Extrusion Nozzle Shaping for Improved 3DP of Engineered Cementitious Composites (ECC/SHCC)

Wes McGee[1,2](✉), Tsz Yan Ng[1], Kequan Yu[2], and Victor C. Li[2]

[1] Taubman College of Architecture and Urban Planning,
University of Michigan, Ann Arbor, USA
wesmcgee@umich.edu
[2] Department of Civil and Environmental Engineering,
University of Michigan, Ann Arbor, USA

Abstract. This paper focuses on the development of a nozzle steering and shaping system for concrete 3D printing (3DCP) of Engineered/Strain Hardening Cementitious Composites (ECC/SHCC). The investigation highlights the development of an integrated system that includes robotic end-effector tooling, automated control associated with the delivery and deposition processes, as well as multi-axis nozzle steering for enhanced surface quality of the printed components. The results are discussed along with demonstrated prototypes. While significant improvements to the speed and efficiency of 3DP cementitious materials have been developed in recent years, only a few precedents, discussed in the paper, have aimed to improve geometric surface quality of the final printed components. In addition to improving the surface quality, the designed extrusion shaping process has the potential to improve mechanical performance of ECC by maximizing interfacial surface area and improving fiber alignment. Material effects will also be discussed in relation to the development of the overall system. An overview of the geometric capabilities and limitations of the proposed system will be presented in comparison with existing 3DP techniques.

Keywords: 3D concrete printing · ECC/SHCC · Computational design · Digital fabrication

1 Introduction

Additive manufacturing (AM), more commonly referred to as 3D printing, is poised to revolutionize the building construction industry. It has attracted significant commercial interest due to its potential to reduce time, labor, and material use, while improving overall building performance through computational optimization. The most promising application for the construction industry centers on concrete, where a significant portion of the construction cost is attributed to formwork production, often as much as 50% of total project cost [1]. Concrete 3DP (3DCP) holds the promise of reducing or eliminating the need for molds. One challenge to this process is that layer-based extrusion approaches do not yield surface finishes which can compete with molded concrete. While hybrid approaches, such as robotically post-finishing a deposited

F. P. Bos et al. (Eds.): DC 2020, RILEM Bookseries 28, pp. 916–925, 2020.
https://doi.org/10.1007/978-3-030-49916-7_89

surface [2] or troweling [3] have been tested, there are limitations to the geometric freedom of the printing process and overall formal complexity of the printed part.

Another widely discussed challenge to the adoption of 3DCP is the difficulty of combining the process with existing methods of reinforcement, which is required due to the brittle nature of concrete materials. Novel approaches to overcoming this limitation have been explored, including embedding continuous reinforcement, such as steel cables, as well as post-tensioning of structures [4]. Both approaches present compromises in the printing process or limit the design freedom of 3DP structures. Engineered Cementitious Composites (ECC) (also known as Strain-hardening Cement-based Composites, SHCC) are a class of materials which were developed to challenge the notion of concrete as a brittle material, and have been shown to possess significant ductility (as much as 400x that of normal mortars) [1, 5]. Not surprisingly, a growing number of research teams have focused on adapting 3DCP to take advantage of the self-reinforcing properties of ECC with polyvinyl alcohol (PVA) or polyethylene (PE) fibers [6, 7].

This paper will discuss the development of a robust system for 3DP ECC, including an extrusion nozzle shaping system and its influence on both the overall geometric form and surface finish. This research has multiple, inter-related goals. The first is to develop a 3DCP system compatible with ECC, which maximizes the geometric freedom of the deposition process while improving the surface finish to approximate that of cast concrete. The second goal is to prototype examples of full-scale building components that leverage the capabilities of the robotically controlled printing process. The paper will elaborate on the integrated design to fabrication methodology that enables direct translation from digitally designed geometry to machine toolpaths, taking advantage of the additional degree of freedom of the steering system. The developed software also enables geometric features such as variable layer height, and digitally simulates the printed result along with metrics such as material utilization and time estimation.

2 Challenges

2.1 Material, Process, and Geometric Considerations of 3DP ECC

The challenges of 3DCP are widely discussed and have been the subject of extensive research, particularly in relation to time-dependent rheological properties like pumpability and buildability. These challenges are typically identified within the three phases of 3DP, namely, mixing, transport, and placement - where equipment, process, and material have corresponding effects upon one another [8]. At a typical loading of 2% fiber by volume there is a significant impact on the rheological characteristics of the material. Additionally, there are secondary impacts that high fiber and high fly ash mixes have on the pumping system. While the addition of fly ash is known to increase pumpability, significant increases can cause bleeding. This effect, coupled with high fiber volume fractions, risks separation and blockage of flow in the system.

