IMPLEMENTATION OF A CONTOUR CRAFTING SYSTEM TO A 3-DIMENSIONAL CONCRETE PRINTER


Abstract: This paper examines the benefits of implementing a contour crafting system to a 3-dimensional concrete printer in order to improve the surface finish and geometrical shape of the printed concrete. This system was supplemented by three additional axis of rotation: two of which set the angle for the trowels that shape and smoothen the edges and the last that rotates the nozzle head around the Z-axis. Additional software was developed to modify the G-code and provide instructions for the three additional axes. Tests were performed measuring the surface roughness and the geometrical shape of the printed concrete object. The results show that the geometry can be improved by this contour crafting system. Applications for this technology can be small scale concrete structures for architects, non-standard pre-manufactured concrete elements and other minor concrete objects.

Keywords: layered manufacturing, additive, rapid prototyping.

1. INTRODUCTION

3D printing has become one of the fundamental processes for rapid prototyping and is currently being applied to actual manufacturing of components [1]. 3D printing was originally used to make plastic objects, but lately many alternative materials are being suggested for 3D printing such as different metals and concrete. Concrete 3D printing could, if implemented correctly, reduce building costs of concrete structures such as houses as no mold is needed and introduce a fast and flexible way for building emergency shelters. But as this idea is quite new, research into the subject is still needed to make it feasible and correct the existing problems such as: finding a viable concrete mixture, adding reinforcement to the concrete, logistics of the printer, improving surface quality and finding a way for the concrete to be made into free forms. This study will focus on the last two of these problems, which is adding a free form system called contour crafting to a 3D concrete printer which improves surface quality. Contour crafting is a system used in layered fabrication processes, where trowel like plates are used to smoothen the outer edges of the printed concrete from the concrete printer nozzle. This gives the printed concrete a more uniform shape, instead of the layered shape of an object printed without contour crafting. The trowels improve the surface quality of the concrete and the aesthetics of the finished product. [1][2]

Previous research in this area has been made primarily at the University of Southern California and at Loughborough University. The University of Southern California built a 3D printer for various materials, which uses contour crafting to make angled forms possible. The printer uses a six axis system, three for linear movement, one for extrusion, one for rotating the nozzle and one for the singular trowel [3]. Loughborough University has also done research in this field [4][5][6].
This paper will focus on the implementation of a contour crafting system to a 3D concrete printer. The goal is to create a system which gives the user a greater degree of freedom in designing different forms, and that improves the aesthetic of the finished product. This is achieved by using trowels that can be angled at the sides of the nozzle. The goal of this project is to increase the surface quality significantly and introduce the possibility of printing angled walls.

2. METHODS

The original 3D concrete printer moves the nozzle head a maximum of 475 mm in the X-direction and 650 mm in the Y-direction and the printing bed 750 mm in the Z-direction (Figure 1). This is done by 300 W servomotors which actuates linear screws. A 660 watt servo motor drives a screw-type extruder [7]. The concrete printer is controlled by LinuxCNC, which is an open source software made primarily for CNC milling machines. An open source slicer - software converts stereolithography files to the G-code instructions used by LinuxCNC.

Fig. 1. The concrete printer setup.

2.1 Hardware

The purpose of contour crafting is to smoothen the surface of the concrete flowing out of the extruder. To implement this to the concrete printer, a new nozzle with trowels that follow the outer edge was needed. The trowels should also be able to be angled according to the shape of the printed object to allow angled walls to be printed. Additionally the trowels need to be completely lifted during the fill cycle.

Fig. 2. The new nozzle assembly.

