# Spatially Graded Modeling: An Integrated Workflow For 3D Concrete Printing

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**Abstract.** While 3D concrete printing (3DCP) has surged in popularity, methods to harness its design potential remain largely underdeveloped. Existing design-to-manufacture workflows most commonly restrict the design to the overall geometry and a set of print parameters that may fall outside of the scope of the designer. This study presents a novel approach to integrate design and manufacturing by an integrated design-to-manufacture workflow that allows the gradation of the wall thickness along the printed part, which can be independently manipulated using established computer graphic techniques like texture projection and mesh coloring. The effectiveness of this workflow is demonstrated through the fabrication of a test body featuring a customized surface pattern. This approach aims to extend the design scope for 3DCP, enabling the addition and editing of surface patterns without geometry or code manipulation.

**Keywords:** Robotic fabrication, 3D concrete printing, Variable filament width, Design for manufacturing, Print path design.

## 1 Introduction

Extrusion-based 3D Concrete Printing (3DCP) has become the leading technology for digital fabrication with concrete. As with other 3D printing techniques, 3DCP is an additive manufacturing process that builds an object through the layer-by-layer deposition of materials according to a 3D model. Although there are other methods for 3D printing with concrete, 3DCP most commonly refers to the dominant approach of extruding fresh cementitious materials (Bos et al., 2022). The key advantage of 3D printing lies in its ability to build complex geometries and intricate structures that might be not economically or technically feasible with traditional methods. When applied to construction, 3D printing can increase productivity by building parts with extra functionality or by allowing the creation of material-efficient structures where the material distribution follows the distribution of forces (Menna et al., 2020).

Although several academic institutions and companies are rapidly expanding the possibilities of this technology, methods for exploiting the design potential are still largely underdeveloped (Ma et al., 2022). In particular, design methods mostly remain unchanged from the workflows of the early development of 3D printing. A typical design-to-manufacture workflow has at least three distinct steps: i) the design of the overall part, ii) the design of the material distribution, and iii) the generation of manufacturing instructions. While step i) can be easily associated with CAD software, steps ii) and iii) correspond loosely to what is referred to as ‘slicing’ and are usually performed using a different software tool. Between steps ii) and iii) the file is exported, establishing a sharp line between design and manufacturing, where design is restricted to the overall geometry of the part and a limited set of printing parameters, such as number of walls, infill patterns, and density. This gap between design and manufacturing is typically restricted to the information conveyed through STL files, a simple triangulated format that can only describe the surface geometry without any information related to scale, color, texture, or any other metadata.

One innovative approach to enhance this workflow is by incorporating color information into a model that can be used as an extra degree of freedom. Beyond its literal application in 3D printing methods that allow color printing, it can be used to represent variable properties in different parts of the printed part. This idea of a ‘color’ 3D printer has been formulated as a reference for advanced 3D printing methods (Bos et al., 2016), but it remains a challenge, both in terms of technical capabilities as well as the corresponding design methods for this extended design space.

This paper presents a design-to-manufacture workflow that enables the application of color information to control customized printing properties. This allows the independent manipulation of the color grading using established computer graphic methods, such as texture projection and mesh coloring. Color information is stored in a separate data source representing material gradations as extended degrees of freedom. This is done through a modularized slicing process that can spatially adapt printing parameters in specific regions of the concrete element. Specifically, the color information informs the variable filament width, which in turn leads to variable wall thickness. The upcoming sections present a background on current methods, the proposed design for manufacturing workflow, and the printing process for experimental validation of the proposed method.

## 2 Existing Workflows

The prevalent workflow for 3DCP relies on conventional methods for 3D printing that do not allow the specification of material properties. The reliance on separate design and slicer software, and the use of STL files to transfer the information between the two, create a technical limitation to the scope of design.

While STL is still the industry standard, there have been substantial efforts to solve the limitations of this file format. AMF (Additive Manufacturing Format) was proposed as an open-source alternative defined by the ISO/ASTM 52915:2020 standard (ISO, 2020). Similarly, the 3MF file format is backed up by several manufacturers and software companies (3MF Consortium, 2022), which is also an open-source alternative that is better supported. Nevertheless, the adoption of dedicated 3D printing file formats has been slow.

