Robotic AeroCrete

A novel robotic spraying and surface treatment technology for the production of slender reinforced concrete elements

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This research paper presents a novel method for robotic spraying of glass-fibre reinforced concrete (GFRC) on a permeable reinforcement mesh. In this process, the mesh acts as a functional formwork during the concrete spraying process and as reinforcement once the concrete is cured, with the goal of producing slender reinforced concrete elements efficiently. The proof of concept presented in this paper takes inspiration from ``Ferrocement'' technique, developed in the 1940s by Pier Luigi Nervi (Greco, 1994) and shows how robotic spraying has the potential of producing such slender and bespoke reinforced concrete elements while also having the potential of reducing manual labour, waste and excess material. The system is coined with the name ``Robotic AeroCrete'' (or RAC) in reference to the use of an industrial robotic setup and the pneumatic projection of concrete.

Keywords: *Shotcrete, Digital Fabrication, Robotic Fabrication, Ferrocement*

1. INTRODUCTION

Concrete is one of the world's most ubiquitous materials and has been dominating the building sector around the globe for centuries due to its low cost, availability, and versatility. However, when casting geometrically complex elements from concrete, the economic and ecological consequences of fabricating the required bespoke formwork can be limiting, often to an extent, that it prohibits the design intention. With the aim of circumventing the constraints of formwork, several industry and research institutions have been investigating methods that enable to create complex geometries from concrete without the need of expensive formworks, these methods range from 3D printing of concrete to methods using flexible mould systems of various kinds (Wangler et al., 2016). However, only few of these new methods enable the inclusion of structural reinforcement. One such approach is demonstrated by the research project Mesh Mould, where a volumetric or single layer matrix is robotically fabricated to unify formwork and reinforcement (Hack et al., 2017). Yet, this approach currently requires manual concrete casting and surface finishing. One solution to overcome this bottleneck could be Robotic AeroCrete, which takes its starting point ShotCrete, where the fresh material is conveyed, placed and compacted at the same time for the construction of large monolithic concrete surfaces such as tunnel constructions, slope stabilization and general erosion control, just to mention a few.

Recent research of shotcrete 3D printing developed at ITE TU Braunschweig, 2018 demonstrated the potential of the robotic application of shotcrete for architectural structures (Hermann et al., 2018). However, mainly limiting the process to the spraying of horizontal layers, similar to 3D printing. The Smart Slab by dbt ETH Zurich was realised by manually spraying Glass-Fibre Reinforced Concrete (GFRC) onto 3D-printed sand moulds. With this technique, thin structurally efficient concrete structures could be produced for a real scale construction at the Dfab House at Empa, Dübendorf (Aghaei Meibodi et al., 2018). However, the process involved tedious manual work and indeed, in this case the formwork could only be used once. Another example of researching on material efficient concrete construction can be seen in the research project: Sparse Concrete Reinforcement in Meshworks (SCRIM) investigated at CITA, Copenhagen, 2018. This project investigates robotic fabrication of lightweight textile reinforced concrete elements by 3D concrete printing on a carbon fibre mesh (Ayres et al., 2019).

In contrast to the projects mentioned above, the research presented in this paper exploits the robotic application of fibre reinforced spray concrete by spraying onto a vertically positioned reinforcement mesh. This novel method is influenced by the "Ferrocement" technique, a method, where fresh concrete is manually thrown against a dense, self-supporting reinforcement mesh. This technique was used to produce material optimized structures, which in addition had geometric expressive and structural forms, as for example shown in Nervi's Magliana Pavilion (Greco, 1994) or in the Salone B Torino Esposizioni complex (Gargiani and Bologna, 2016). Today, Ferrocement is little used, due to the fact that the fabrication of such structures requires a significant amount of manual labour (Designing Buildings, 2019). However, the Ferrocement technique can be reinterpreted today, by combining it with robotic fabrication. Thus, the major goal of Robotic AeroCrete (RAC), the research presented in this paper, is to define suitable spraying strategies and to prove a high potential for using shotcrete for the production of bespoke slender reinforced concrete structures.The potential of RAC was demonstrated in a feasibility study (MASDFAB, 2018) in which an informed digital design workflow and robotic fabrication process was used to fabricate a slender reinforced concrete structure as featured in figure 1, that could function as a bus stop or shelter for a single person.

