Figure 1. The sandstone Acoustic Mirror (ETH Hönngerberg Campus, Zürich, 2018).](image)

1.1. OPPORTUNITIES OF FABRICATING FREEFORM GEOMETRIES WITH ADDITIVE MANUFACTURING

Since AM was identified as a promising fabrication method, it has been a challenge to bring 3D printing in the larger scale, more so, when bridging 3D printing and construction manufacturing poses challenges in the fabrication time and required tolerances (Lim et al. 2012, p. 262). Nonetheless, AM still offers great advantages that make it relevant for the construction industry such as mass customisation, high precision and easy fabrication of complex geometries.

The recently fabricated Smart Slab at the DFAB unit of EMPA in Zürich, Switzerland has shown how one can produce highly articulated building components out of concrete using 3D printed formwork, while reducing the weight of construction and on-site assembly time (Aghaei-Meibodi et al. 2018, pp. 320-327). Binder-jetting AM has also been used by the Block Research Group to fabricate a compression-only, shallow-vault, sandstone slab. Using graphic statics, they managed to use this brittle material to reduce by 70% the weight of a conventional building slab (Rippmann et al. 2018, p. 258).

However, there is unexplored potential that lies in binder-jetting technology, as the biggest industrial printer reaches the building volume of 4000x2000x1000 mm. It also offers great advantages in comparison to other 3D printing methods as it requires no support material and is a very fast printing method, it has great bending strength, offers high resolution (200-300μm) and uses a sustainable material with no residues (Dillenburger and Hansmeyer 2014, p. 94). Nonetheless, long-term
performance of binder-jetted sandstone remains completely unexplored.

In parallel, there are still no studies about the performance of bound silica sand for exterior use, or its response to changing environmental conditions. This research project addresses exactly these issues with a strategy for design and fabrication of sandstone, while presenting an opportunity to get measurable data of this building material, by continuous use and exposure to real world conditions and constraints.

2. The Acoustic Mirror

Acoustic Mirrors, Sound Mirrors, Whisper Dishes are all different names for the same device. Although, their concept dates back to ancient times, the first practical applications of such a device was during the 1930s (Wahlström 1985, p. 418). These concave dishes are passive devices that reflect sound waves in a parallel plane and reconcentrate them to a focal point. They have a parabolic shape that guarantees the unique existence of this point and usually work in pairs to act as an emitter and a receiver, respectively. Sound waves fade away as they leave the source and travel distance gets longer, whereas acoustic mirrors contradict this sonic effect. As a result, people can paradoxically communicate over very large distances without any other equipment.

As far as their fabrication is concerned, recently constructed acoustic mirrors, are fabricated as massive concrete/stone structures, or in steel, placed upon a standardised steel structure. Although concrete is a robust material for outdoor use, it is also not an easy one to produce formwork for, when dealing with non-planar geometries. Scaffolding and custom-fitting machined parts with traditional methods require equipment and excess human labor, increasing significantly the budget, while fabrication tolerances grow bigger for non-standard elements. As the increase is exponential when the geometry is 3-dimensionally freeform, it is impossible to fabricate conventionally, therefore, all fabricated acoustic vessels have very regular back structures.

2.1. THE REFLECTIVE SURFACE

Acoustic mirror designs are primarily driven by the shape of their curved surface. This is the sole element that defines in all examples the size and the overall geometry of the object. As different parabolic shapes and sizes correspond to different areas of influence and accuracy, this is the first element that needs to be determined. Relatively high accuracy is needed in the construction of this surface to ensure a successful reflection; the specific shell must have a fabrication and finishing accuracy higher than the smallest wavelength of the range of sounds perceivable by the human ear (100 to 2000 Hz), which corresponds to 8mm, making this installation a very good test case for the specific fabrication method.

The geometry of the mirror’s cap is defined according to the following criteria, in order to achieve the maximum sound amplification:

- the shape of the reflective surface (spherical, parabolic, etc.)
- the position of the focal point and
- the fabricated depth of the parabolic shell.
The size and shape of the parabolic cap, that also dictates the position of the focal point in relation to the structure are identified through a series of tested scenarios with the aid of a custom software provided by the EMPA Research Institute and developed by Dr. Kurt Heutschi. This custom software analyses and displays the propagation of sound in the free field, as well as how different parabolic shapes in specific positions affect this travel path and the intensity of the emitted sound.

The simulation is 2-dimensional and tests different configurations of various parabolic shapes in differentiated distances (see Figure 2). This way one can test scenarios where, for example, the user, or mirror, is not positioned exactly at the focal points, or the distance of the installation increases. Through a series of comparative graphs, the designer can evaluate the optimal shape and size of the reflective surface needed for the maximum amplification (in dB) in a specific setup, considering all the factors. This, also, acts as an evaluation table to identify the tolerance of the system and whether the amplification of sound is adequate for a perceivable sonic effect.

