ARCS: Automated Robotic Concrete Spraying for the fabrication of variable thickness doubly curved shells

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Abstract. The fabrication of doubly curved concrete shells traditionally poses challenges in terms of material deposition and formwork manufacturing. Recent advances in digital fabrication techniques including robotics in construction have created tools to better tackle these challenges. We present a digital fabrication system to accurately deposit cementitious materials onto doubly curved surfaces using robotic concrete spraying in a process for prefabrication of structural shell components we call *ARCS* (Automated Robotic Concrete Spraying). Using inputs of a generic variable thickness shell volume, a robotic path is generated to deposit material onto the formwork surface where required. Paths are generated on the surface using geodesic lines as guides in order to create iso-curves for evenly spaced spray paths. Additionally, layers are incrementally deposited to allow for variable thicknesses across the surface. This approach is flexible enough such that additional features can be embedded onto the shell such as ribs. We demonstrate this automated fabrication process on a 1.8 m by 1.8 m scale shell specimen.

Keywords: automated construction, digital fabrication, robotic fabrication, concrete spraying, robotic trajectory, concrete shells, fibre reinforced concrete.

1 Introduction

While shell structures are a materially efficient means of spanning large distances, their manufacturing has proven to be a costly endeavour. However, recent advances in digital fabrication techniques for concrete have the potential of lowering the fabrication cost of such members, increasing their attractiveness for structural use [1].

We present a system for the fabrication of double curved concrete shell members called ARCS (Automated Robotic Concrete Spraying), which robotically sprays glass fibre reinforced concrete (GFRC) to create concrete shell members. In recent years, the use of robotic concrete spraying has been explored as a means of digitally fabricating concrete shells [2] and walls [3]. ARCS is unique in that it focuses on providing a start to finish design process to generate the spray trajectory for the fabrication of a doubly curved surface for use along with a physical robotic setup.

This paper outlines the two main components of ARCS. Section 2 provides details regarding the generation of the robotic trajectory for the spray path as well as a sequence for spraying developed heuristically. Section 3 then details the fabrication, including the physical robotic setup and an example ribbed shell fabricated using ARCS. While the approach is general enough such that the GFRC material should be sprayable on any type of mould (e.g., curved fibre, rubber moulds, wax moulds, etc.), we demonstrate this using a timber lateral frame in combination with a flexible fabric formwork on a pin-bed mould [4].

2 Spray Path Generation

The general approach to spraying is performed on a per layer basis, reminiscent to a curved-layer printing approach for 3D printing where the layers are not restricted to flat two-dimensional slices [5]. This approach minimises material slumping or toppling compared to spraying the full thickness in one pass and allows spraying of variable thicknesses.

2.1 Methodology

To achieve a uniform distribution of sprayed material, a set of iso-curves for each layer is generated using geodesic lines as guides [6]. These geodesic lines are generated on an extended surface to ensure that the paths encompass the entirety of the target surface. The orientation of the geodesics are such that they are aligned orthogonally with the general direction that the spray path will be aligned to. Varying this direction along the layers provides a means of preventing material valleys and accumulation. The valleys can also be minimised by reducing the spray path distance, thereby creating overlaps between adjacent spraying curves.

Using these geodesic lines as distance functions, points are calculated along each curve which will be separated by a constant distance on the surface. The starting points are calculated based on an intersection between the geodesic lines with a starting curve – in this case an edge curve of the target surface. Connecting these points orthogonally creates the desired spray path as curves, which are finally trimmed to the target surface. Increasing the number of geodesic lines leads to more even separation between spray paths at the expense of increased computational time. The process described is illustrated in Fig. 1.

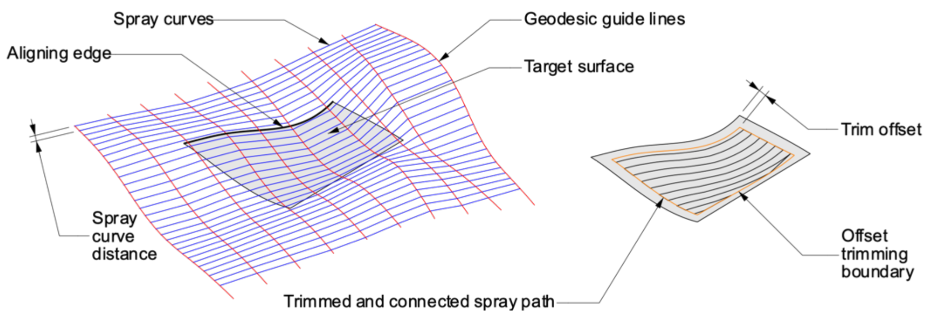

Fig. 1. Generation of evenly spaced spray paths using geodesic lines as guides. The spray curves formed on the extended surface are then trimmed to cover the desired target surface with an offset from the boundary.