Figure 1
Robotic AeroCrete (RAC) Final Demonstrator

2. METHOD

Robotic Setup

In order to enable the robotic spraying and surface treatment of an arbitrary doubly curved mesh, a custom mobile robotic spraying setup is developed. The setup can be manually relocated and adjusted according to different workspaces and variable mesh sizes. It consists of a table-sized robotic arm "UR10" with a reachability of 1300mm (Universal Robots, 2019), mounted on a 1370mm steel col-

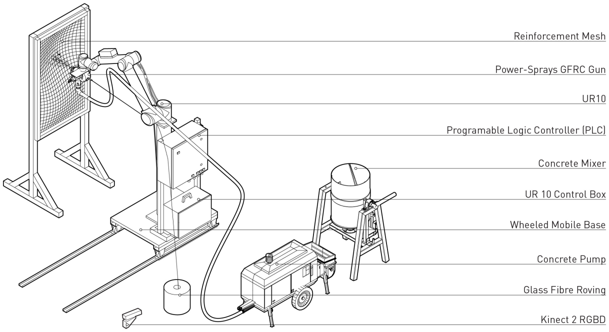


Figure 2
Mobile setup for the Robotic AeroCrete (RAC) process

umn and a wheeled steel base. The end effector is a "power-sprays" concentric GFRC spray gun (Power-Sprays, 2019) that chops glass-fibres in a chamber into desired lengths, and then mixes the wet concrete with the fibres at the nozzle level. The setup further includes a Kinect 2 RGBD sensor, a portable concrete pump, a high-shear concrete mixer and a programmable logic controller (PLC), with five pressure valves that control the pneumatic motor, concrete nozzle, fibre-chamber, spray-nozzle, and concrete pump. As illustrated in figure 2.

Design Process

As replacement of steel reinforcement, carbon fibre was chosen as the reinforcement, as this enabled to cut and bend woven textile carbon fibre meshes into doubly curved shapes easily. The mesh roving is 38x38mm (Solidian, no date). After a series of manual cutting and bending studies, a digital form finding process was developed. This process started with drawing a cutting pattern for the reinforcement, after which a mesh simulation algorithm was applied using customized physics engine software (Piker, 2017) where fixed edge length constraints were applied to the drawn geometry. This approach allowed to explore and simulate various design options as featured in figure 3.

The cutting pattern of the final chosen design was printed on paper and overlaid on the mesh to serve as a cutting template. Thereafter, it was elastically bent into the desired shape and tied with zip ties to a support structure (see Figure 4).