The material transport system is one of the fundamental components of 3DCP technology. The most common pumps used are either of the progressive cavity or peristaltic design. While both are considered positive displacement pumps, they each possess advantages and disadvantages. Progressive cavity (PC) pumps are known to work well with highly viscous materials and transported solids. They have highly linear flowrates relative to pump speed. At the upper end of the viscosity range this linearity depends on the inlet pressure being maintained. In the case of transported fibers, PC pumps have challenges which will be discussed in Sect. 3.1. Peristaltic pumps have similar capabilities for high viscosities and solids but have the disadvantage of significant pulsation, though this can be mitigated with pulsation dampeners. Their relatively open flow design improves the passage of fibers through the pump. It is also worth mentioning that peristaltic pumps, without any disassembly, are easier to clean and flush, whereas PC pumps require the removal of the stator from the rotor in order to remove any concrete and fiber buildup.

The other fundamental component of 3DCP is the deposition or placement process, which is coupled with a motion control system. Various approaches using CNC and robotics have been studied [3, 8, 9]. In order to achieve the goal of maximum geometric freedom, a minimum of 5 degrees of freedom (DOF) is recommended. In the case of extrusion nozzle shaping approaches, this increases to 6 or more. In order to support more complex toolpath geometries, such as branching structures, it also becomes critical that the deposition system be able to dynamically control the start and stop of the extrusion. There are two primary approaches to controlling this behavior, one utilizing a valve, and the other utilizing a frequency-controlled pump (and some approaches combine the two). A valve, being compact, can be located near the extrusion point, which improves the dynamic response of the system. Typical valves used in 3DCP are “pinch-valves”, but more study is needed to determine their compatibility with ECC. A frequency-controlled pump has the added advantage of allowing for different speeds of extrusion, either to match different speeds of the motion control platform, or to extrude layers of different thickness or width. Depending on the overall system arrangement, such as a supply pump feeding a long hose to the placement head, this approach may not offer enough control over start/stop dynamics. A critical component of this research is to explore an integrated approach which has highly dynamic control of material flowrate and start/stop behavior.

2.2 Surface Finish

In more common AM technologies, such as Fused Filament Manufacturing (FFF), surface finishes are governed by the layer resolution; smaller layers lead to a higher fidelity between the design and the manufactured component. Experiments during this research have utilized layer thicknesses ranging from 5–15 mm, with the typical thickness being 10 mm in order to strike a balance between material demand and the overall scale of the prototypes. In the case of full-scale construction, it will be necessary to balance the desired resolution with an acceptable overall build rate. At 10 mm layer thickness, the differences between various nozzle designs and bead shaping approaches become readily apparent. The achievable surface finish is closely related to the process challenges discussed above in Sect. 2.1. In the case of the commonly used round extrusion nozzle, any pulsation or change in flowrate relative to the motion of the extruder tool center point (TCP) will change the bead width, resulting in a wavy edge and also causing potential mechanical flaws in the structure. In the case of 3DP ECC, experiments have also shown that even with soft fibers such as PVA or PE, the fibers often penetrate the surface. Higher viscosity mixes, or those that are reaching the end of their "extrudability window", often show buckling effects or tearing as they exit the nozzle. The goal of the proposed nozzle design is to reduce or eliminate these negative effects in printing with ECC, while striking a balance between resolution and printing efficiency.

3 Experimental Approach

3.1 3DP ECC Process Setup

The most current 3DCP setup used in this research was developed to maximize geometric control while addressing the challenges and opportunities of printing with ECC. The devised system is based on a 6-axis industrial robot with 2.8 m reach and 120 kg payload, mounted to a linear gantry (Fig. 1). In order to address the start/stop behavior, as well as to support dynamically variable material flowrates, the transport/placement system consists of a hopper mounted to a servo-driven peristaltic pump. This feeds a 4 m supply line connected to a custom-built servo-driven PC pump, mounted at the end of the robotic arm. A pressure transducer at the inlet of the PC pump provides feedback to the peristaltic pump in order to maintain constant inlet pressure, even as the PC pump starts/stops or varies flow. Due to the pulsation inherent in peristaltic pumps, and the deadtime between the pump and the transducer, the current setup causes a significant pressure swing, which can overcome the pressure-holding ability of the single-stage PC extruder and lead to excess material in the nozzle. By modifying the nozzle geometry to create an "open" area in the leading face, these material pulses can be buffered and shaped as they exit the nozzle.