Once the base spray path is generated, layering is then performed. A top surface which, in combination with the base target surface, is used to determine the regions which needs to be sprayed at each layer; by offsetting the base target surface by the currently sprayed thickness along the vertical, the intersection of the two surfaces can be used to determine the regions which requires additional material. This can be done consecutively after each sprayed layer until the entire volume has been sprayed, as shown in Fig. 2.

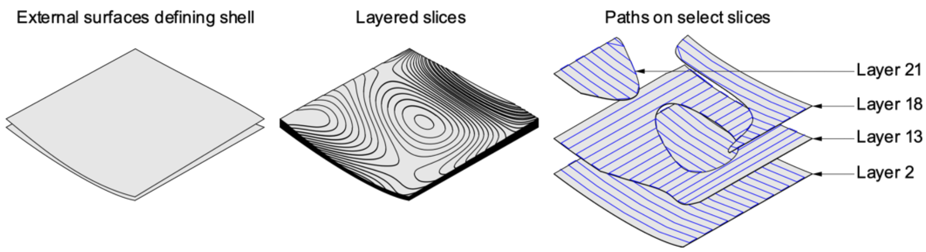

Fig. 2. Variable thickness is achieved by layering spray paths at regions determined by the intersection of the two external surfaces displaced by the current thickness. The layers create slices similar to contours on a shell.

The spray path generation is implemented as a plug-in in C# for the Grasshopper visual programming environment for Rhino3D. Robotic code compilation is performed by HAL Robotics – a Grasshopper plug-in which performs inverse kinematics based on target points and their orientations for robotic code generation. The orientation of the spray trajectory can also be controlled and is set to be orthogonal to the surface, except for at the boundaries which is sprayed at an angle from the normal to better reach the edges and corners of the frame.

2.2 Sequencing

Further control and refinement can be added to the previously described methodology by sequencing and chaining together separate spray paths. This allows designers to separate the process for different parts of the shell. For example, sequencing is especially useful for boundaries which benefits greatly from separate treatment compared to the interior of the shell to better reach the edges and corners of the timber frame. Furthermore, additional features can be integrated into the specimen through sequencing; here, ribs are illustrated as an example feature which are formed by adding separate volumes on top of the base shell.

The following sequence of stages (illustrated in Fig. 3) were found through iterative experimentation to produce high-quality GFRC prototypes:

1. Spray the bottom coating layers without fibre;
2. Spray half the required thickness of the boundary at an angle of 15° from the normal;
3. Spray the interior region targeting a reduced surface area to avoid excessive accumulation of material at the boundary;
4. Spray the remaining boundary layers;
5. Spray the ribs on the base shell volume;

7. Spray the top coating layers without fibre.

Manual corrections (stage 6) may be necessary due to inaccuracies arising from various parts of the process (i.e., misalignment of the frame, tolerances of the timber frame and its joints, disruption to airflow supply causing irregularities, etc.). At the expense of some manual intervention, this stage affords designers with the flexibility to compensate for these tolerances for a robust process. In addition to these stages, intermediary repositioning to a designated waste bucket was programmed in for practical fabrication purposes, such as to adjust any settings, change the fibre roving, or allow time to refill the concrete slurry into the spraying tank.