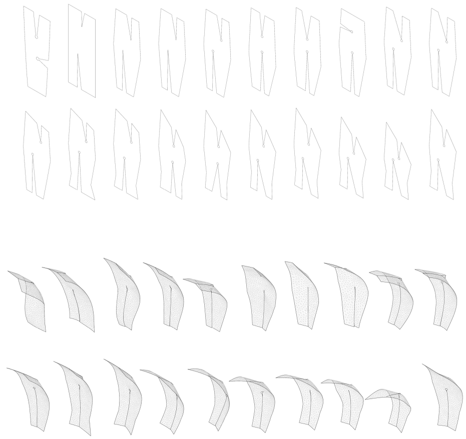


Figure 3
Design explorations using physics simulation

Figure 4
Mesh support structure

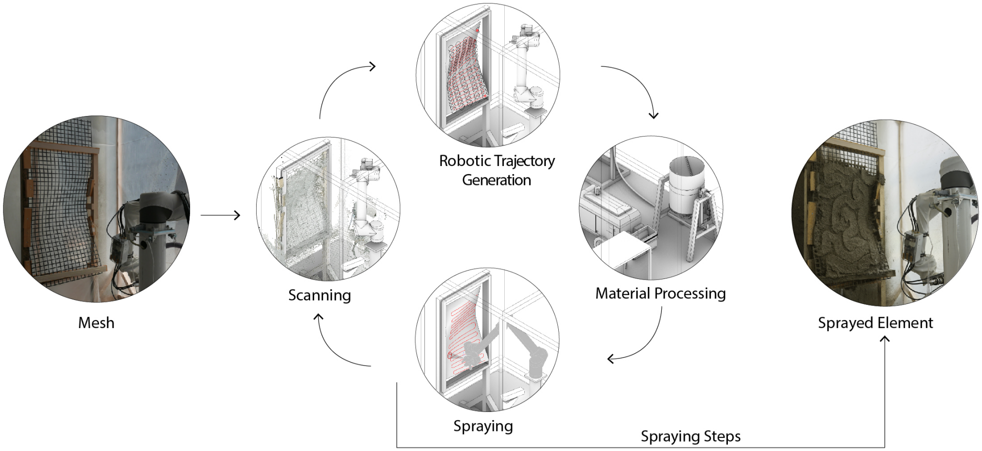


Figure 5
Robotic AeroCrete (RAC) Fabrication Process

Fabrication Process

To start a process a mesh is bent and stabilized into a desired shape that fits within the robot building space (see Figure 5). In a next step, the mesh is scanned using a Kinect 2 RGBD sensor. The obtained point cloud from the Kinect reconstructs the mesh surface using a customized software (Newnham, 2016) from this reconstructed surface serves as the base for the generation of the robot spraying trajectories. For the robotic spraying process, the concrete material is mixed and, pumped through a hose to the spraying gun, where it is mixed with glass-fibre at the nozzle just before it is sprayed onto the mesh. For the presented work, the process is repeated for several consecutive robotic spraying steps that will be explained in detail in the final demonstrator section.

The size of a designed mesh generally exceed the robot static workspace, therefore the setup enables to manually relocate and adjust the robot position. Thus, meshes larger than the robotic workspace can be produced. Three positions were predefined for the final demonstrator (see Figure 6).

Experiments

The initial experiments were conducted to define the operational values for the spraying process such as robot trajectory, speed, distances of spraying from the mesh, fibre length and spray nozzle orientation (see Figure 7). Here the experiments determining the optimal fibre length in relation to mesh opening size turned out to be crucial, as the correct relation was what enabled to clog the openings of the mesh and assure that the concrete adhered on the mesh while also assuring that excess of material penetrating through the mesh during the fabrication was minimized.In addition, a multitude of experimental trial and error tests had to be conducted to define the throughput of material and correct overlap of the spray path, to assure that the material was evenly distributed on the mesh (see Figure 8). Additionally, test were made to evaluate the hydration time of the sprayed on material.

After dozens of initial tests of which many have failed. One failure for example happened due to material adhesion ability to the mesh, where the overweighed material dropped after 10 minutes (see Figure 9). The following optimal values were obtained and later used for the final demonstrator's fabrication (see table 1).

Figure 6
Robot Predefined Spraying Positions

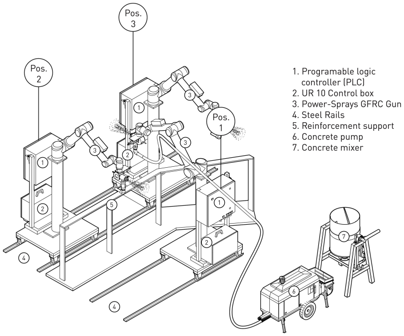


Figure 7
Spray nozzle orientation

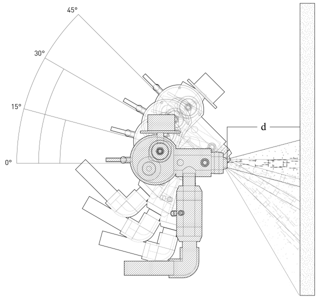
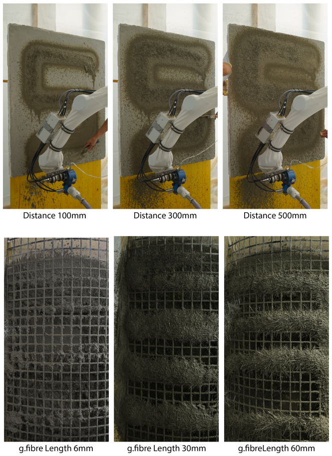


Figure 8
Left: spraying distance tests.
Right: glass-fibre lengths test results.
Each done in four angles as illustrated in Figure 7.