Unlike small-scale 3D printing, 3DCP imposes several manufacturing constraints that favor simple and continuous print paths. An interesting alternative to extend the design scope of 3DCP is based on the direct manipulation of print paths i.e., the trajectory followed by the printer when depositing concrete, as the base for the design. Given the comparatively low resolution yielded by 3D printing with the 20-50 mm nozzles typically used at the construction scale, customized design features can be achieved by manually editing the print paths obtained after the slicing process. These techniques expanded rapidly, especially with the popularization of clay 3D printers (AlOthman et al., 2019; Aguilar, 2020). Parametric methods, which use algorithms to drive the design process, have contributed to further extend the design spectrum by procedurally creating or altering the shape of print paths to generate different material effects and surface qualities (Breseghello, 2021; Breseghello & Naboni, 2022; Westerlind & Hernández, 2020). Nevertheless, most of these methods are confined to the generation of specific geometries and depend on the expertise of a proficient designer or programmer in ad-hoc solutions. Similarly, procedural print path generation, i.e., generating print files without a 3D model, offers great flexibility in grading material properties (Moetazedian et al., 2021), but its applicability is limited as the method is based on direct code manipulation.

Printing with soft printable materials allows the modulation of the filament width by simply adjusting the ratio between the traveling speed of the nozzle and the extrusion speed (Yuan et al., 2022). Increasing the extrusion speed results in wider printed filaments, while conversely, increasing the traveling speed reduces the filament size. An advantage of this method is that it provides the ability to dynamically control the printing dimensions without requiring specialized printing equipment. This adaptability in the dimensions of the printed filament serves a dual purpose: it can be used to optimize material use and process efficiency while concurrently expanding the design possibilities of 3DCP.

Grading material properties has also been an interesting field of research in smaller-scale 3D printing (Zhang et al., 2019). While some attempts have been already tried using concrete (Ahmed et al., 2020; Craveiro et al., 2020), integrating functionally graded concrete by 3DCP remains a challenge (Hernández Vargas et al., 2022). From a design standpoint, this also presupposes the tools to develop designs featuring spatial gradations, a capability that is not available in traditional workflows. Currently, there is a shortage of design workflows that can accommodate these extended capabilities. This paper aims to address this gap by integrating design and slicing into a flexible design-to-manufacture workflow that extends the scope of design for 3DCP beyond the 3D model.

## 3 Methods

The present method aims to enhance flexibility in the definition of material properties during the slicing process in a flexible manner. This is done through a two-part slicing process, which integrates volumetric data with spatial gradations that can be applied on top of the 3D model: First, the object is sliced into equally spaced contour lines, which are in turn divided into control points for manufacturing. Secondly, the color information is sampled for each control point to determine variable printing parameters. Consequently, a spatial gradation from color information can be manipulated and stored as colored meshes while the other is based on projected raster images, akin to texture mapping in computer graphics. Thus, a single object geometry can be infused with properties specified by different images, creating design variations that can be achieved just by editing these input textures, as displayed in Figure 1.

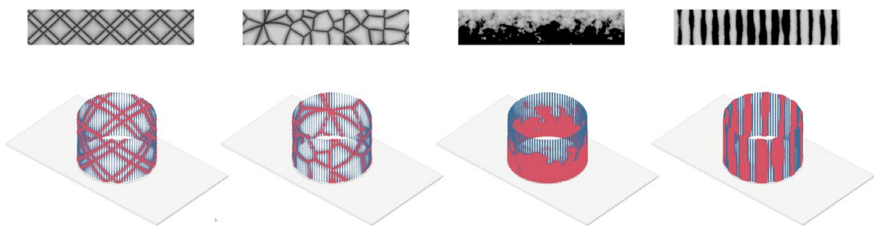

Figure 1. Design variations by applying different textures over the same geometry. Printing properties can be modulated by sampling the information from the texture, in this example as variable printing speed represented by the size and color of the control points.

Color information can be mapped to contain an extensive amount of data. In this study, only the value parameter is extracted from the HSV (hue, saturation, value) color model. This means that, when using 8-bit precision, a printing parameter can be specified with 256 distinct levels, that are used to specify the width of the printed filament. However, using all three channels allows the user to represent three-dimensional data with the same precision. Alternatively, the combination of all three color channels into a single parameter with the full 24-bit range allows more than 16 million distinct values, which expands the potential for further innovations in future applications. Furthermore, the support for RGBA colors in AMF and 3MF file formats can provide even more room for data storage.

In this example, the image controlled the wall thickness that is remapped into corresponding values for each control point. This forms a four-dimensional array of control points with a speed parameter that can be used to inform the manufacturing process. In the printed prototype, color values between 0 and 1 were sampled into printing speeds between 45 and 150 mm/s respectively i.e., thicker printing width in darker areas and thinner ones in lighter parts. These are represented as colored spheres, as displayed in Figure 2, where the radius and the color indicate the required printing speed and accordingly the estimated filament width.