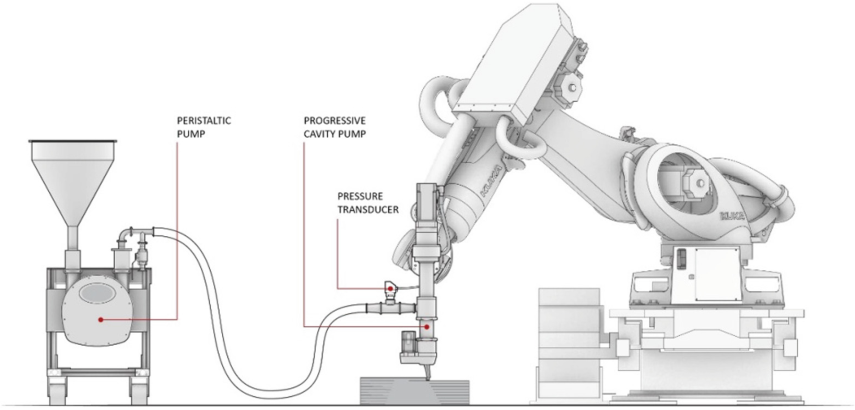

Fig. 1. 3DCP system consisting of supply pump and robotically positioned extrusion head.

Sizing of PC pumps is typically based on desired flow rates, and there are strict rpm limits due to the excessive stator wear and friction that results from higher speeds. With ECC mixes, the rotor/stator geometry requires a significantly larger pump to minimize the interaction or pinching that occurs between the fibers and the rotor/stator, even with soft fibers. This pinching leads to higher friction/rotor torque which could result in catastrophic damage to an otherwise properly sized pump. While friction can be reduced by lowering the mix viscosity, it is also observed that it is important to maintain a minimum mix viscosity to prevent bleeding.

3.2 Extrusion Bead Shaping

Previous research has adopted several approaches to controlling the shape of the extruded bead in 3DCP. The most basic approach utilizes a rectangular extrusion die opening that can be rotated around the axis of extrusion [9]. Other variations of this approach include the addition of one or more "side trowels" which shape the material as it exits the extrusion die [2]. In the following diagrams*, u, v, w* notation are as follows: with *u* designated as the direction of travel of the nozzle, *v* perpendicular to the bead direction but in plane with the bead, and *w*, perpendicular to the bead plane. As a starting point, the chosen cross-section of the extruded bead was rectangular, 10 mm × 30 mm (*w, v*). The chosen shape of the extruded bead also has implications on overall component geometries that can be produced, as well as the surface finish, as shown in Fig. 2.

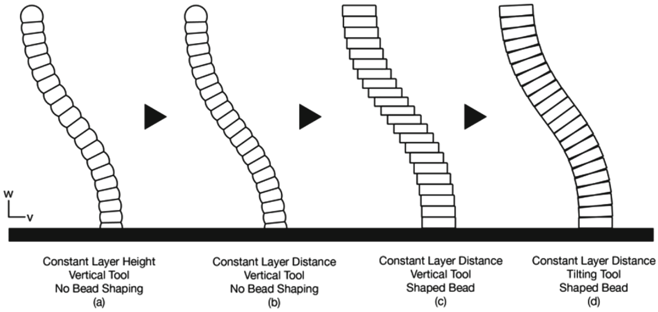

Fig. 2. Effect of tool orientation, nozzle shape, and toolpath strategy on wall cross-section in *v*-w plane. (left two sectional diagrams adapted from [8]).

As discussed in [8], constant height layers applied to a surface which has a curved cross-section will produce a layer interface with variable surface area as the vector distance between paths changes (further, the diagram does not account for the change in width that will occur if the extrusion rate is held constant) (Fig. 2a). By designing the toolpath using a constant tangential offset along the surface, a consistent layer interface surface area (per unit length) can be generated (Fig. 2b). The addition of bead shape control combined with a vertical tool produces a "corbelling" effect, similar to brick masonry, and results in a stepped surface with considerable roughness (Fig. 2c).