For the automation process, these listed variables were processed with the set up described in figure 6 using the customized software. As a final step prior, the production of the final demonstrator, a number of tests, not reported in this paper, were used to define four consecutive spraying steps that are summarised in figure 9 and will be further described in the section final demonstrator.

Final Demonstrator

Based on the initial experiments, which provided the nine needed calibration variables listed in table 1 and the five consecutive fabrication steps that are: 1) Scanning of mesh, 2) Bracing Paths, 3) Full Cover, 4) Microfibre Full Cover and finally 5) Microfibre Custom Paths (aesthetic pattern layer). The following section will describe each step that were also used for the fabrication of the final demonstrator.

1) Setup of mesh and scanning. The first step of the process was used to setup the mesh where after the mesh was scanned with Kinect 2 RGBD and reconstructed the obtained point cloud as surface geometry using a customized software (see Figure 10).

2) The first, diagonal spray bracing paths was generated by using an algorithm that takes the four edges of the digitally reconstructed surface as input, divides them into points and interpolates between them. The paths is generated for the front and back sides of the surface. Then the path planning was split following the three predefined robot positions (see figure 6). After the digital path was ready, the bracing path was applied on the reinforcement mesh (see figure 11). The bracing layer cured within 24h to increase the stiffness of the carbon fibre mesh, assuring that it withstands the weight of the subsequent fully GFRC cover layer.

Figure 9
Robotic AeroCrete (RAC) spraying steps.

robot trajectory speed	spraying distances (d)	spray nozzle orientation	glass-fibre length (3 blades)	robot paths overlap ratio
500mm/s	200mm	5 degrees	42.5mm	40%
air pressure supplied to spray gun glass-fibre chopping motor	**air pressure supplied to spray gun glass-fibre chamber**	**air pressure supplied to spray gun nozzle**	**air pressure supplied to spray gun concrete valve**	
2.1 bar	1.45 bar	2.20 bar	2.70 bar	

Table 1
The nine calibration variables needed for a successful spraying process.

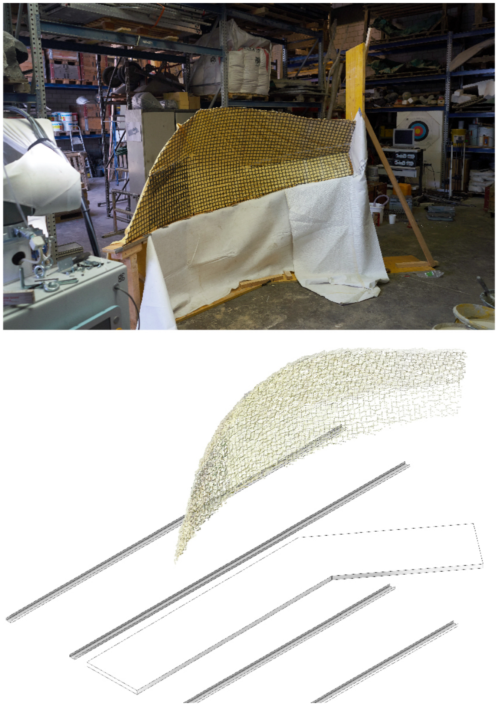


Figure 10
Top: the physical mesh with a fabric on the back-side to increase the contrast. Bottom: recorded point cloud from Kinect scanning process.

3) The GFRC Full Cover layer was applied with the house mix of BürginCreations, using the calibrated fibre length of 42.5mm. In this layer, the robot trajectories were derived from an algorithm that takes the whole digitally reconstructed surface as input and divides it according to spraying spread radius, which has been empirically determined through several experiments that comprised of several spraying distances from the reinforcement mesh. The robot trajectories were generated horizontally on the mesh's front-side, starting from bottom to top (see Figure 12). However, on the backside the path was generated vertically according to the predefined robot positions, starting from position three towards position two as featured in figure 6. After the robotic spraying process was done, manual compaction, using a rolling devise, was required to lay the glass-fibres flat and eliminate air-entrainment. Again as in the previous bracing layer, the GFRC full cover layer was left for 24h to hydrate.