The chosen parabolic surface for the installation over 50 meters in the ETH campus with focal accuracy of 70mm, after a series of test runs, is a spherical cap of 1000mm radius. Both its center and focal point are situated at the height of 1550 mm, to match an average human height of 1700 mm. The analysis demonstrates that the amplification effect is fundamentally related to the curvature of the reflective surface. Several tests of different section sizes point out that the performance of the installation is augmented as the radius becomes smaller. In this respect, the final 1000mm-radius shell achieves an amplification of approximately 15dB, which allows a perceivable difference in the receiving end.

3. A design strategy for sandstone acoustic mirrors

3.1. PROPERTIES OF SANDSTONE

Considering the design parameters and tolerance expectations, binder-jetting AM provides good dimensional accuracy for the fabrication of the acoustic mirrors. However, silica sand shows little to no tensile strength, due to the material properties and the binding process. That is precisely the reason applications so far have used sandstone prints as an intermediate state of manufacturing and not directly as the end product. However, with additional post-treatment the objects can be stiffened after printing by epoxy resin infiltration, hardening by baking,
surface treatment etc., or a combination of those.

On the other hand, the same material behaves well under compression force in a range dependent on the binding material and further resin infiltration. More specifically, resistance ranges from 8.4MPa-12.8MPa for furan-based binder and 8.5MPa-12.3MPa for phenolic binder. These properties were taken into consideration while designing the overall form of the two objects, as the installation should abide by safety regulations and will be used daily by hundreds of visitors.

3.2. OPTIMIZING THE MATERIAL DISTRIBUTION

Considering the given properties of the material and fabrication process as an opportunity for a completely different approach to the design of acoustic mirrors, topology optimisation (TO) was used for optimal material distribution to critical areas where stiffness is required and topological form-finding to limit tension forces within the geometry. The increasing number of applications of TO in engineering solutions exhibit the potential of this method to evaluate form and structure jointly. Many examples can be found in the architecture field, such as the QNCC designed by A. Isozaki (Bialkowski 2016, p. 258), or Arup’s optimised node designs, that maximize structural performance (Ren and Galjaard 2015, pp. 35-44).

For this specific project, a multi-level sub-structuring eigensolver finds an optimal material distribution and topological arrangement of the supporting pillars. The algorithm is used as the basic form-finding tool that is later refined according to the design intention. During the iterative process of optimisation design inputs, geometrical constraints and structural evaluation are integrated to achieve the desired objective. An input geometry is provided, in this case, the 2000x2000x1000 mm bounding box with the subtracted volume of the spherical cap, calculated earlier. The material parameters required for the description of the object’s behaviour are set according to the properties of silica.

Given the outdoor placement of the installation and the local climate conditions, the active forces on the geometry can be summed up as the self-weight/gravity, and the wind pressure forces. Finally, the optimization task is performed to reach the goals set for this project; minimal strain energy and reduction of material to a fraction of 0.3 of the massive printing bounding box (see Figure 3a).

3.3. DESIGN REFINEMENT

The new design space resulting from the optimisation algorithm is refined in the Rhino/Grasshopper environment. Following the distribution of material, a three-point support base is generated following the trajectories of the stress paths provided by the TO software. This buttress structure, referring to gothic stone architecture, consists of two ribs on the back side to withstand wind pressure, and four in front, blending into one, that bear the cap’s self-load. The two sides are interconnected with thinner ribs for extra stiffness. A parametric definition builds the initial skeleton into organic ribs of different section profiles, which are blended in a specified sequence (see Figure 3b).
The thickness of the spherical surface is revisited as well, after consultation with the printing partner, to meet the minimum binder-jetting requirements and prevent cracks and holes during printing. The large surface contributes a substantial amount of mass to the overall structure. In order to reduce this mass and stiffen the shell, an organic hierarchical microstructure was designed to branch from the main support elements and subdivide the overall backside with stiffening ribs. With this shape/topography optimisation, the thickness of the spherical cap could be reduced from 50 to only 23mm. Lastly, symmetry on the vertical axis is maintained for better performance (see Figure 4).
then adjusted within the parametric setup to prevent tilting and ensure structural stability. The volume of the final redesigned geometry is 0.28 m³, in line with the TO results, while the weight is only 600Kg of a stone object of 2000x1350x1000 mm.

3.4. INTEGRATING CONSTRUCTION DETAILS IN THE WORKFLOW

Refining the overall geometry was challenging mainly because of the integration of details for the final installation on site. Safe rotation and lifting of the mirror from the printbed needed to be addressed as it was printed flat and not in the direction to be installed. Stability was required and achieved in the flat and vertical position, but also for the rotational moment. The position of the gravity center also came into play here, as its relation to the lifting points was crucial for this operation. Lastly, secure installation on site required anchoring details to the ground.

The lower, seemingly solid, part of the object consists of two parts, a solid upper layer and lower waffled substructure with integrated cylindrical voids (D= 40 mm) in the X,Y axes, which can accommodate metal lifting bars (see Figure 5). On its top surface, an engraved area indicates the position of the calibrating tool, which will ensure the perfect alignment of the two focal points. For the alignment on the vertical axis, a leveling steel plate is integrated. The connection of the steel plate to the object is achieved by four vertical steel plates, that will host threaded rods anchored at the two sides of the printed object. These provide support for taking tension forces in extreme cases of wind pressure, where minor displacements within the tolerances might occur. To test the quality of the final result test prints of different scales were produced to examine all the parameters. As a benefit of the specific fabrication technique, custom pieces are printed within the same print job to cover seamlessly the anchoring detailing, as well as the holes for the lifting rods.