When combined with 5 DOF tilt, however, the cross-section can be produced with nearly identical interface contact area, thickness, and relatively low surface roughness (Fig. 2d).

When viewed from the *u*-*w* plane, there are several considerations, as shown in Fig. 3. In the simplest case, a rectangular die extrudes the material vertically, and it sharply transitions from the *w* to the *u* direction. Based on previous experience with round extrusion dies, this was expected to be problematic, particularly with ECC, where the high fiber content and internal friction leads to shape deformation as the bead bends. A second iteration includes a transition section in the trailing edge of the nozzle and was used to print the diagrid panel in Sect. 4.1. This version shifts the TCP of the nozzle to align with the axis of rotation in plan (assuming a steered nozzle). While shifting the trailing edge to align with the rotation axis is not strictly required, it simplifies path planning and simplifies the kinematics of the tool. The third iteration shows the addition of fixed “shaping blades” and was used to print the column in Sect. 4.1.

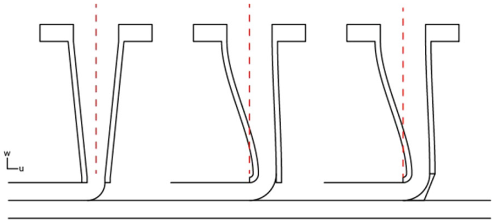

Fig. 3. Iterative design of extrusion nozzles, *u*-*w* plane.

In order to guide the rectangular die opening and/or the shaping blades, the extrusion tool requires an additional, sixth DOF, which keeps the nozzle tangent to the toolpath in the *u* direction. In the versions equipped with shaping blades, the specific shape of the blade creates additional constraints on the overall component geometry, particularly the minimum corner radius (Fig. 4). The geometric requirements also vary based on the projection length of the side blades. Figure 4 illustrates a nozzle with shaping blades extending beyond the previous layer to smooth the interface. However, fixed shaping blades prevent certain path topologies where lateral intersections between paths are desired; retractable blades are a potential solution to this problem.

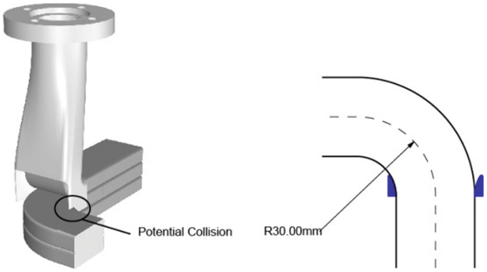

Fig. 4. Left, axonometric view of nozzle. Right, side blades (blue) and minimum centerline radius.

The final nozzle design parameters relate to the effect the cross-section has on the fiber alignment in the extruded bead. Ongoing work is underway to study and quantify the “wall effect” on the fiber alignment, and to understand how to best amplify this effect in future iterations of the nozzle. While prior work has addressed nozzle shaping strictly for its benefits to surface finish, this research suggests that especially in the case of ECC/SHCC, the design of the nozzle can have additional effects on the mechanical properties of the extruded bead as well as the behavior at the layer interface. This is an area which needs further study.

3.3 Integration of 6 DOF Nozzle Shaping into the 3DCP Workflow

Most 3D printing systems utilize only 3 degrees of freedom, and typical 3D CAD/CAM workflows treat extrusion as a fixed tool following a path at fixed speed, with no consideration for the shape of the bead. The 6-axis robotic manipulator offers the additional DOF necessary for complete control over the nozzle orientation, however, due to the size constraint of the PC pump and mounting/reach requirements shown in Fig. 1, an additional axis to control the nozzle rotation is attached to the end effector of the robot. This axis is integrated as an external axis, and the kinematics of the toolpath are solved using a custom-developed off-line programming (OLP) plugin for the Rhino3D modeling software [10]. The OLP approach allows the nozzle rotation and tool orientation to be synchronized kinematically, and output in standard machine instruction code. This research utilizes the Kuka Robotic Language (KRL), but the software can be easily adapted to other languages.