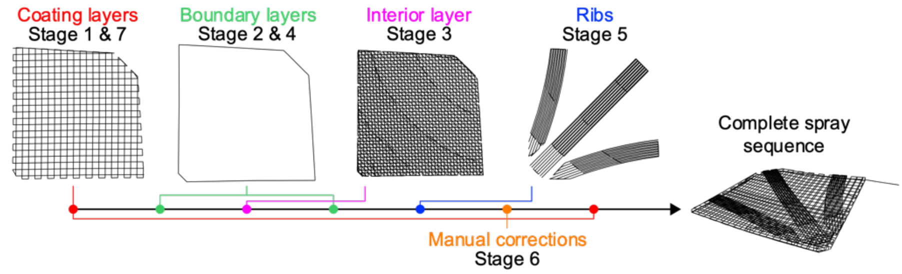

Fig. 3. Sequence of spraying for a ribbed shell, showing the various regions sprayed and how they overlay on top of each other.

3 Concrete Shell Fabrication

We demonstrate the previously described spray path generation method and sequencing on a prototype 1.8 m by 1.8 m doubly curved GFRC shell with integrated rib features.

3.1 Setup

Fabrication was carried out at the National Research Facility for Infrastructure Sensing (NRFIS) at the University of Cambridge. The robotic cell contains an ABB 6400R 200kg/2.8m six-axis robotic arm, a Power-Sprays PS9000i GFRC spray station, and a custom designed actuated pin-bed mould as formwork for the specimen to be sprayed on [4]. The spraying gun is attached to the end of the robotic arm using a custom gripper and deposits the cementitious material along with optional fibres that are chopped from a filament directly fed into the gun. The boundary of the shell is formed using a timber frame, milled with a handheld CNC router.

The recommended concrete mix by Power-Sprays has an approximate water to sand to cement ratio of 1:4:4 and density of 2.0 kg/L. The amount of water is adjusted to reach the required workability of 3 circles on the slump testing apparatus based on BS EN 11701:1998. Additional additives are added to help with curing, flowability, and to prevent separation of the slurry matrix when pumping. A fibre content of 5% by weight is targeted by adjusting the concrete sprayer machine settings. The suitable spray settings found mainly through testing and experimentation are shown in Table 1.

Table 1. Spray parameters used to manufacture the prototype shell.

Spray parameter	**Value**
Slurry output rate	12 kg/min
Distance of spray gun to top of surface	225 mm
Percentage overlap between adjacent sprayed paths	40%
Primary spray speed	350 mm/s

3.2 Prototype

An example shell fabricated using ARCS is shown in Fig. 4, with a dimension of 1.8 m by 1.8 m and a variable thickness ranging from 60 mm to 40 mm. The boundaries between the layers of the interior regions are visible during the spraying process. The ribs, visible on the final specimen, demonstrate the versatility of the approach in adding features on shell surfaces. A local thickening effect can also be seen in the edges of the shell due to the separate treatment of the boundary. While this deviates from the designed thickness, this thickening effect helps to reinforce the specimen at the edges which can be susceptible to honeycombing.

Fig. 4. Fabrication of a ribbed shell using ARCS: during the addition of one rib and with visible slice boundaries (left); and the cured specimen with visible ribs and faded layer boundaries (right).

The prototype demonstrates that the speed at which shells can be manufactured with the ARCS process is a benefit. Fabricating the prototype measuring approximately 1.8 m by 1.8 m took less than 30 minutes to complete thanks to a slurry output of 12 kg/min (or approximately 100,000 mm^3/s) – a volumetric rate that is considerably higher compared to conventional concrete 3D printing approaches which typically ranges from 300 to 25,000 mm^3/s [7].

4 Conclusion

ARCS provides designers and builders with a start-to-finish process to fabricate doubly curved concrete shells. Using a robotic arm and concrete sprayer assembly, material is deposited layer by layer where needed to create a variable thickness shell. Path generation is performed using geodesic lines as guides, and layering using -

curved slicing of the shell volume. The outlined spraying sequence and heuristics for robotic concrete spraying was able to quickly produce variable thickness shells with surface features, demonstrated through the prototype fabricated shell. This fabrication method was used to create a segmented shell structure as part of the Automating Concrete Construction (ACORN) research project (EP/S031316/1).

ARCS serves as a base by which further modifications will be incorporated. While only ribs were demonstrated, voids, holes, and graded concrete shells can also be formed using ARCS. In addition, the layering approach also lends itself to variable fibre content distribution across the shell surface and depth, enabling increased material and carbon efficiencies. Future work will also seek to increase the precision of the other aspects of the fabrication process, such as the accuracy of the timber frame, to minimise the need for potential manual corrections.

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