The new nozzle model is illustrated in Figure 2. The top of the nozzle (2) is threaded, to be screwed on to the extruder. The rest of the extruder assembly is fastened with a ball bearing and rotates around the top part. The rotational movement is controlled by a 63 watt servo motor, which is connected to the timing pulley (3) on the nozzle by a timing belt. The trowels (6) are made of 2 mm rubber and stabilizing aluminum pieces. The angle for each trowel is set separately by servo motors (5) that are mechanically connected to the trowels. Each trowel can be angled 135 degrees, as seen in Figure 3. Power and signals to the servo motors are supplied by a coiled cable (1), running through the nozzle assembly. This cable limits the rotational movement of the axis to ±540°. When zeroing the rotational angle, a cam (4) activates a limit switch on the frame of the concrete printer. Concrete is extruded through the 22 mm bottom part of the nozzle (7) and smoothened by the trowels. Between the upper and lower part of the nozzle assembly a sealing ring is used to prevent concrete from entering the nozzle assembly. This can be seen in the section view in Figure 3. The parts of the nozzle assembly that are in contact with concrete, are made of S355 steel, while other parts are made of aluminum.
2.2 Software

To implement contour crafting, G-code for the additional axis is also needed. In the original setup of the printer, G-code is generated from a CAD model by the open source software slic3r. Slic3r breaks the CAD model in stereolithography format down to points in the X-Y plane. LinuxCNC then moves the nozzle according to the path given by the G-code. In order to control the additional axis, a program was written in C11 programming language. The program reads the coordinates, written in the G-code file and calculates the angle for the nozzle and the trowels. The rotation of the nozzle is limited to $\pm 540^\circ$, so the spiral cable does not extend beyond its elastic limit.

The software has some considerations to avoid damaging the printed perimeter. If a sharp angle turn is detected, the program lifts the trowel that would cut into the printed concrete to avoid collision. This slightly worsens the surface quality near the sharp angle turn, but it is necessary to keep the form intact. The software also considers the movement of the trowels when returning to the starting point of the current layer, as in some shapes the trowel can collide with the printed concrete.

2.3 Concrete mixture

Contour crafting puts some additional requirements on the properties of the concrete being used. Measures of the printability of a concrete mix are defined as extrudability (the ability of the mass to easily flow through the extruder), buildability (the resistance against deformations by the subsequent layers) and formability [7]. The pre-existing recipe [7] is modified to accommodate the implementation of the contour crafting system. The water and plasticizer content of the mix was adjusted until the criteria listed above were deemed fulfilled.

A compression test was made on the resulting mixture, to test the properties of the concrete. To evaluate the contour crafting system two test shapes were printed with and without the contour crafting system. The shape was made in CAD software and is a cone with a base diameter of 155 mm and a slope of 78°.

The composition of the concrete mixture that was used for these tests is found in Table 1.

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Composition [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand R 1-2 mm*</td>
<td>301.4</td>
</tr>
<tr>
<td>Sand R 0.5-1.2 mm</td>
<td>241.2</td>
</tr>
<tr>
<td>Sand R 0.1-0.6 mm</td>
<td>241.2</td>
</tr>
<tr>
<td>Filler</td>
<td>211.0</td>
</tr>
<tr>
<td>Cement**</td>
<td>464.0</td>
</tr>
<tr>
<td>Fly ash</td>
<td>133.8</td>
</tr>
<tr>
<td>Silica fume</td>
<td>22.4</td>
</tr>
<tr>
<td>Water</td>
<td>221.2</td>
</tr>
<tr>
<td>Super plasticizer</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*) The aggregates used in the mix were 30% [R1-2], 24% [R0.5-1.2], 24% [R0.1-0.6] and 22% Filler.
**) Rapid cement [CEM II A 42.5R]

Table 1. The composition of the concrete mix.
Rapid cement [CEM II A 42.5R] type was used in the concrete mix. The cement was produced by Finnsementti’s cement plant at Parainen. The aggregates used in the mix was natural granite gravel, which was washed, dried, and graded by sieving. The grading of the combined aggregates is shown in Figure 4. The water used was normal tap water provided by the water distribution system of the city of Espoo, Finland and its temperature was 20±2°C. The water-reducing agent was superplasticizer (Glenium 51), manufactured by Finnsementti Oy Finland. This agent was stored in a polyethylene bottle at room temperature.

The dry ingredients were hand-mixed for one minute after which it was poured into a container of wet ingredients for another 3 minutes of mixing. The batch was then immediately poured into the printer.

3. RESULTS

When comparing the pieces printed with the contour crafting method and the pieces printed without contour crafting it can be seen that the surfaces of the new printed pieces are smoother. The indentations appearing between each layer were measured on both types of printed pieces and were much deeper on the pieces printed without contour crafting. The indentations on the pieces without contour crafting were on average 7.9 mm, while the pieces with contour crafting had indentations with an average depth of 3.4 mm. Figure 5 illustrates the difference between a cone printed with and without contour crafting.