In addition to the nozzle rotation, the PC pump is also integrated as an external axis, in this case treated as a continuous (feed) axis. The rate of motion of this axis is computed in the OLP plugin and calibrated to the motion of the servo driven PC pump, yielding the potential for continuously variable extrusion rates (it can even be reversed to allow for retraction behaviors which are common in paste/filament extrusion). This opens the possibility of variable layer thicknesses, which are encoded into the machine instructions during the geometric analysis by the OLP software. These “virtual” axes are synchronized by the robot motion controller, and the positioning data is fed to a programmable logic controller (PLC), providing motion and process control for the entire 3DCP system.

4 Demonstration and Results

4.1 Evaluation of Nozzle Performance and Surface Finish

The nozzle design parameters described in Sect. 3.2 were tested using an iterative approach in order to determine their influence on the printing process and the resulting surface finish. As a proof of concept, two case studies were developed to demonstrate the constraints and benefits of the nozzle shaping system.

Diagrid Panel. The first case study is a façade panel with a doubly curved face, stiffened by a network of ribs (Fig. 5). As opposed to printing the panel in the vertical orientation, it was printed horizontally on a prepared mold, with the goal of improving the surface finish of the doubly curved face. This design provided the additional opportunity to test the ability of the 3DCP process to aggregate layers horizontally for the face layer, as well as vertically for the stiffening ribs and flanges for the panel. Using the variable extrusion rate capabilities described in Sect. 3.3, the ribs are designed to have variable depth, but the same number of layers at every point in the *w* direction. This allows the doubly curved surface to resolve to a level datum at the upper layer. While demonstrated as a panel, this process presents numerous potential applications for the design of variable depth waffle slabs and non-rectilinear masonry units.

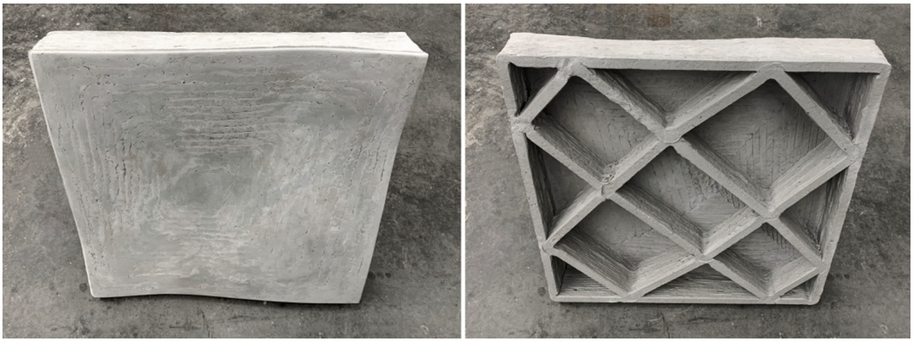

Fig. 5. (left) Double curved face printed on finished mold. (right) Stiffening Ribs and flanges printed with variable layer thickness.

In order to aggregate the layers horizontally, as well as allow the stiffeners to intersect and join at corners, the panel required the use of a nozzle without side blades. To achieve a seamless face coat on the mold, attention to the overlap of each successive bead was crucial, as well as an increase in the flowability of the mix. In this experiment, the print path has an offset equal to the nozzle width, and the flowrate is manually increased by 5%. After printing the face layer, the path continues directly into the stiffeners. The stiffeners also provided an opportunity to test the achievable surface finish without fully guiding the extruded bead. The results showed that the shear and bending stresses on the extruded bead cause a loss of fidelity as it makes the transition from the *w* to *u* direction in an unsupported way. Subsequent tests reveal that it is important to support the extruded bead for as long as possible to allow the deposited material to stabilize.

Bifurcating Column. The second case study was developed as a twisted, hollow column which bifurcates and recombines twice in elevation (Fig. 6). This study was developed to test the start/stop behavior of the system, to explore increased tilt steering with the 6 DOF system, and to test moderate overhanging of the geometry. Additionally, the corner radii were set at the minimum radius for the nozzle, which was designed with fixed side blades at 14 mm long.

The column print demonstrated that the nozzle shaping system could produce improved surface finishes relative to the nozzle without side blades. The performance of the printing system is highly dependent on proper tuning of the flowrate. In the absence of a closed loop monitoring system, the flowrate required frequent adjustment. In part this is due to time-dependent material properties; at a given inlet pressure, as the mix viscosity begins to increase at the end of a batch, the flowrate decreases. In order to address this, the PLC motion controller, equipped with an operator override, allows adjustment of the flowrate as needed. Excessively low flowrates cause incomplete bead formation, whereas high flowrates cause excess material to pass below the side blades, producing small extensions at regular intervals which can be observed on the prototype. As such, future development in this area includes a sensing device which can evaluate the bead shape and adjust the flow rate automatically, building on approaches described in [11].