4) The next layer, referred to as the Full Cover Layer in figure 9 principally serves as the surface finish layer. In this layer, the glass fibres were replaced

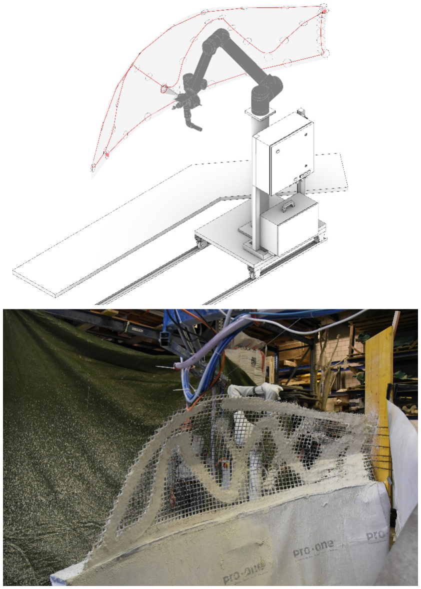


Figure 11
Top: the front-side digital GFRC bracing path. Bottom: the physical prototype featuring the sprayed material on the mesh.

by cellulose-based micro-fibres, in order to reduce shrinkage cracking. Again, as in the previous steps the trajectories were generated and split according to the three predefined successive robot positions, but in this case with a 90° rotation to assure better layer adhesion (see Figure 13).

5) An additional Custom Paths micro-fibre reinforced concrete layer was applied, demonstrating the ability to spray freeform trajectories robotically with varying robotic distances ranging from 300mm to 100mm and speeds ranging from 150mm/s to 300mm/s (see Figure 14). It resulted in several spread widths and material concentration. For this step, the spraying was done with higher-pressure value, 4.5bar for each of the spray gun's nozzle and chamber, to enable variation in the pattern.

After the shell was finalised it was released from the support structure and cast into a base using an off-the-shelve SCC. In its vertical position, the element's edges were manually cut with a circular saw and mortar admixture was applied manually to achieve a sharp edge finish.

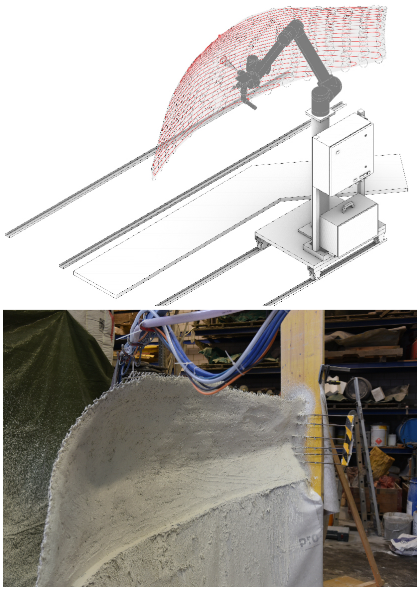


Figure 12
Top: the front-side digital GFRC full cover path. Bottom: the physical prototype featuring the sprayed material on the mesh.

3. CONCLUSION

Results and Conclusion

The research presented in this paper proposed a process of robotically spraying concrete directly onto an arbitrary shaped reinforcement mesh. This reinforcement mesh acts as a permeable functional formwork and facilitates the production of slender reinforced concrete structures. The final demonstrator featured in figure 15 is a cantilevering shell-like structure intended as a bus stop or shelter for a single person, with an area of 2.6m2 and an average thickness of 3cm, the 2.5m tall structure. The element weighs less than 80kg (300kg including the base). The final surface intends to demonstrate the potential of a process inherent surface quality, which indeed need to be further investigated in terms of design alternatives.