3.5. POST-PROCESSING

3D printing sandstone is characterised by its porosity. As the loosely packed sand will result, after binding, at approximately 64% of solid material (Hodder, Nychka and Chalaturnyk 2018, p.2), it is necessary that printed parts receive additional post processing to meet the qualities of structural elements. Among those is the bearing
capacity of the object and the ability to withstand changing weather conditions and fluctuations in temperature. There are risks involved due to absorption of water, development of cracks in the surface, exposure to UV lighting, and non-uniform deformations due to low resistance of the material bond (Kladeftira et al 2018, p. 330).

Tests of different sealing resins were made on test bars to achieve both structural strengthening of the printed silica sand and sealing of the material pores in order to make them water resistant. The test bars were exposed alternatively to different environments -hot, cold, humid, dry- in order to identify the most suitable one for outdoor use. Out of four sealants, only one was found to meet the quality of a finished building material in terms of performance and surface quality. Its chemical base is silane-based impregnation in ethyl alcohol and performed well as it penetrated deep into the surface, thus, showed great resistance in absorption of water, while providing UV resistance without yellowing of the material. As an additional step, acrylic paint was applied on the resin-infiltrated object for aesthetic reasons, but also as a final sealant and water repellent of the outer surface.

The post processing steps are crucial for the printed object as it only gains its final attributes after the aforementioned process. For this reason, it is important to consider in the design process whether the printed object will be post processed in the same facility or it needs to be transported while in the state of intermediate strength. This information might affect the design attributes of the object as lifting from the print bed, packaging and transporting may cause stress in the material that will result in failure of the bond. However, a related advantage of post processing is that the surface, even if minor faults occur, can still be treated during this process with filling resin or paste materials applied at the surface, before spraying the infiltration layer (see Figure 6).

4. Results and Outlook

The two acoustic mirrors were printed, post processed and installed successfully on the ETH Hönggerberg Campus for visitors’ use. During the testing process small scale prototypes were made to test the feasibility, stability, aesthetics, vapor-water permeability, and fumes of the infiltration resin. These were helpful for validation and identification of flaws in the process, but most importantly to shed light
on improvements during the refining of the geometry that resulted from the TO algorithm.

Examining the test prints and in contact with the printing company it was possible to determine the proper thickness of the redesigned ribs and reflected surface, as the object was not optimised for lifting and rotating from the print bed, but only for its permanent positioning. The key achievement was to determine the suitable design strategy for the material properties of silica sand by addressing the low tensile capacity as a design driver rather than an obstacle. The mirror, designed for reducing tension forces to the minimum, making this production method a suiting fabrication technique.

Another achievement was the finding of a suitable infiltration material that protects the object from the changing weather conditions of Zurich, Switzerland. Among the sealants proposed by our partner company, we found that the infiltration material plays a big role in the material behaviour long term and identified the suitable resin for outdoor use. The two objects have now been standing outdoors for four winter months, which are the most crucial in Switzerland, and have exhibited excellent performance, showing no sign of wear, despite sudden fluctuations in temperature (±15°C) or rain.

Lastly, such a geometry, requiring high accuracy, with a complex substructure could not have been fabricated with a traditional technique, as it would be very expensive and time-consuming to manufacture the 3-dimensional supporting structure. The geometric freedom offered by sand binder-jetting complements the design approach by offering a single process of production for specialised forms.

The project also highlighted areas where future research would need to investigate further. The following topics would need to be addressed in the next steps for future applications:

- Tests on the structural strength and durability of the parts after a long exposure to outdoor conditions. Forces should be gradually applied on the object to determine the point of failure. Metrics of the surface quality and overall behavior should be provided during the long exposure in different weather conditions.
- Additional research on different types of binding chemicals. This method used furanic binding agents, but inorganic alternatives, environmentally friendly, should also be tested in combination with the infiltration resins.
- Investigation of smart joining systems for larger parts than the printing capacity of a single printer. This will inform the geometry of the prints and watertight sealing mechanisms should be tested.

5. Conclusion

The installation of two mirrors (see Figure 7) showcases how a cutting-edge digital fabrication technology can be used to produce bespoke, performative objects for outdoor installations, in a two-step process. It addresses the topic of scaling up AM for realising unseen, complex architecture by proposing a complete method of designing and 3D printing sandstone, overcoming the restriction of indoor use.

The so-far unknown ageing behavior and life expectancy of the material
are addressed to provide valuable information for further applications in a cost effective, direct manner. It can be considered a step in a long process of standardization of silica sand as a building material.

Figure 7. Test Installation in ETH, Zürich, 2019. Photo by ©Axel Crettenand.

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