Fig. 6. (a) Section through the column. (b) Printed Result. (c) Close up of layer surface finish.

Material Effects. It was observed that ECC mixes can be adjusted to improve their shape-ability as they exit the nozzle. The shaping blades tend to stabilize the bead, possibly due to fiber alignment effect. This effect seems to be shear stress dependent (and thus is affected by the print velocity). This was particularly evident when the print speed was reduced in order to extend the time between batches. While the flowrate of the system is synchronized to the print velocity, the change in surface finish at low speeds suggests that a "stiction" effect can occur in the shaping nozzle. It is hypothesized that the thixotropic nature of the ECC mixes is contributing to the shaping effect, and that there is an optimum velocity which produces an ideal viscosity as the bead exits the nozzle. It also suggests that the mix design may have to be modified to offset shear-thinning as print speed increases.

5 Conclusion and Future Work

This research has explored the basic implementation of a nozzle shaping and 3DCP infrastructure which can support the deposition of ECC/SHCC materials with an improved surface finish compared to approaches which use a static printing nozzle. Further work will explore nozzle shapes and mechanisms which produce improved surface finishes across a wider range of component geometries, including those with self-intersecting paths. In addition to improving the surface finish of 3DCP building components, future work will focus on the development of a system which can support the deposition of materials with enhanced ductility and strength, with longer and/or higher volume fraction of fibers for reinforcement and stiffer matrices for higher buildability. Further study will also attempt to determine the impact of internal nozzle geometry on fiber alignment in ECC/SHCC mixes, as well as the effect on the shear thinning behavior at the deposition point in 3DCP. By taking an integrated approach to the design and manufacturing workflows used in 3DCP, the over-arching goal of this research is to develop a process which can produce highly refined, self-reinforcing building components with minimum material usage.

References

1. CRSI homepage. https://www.crsi.org/index.cfm/benefits/econ-construction. Accessed 30 Jan 2020
2. Bard, J., Cupkova, D., Washburn, N., Zeglin, G.: Robotic concrete surface finishing: a moldless approach to creating thermally tuned surface geometry for architectural building components using Profile-3D-Printing. Constr. Robot. **2**, 53–65 (2018)
3. Khoshnevis, B.: Automated construction by contour crafting—related robotics and information technologies. Autom. Constr. **13**, 5–19 (2004)
4. Asprone, D., Menna, C., Bos, F.P., Salet, T.A., Mata-Falcón, J., Kaufmann, W.: Rethinking reinforcement for digital fabrication with concrete. Cem. Concr. Res. **112**, 111–121 (2018)
5. Li, V.C.: Engineered Cementitious Composites (ECC). Springer, Heidelberg (2019)
6. Li, V.C.: From micromechanics to structural engineering - the design of cementitious composites for civil engineering applications. J. Struct. Eng. Earthq. Eng. **471**, 1–24 (1993)
7. Soltan, D.G., Li, V.C.: A self-reinforced cementitious composite for building-scale 3D printing. Cem. Concrete Compos. **90**, 1–13 (2018)
8. Buswell, R.A., de Silva, W.R.L., Jones, S.Z., Dirrenberger, J.: 3D printing using concrete extrusion: a roadmap for research. Cem. Concr. Res. **112**, 37–49 (2018)
9. Salet, T.A.M., Wolfs, R.J.M.: Potentials and challenges in 3D concrete printing. In: Proceedings of the 2nd International Conference on Progress in Additive Manufacturing (Pro-AM 2016), 16–19 May, pp. 8-13. Research Publishing, Singapore (2016)
10. McGee, W., Pigram, D.: Formation embedded design: a method for the integration of fabrication constraints into architectural design. In: Integration Through Computation, Proceedings of the Association of Computer Aided Design in Architecture, Banff, Canada, pp. 122–131 (2011)
11. Wolfs, R.J.M., Bos, F.P., van Strien, E.C.F., Salet, T.A.M.: A real-time height measurement and feedback system for 3D concrete printing. In: Hordijk D., Luković M. (eds.) High Tech Concrete: Where Technology and Engineering Meet. Springer (2018)