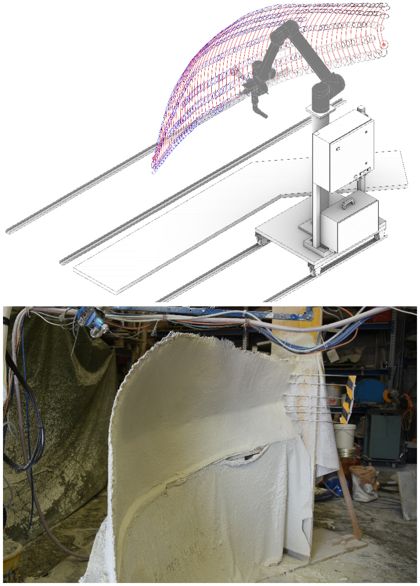


Figure 13
Top: the front-side digital micro-fibre-reinforced concrete full cover path.
Bottom: the physical prototype featuring the sprayed material on the previous GFRC layer.

RAC demonstrates a promising and efficient production process for bespoke slender doubly curved concrete structures without the need of single use expensive formwork, similar to Ferrocementi but revived in a digital age. Furthermore, the proposed process could be a viable method to support project such as Mesh Mould in particular in the application of surface finishing. In addition when using carbon as in this study, the concrete coverage could be reduced to 2-3cm in case of using textile carbon fibre reinforcement (Solidian, no date). The studies proved that achieving a smooth concrete surface using GFRC is possible, with the fact that it is sprayed on permeable formwork. The investigation culminated in a 1:1 final prototype that proofs that the developed process has the potential to enable a differentiated build-up of material and bespoke, perhaps structural ornamentation (Sağlam, 2014), directly from the reinforcement up.

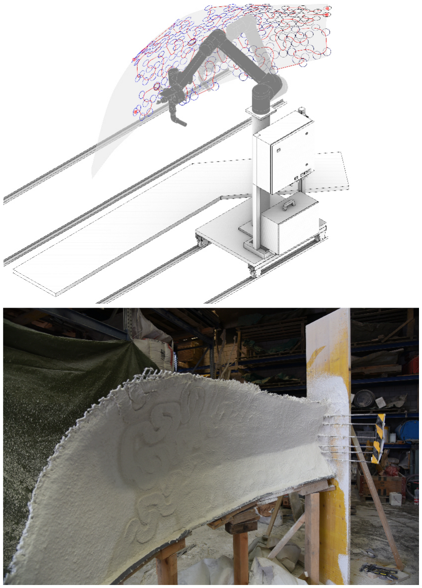


Figure 14
Top: the front-side digital micro-fibre-reinforced concrete customized paths.
Bottom: the physical prototype featuring the visible pattern on the surface.

Outlook

Indeed this proof of concept has only just started, but never the less if brought to industry, such process could be applicable for pre-fab elements, or for on-site fabrication. However, developing a fully functional robotic spraying system for bespoke elements will require further research. Thus, future steps will include development of a closed-loop control system for material handling and robotic control, inline sensing and feedback system. Additionally, the concrete material mix will need to be improved in terms of sustainability and life cycle concerns.

Spraying-related fabrication constraints should further inform the reinforcement mesh design, such as optimization of the mesh gaps sizes, computationally analysing the mesh surface curvature in relation to material adhesion ability. Further studies will need to explore 1) a mesh scanning methodology which can recognize the mesh directly instead of having to cover the mesh, 2) controlling the concrete pump feed rate, 3) synchronising the robot, the programmable logic controller and the concrete pump to allow for controlling air pressure values,

Figure 15
Left, Centre: Process inherent surface texture on front and back sides. Right: Final slender reinforced concrete Prototype.

thus the amount of sprayed concrete at certain path trajectories. The concentric spray gun could also be upgraded to allow attaching different nozzle types and allow for chopping different glass-fibre lengths through in-process blades manipulation. Optimum concrete curing time should also be explored. Furthermore, the potential use of conventional steel reinforcement meshes and the feasibility of a dual robotic spraying process need to be addressed and evaluated. The produced work gives a glimpse of what the future of construction with reinforced concrete might offer, enabled only by the symbiosis of digital fabrication and historic techniques.

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