![Fig. 5. Comparison of old and new result. The object on the right is printed with contour crafting.](image)

To test the strength properties of the concrete, standard compression tests were performed on three cast cubic 100x100x100 mm samples [8]. The cubes were left to dry for five days before the tests were performed. The results can be seen in Table 2.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$f_c$ [MPa]</th>
<th>density [kg/dm$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>46.4</td>
<td>2.199</td>
</tr>
<tr>
<td>Sample 2</td>
<td>44.5</td>
<td>2.209</td>
</tr>
<tr>
<td>Sample 3</td>
<td>43.3</td>
<td>2.139</td>
</tr>
</tbody>
</table>

Table 2. Results from compression tests of the concrete mix.

Cracks in the bend of the rubber trowels were formed after only a few printings. This was suspected to be due to either mechanical wear from the movement of the trowels or degraded elasticity due to chemical reaction with concrete. Another material should be used in this situation. Metal or rubber resistant to chemical degradation is proposed.

4. DISCUSSION

From the results, the conclusion can be drawn that with the new setup of the printer enabling contour crafting, smoother surfaces can be printed. The changes made to the concrete mixture have also helped improve the quality of the printed pieces. Compared to normal concrete casting there is a fundamental problem with layer-based printing of concrete. This is the absence of
steel reinforcements inside the concrete structure. Since the printing is done layer by layer, steel reinforcements cannot be placed beforehand since they would collide with the printer. A solution for this could be to add steel fibers into the concrete mix. This could possibly strengthen the concrete enough to print larger scale structures.

There are multiple ways that this concrete printing system could be improved to achieve more precise forms with better surface quality. One of these is to implement a mass flow feedback system so that the extrusion feed can be adjusted according to the real output of the concrete through the nozzle. This would ensure that the right amount of concrete would be extruded. Further research to optimize the concrete mixture should be performed. The mixture used was designed to emulate the use of industrial construction concrete. Software that generates the needed G-code for all seven axes from the original stereolithography data could be developed. This would remove some of the limitations with the current setup, namely adding the possibility for discontinuous forms. An additional feature that could be added is to have a variable nozzle hole diameter that adjusts itself according to the required thickness of the printed piece. Since the properties of the concrete depends on multiple factors and is time dependent, an automatized way of mixing the concrete continuously while printing could improve the results. This could probably help reduce the differences between printed batches and even remove some of the differences in the same batch, that are caused by the unprinted cement drying while the printer runs.

It should be investigated if this technology could be scaled up to allow bigger objects to be printed. The hypothesis is that a bigger scale would allow the layers to harden more before the next layer is printed on top. This would allow higher objects to be printed. Contour crafting improves the aesthetics of the printed object and allows its forms to be freer.

5. REFERENCES


CORRESPONDING ADDRESS

Panu Kiviluoma, D.Sc. (Tech.), Senior University Lecturer
Aalto University School of Engineering
Department of Engineering Design and Production
P.O.Box 14100, 00076 Aalto, Finland
Phone: +358504338661
E-mail: panu.kiviluoma@aalto.fi
http://edp.aalto.fi/en/
ADDITIONAL DATA ABOUT AUTHORS

Nylund, Jimmy
Phone: +358 50 410 7302
E-mail: jimmy.nylund@aalto.fi

Järf, Alexander, B.Sc. (Tech.)
Phone: +358 50 492 8262
E-mail: alexander.jarf@aalto.fi

Kekäle, Kim, B.Sc. (Tech.)
Phone: +358 40 573 2532
E-mail: kim.kekale@aalto.fi

Rönnskog, Jan
Phone: +358 50 347 1498
E-mail: jan.ronnskog@aalto.fi

Al-Neshawy, Fahim, D.Sc. (Tech.), Researcher
Phone: +358 50 5649 372
E-mail: fahim.al-neshawy@aalto.fi

Kuosmanen, Petri, D.Sc. (Tech.), Professor
Phone: +358 500 448 481
E-mail: petri.kuosmanen@aalto.fi