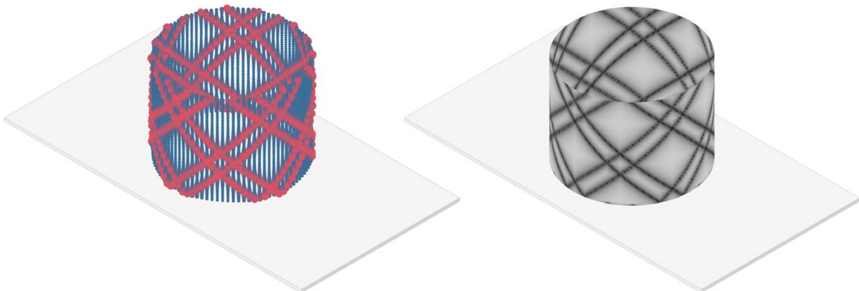

Figure 2. Thickness mapping and control points with variable speeds.

The colored geometry can be stored and edited using different methods: texture mapping or colored polygon meshes. The application of a texture is based on a surface that defines the mapping. After slicing, every control point from the 3D model is projected to its closest point on the surface, which is then used for sampling the color information by relating the UV parameters of the surface to the XY coordinates of the raster image. This model can be saved as a geometry with texture mapping. This method allows the further modification of the part geometry without generating or affecting the mapped information.

Colored meshes use the vertex color property that saves an RGB value for every mesh vertex. Since color information is saved for each vertex and interpolated in between, the mesh size directly influences the resulting resolution from the gradation process. This allows for saving the 3D model with the color information on a single file. However, the resolution is dependent on the size of the mesh, which means that modifying the mesh geometry also affects the existing color information. Also, this method can import colored meshes from structural engineering software that can plot forces to be adjusted during the print.

A third hybrid approach is the use of UV unwrapping, which generates texture coordinates for every vertex in polygon meshes, usually also creating and editing a custom texture. While this is one of the most widely used methods in the computer graphics industry, its vast specialized potential remained outside of the scope of this paper.

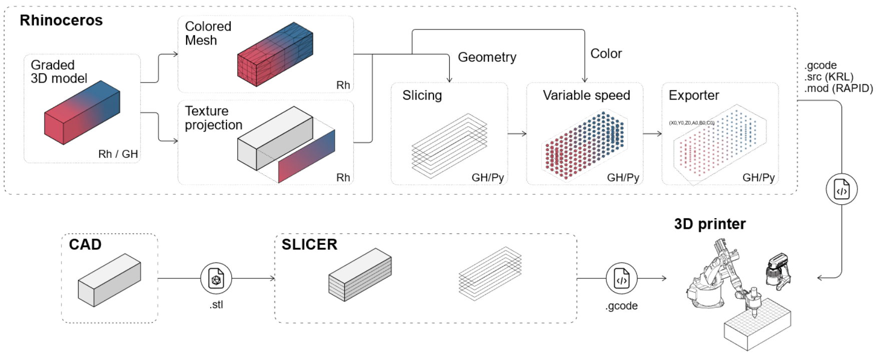


Figure 3. Proposed workflow for the design of graded structures for 3D printing. All the design-to-manufacture workflow is carried out in an integrated software environment as GH/Python scripts in Rhinoceros and then exported as KRL (.src) for printing.

### 3.1 Code Generation

All stages of the workflow take place in Grasshopper for Rhinoceros, a powerful CAD platform with visual programming capabilities. Different modules were written in Python and handled tasks such as slicing, sampling the spatial gradation, and exporting the printing instructions as robot code. The overall workflow used in this study is presented in Figure 3. Instructions for robotic fabrication are typically specified as a list of control planes, each indicating 3-axis position and 3-axis orientation. Since circular nozzles are symmetrical in all directions, they do not need to be orientated to the printing direction when using planar layers. Therefore, all control points are assigned to the same printing orientation. After slicing, a script assigned variable printing speeds according to the color information read from the model. Printing files were generated by another Python module that transforms planes and speeds into KRL code.

By default, the effect of variable filament width will be applied to both sides of the print path. This can be compensated to preserve a flush surface on either side by strategically shifting the print path proportionally to the change in filament width, as illustrated in Figure 4.

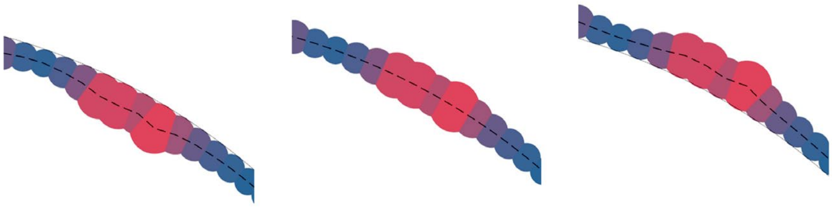

Figure 4. Alignment possibilities of the variable filament width. Shifting the trajectory of the nozzle proportionally to the change in filament speed allows the creation of flush sides in the printed structure. Center: Unmodified print path with the variation affecting both sides of the print. Left: Compensated print path where the variation is contained on the inside while the external face is kept flush. Right: Reversed compensated print path with internal flat surface and external variation.

### 3.2 Printing Setup

The printing tests were conducted at the School of Architecture at the KTH Royal Institute of Technology. The 3DCP system is based on a six-axis Kuka industrial robotic arm coupled with a specially developed concrete extruder based on a screw using a circular printing nozzle of 20 mm in diameter. Extrusion speeds are controlled separately from the robot controller and need to be set up manually. However, the extruder's controller includes a start/stop function that is regulated directly from the robot code.

The material used for the test was Sikacrete-751 3D, a commercially available mono-component dry mix specifically developed for 3DCP. This material was mixed with water and manually fed into the extruder in small batches to maintain a continuous flow. During the printing process, the material was mixed continuously to ensure it remained in a fluid state. This method allowed for an open printing time ranging from 10 to 90 minutes.

## 4 Results

The proposed method was tested through the fabrication of a test planter, measuring 600 mm in diameter and 270 mm in height, printed at 10 mm layer height with a 20 mm nozzle. The text body features a customized surface pattern based on a projected image texture. The design of the planter encompasses two distinct parts: a permeable base and a single-wall envelope with variable filament width. The base consists of a zig-zag infill pattern with 5 mm gaps for water drainage. It was printed at a constant traveling speed of 100 mm/s for which the extrusion speed was calibrated to obtain a printed filament width of 25 mm and then was kept steady for the rest of the printing.

Subsequently, the rest of the body was printed with a variable filament width controlled by the image projection. This resulted in printed filament widths between 28 and 22 mm, as illustrated in Figure 5. The variation in printing speed is also connected to a proportional shifting of the control points so the projected pattern would only be visible on the exterior face of the object. The printing process took place in three batches, primarily due to the capacity of the concrete mixer. Although higher printing speeds were technically possible, the robot speed was reduced to preserve the stability of the print.

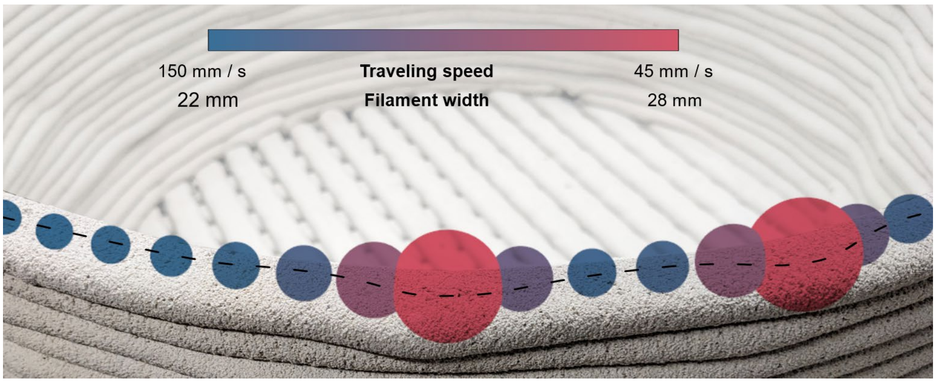


Figure 5. The filament width is modulated by adjusting the printing speed, a parameter that is represented by the color and size for each control point along the print path. These values are controlled by texture mapping, allowing for nuanced control over the material deposition process.

Figure 6. Printed prototype showing the projected image as variable wall thickness. Variations in printing speed are combined with a compensation algorithm to restrict the effect of the variation to the outer face of the printed part.

## 5 Discussion

The proposed method allows the integration of design and manufacturing into a single workflow that takes advantage of the flexibility offered by 3D printing to enlarge the design space, in this case specifically for printing at large scales with cement-based materials. Such integration induces a more dynamic and adaptable design process that can incorporate manufacturing considerations directly into the design phase. While this integration enables design possibilities far beyond conventional workflows, it is challenging to generalize these customized methods as the steps must be adapted for every application.

Both color grading formats, texture mapping, and mesh coloring, were found feasible alternatives for this workflow, generating almost identical results. Whereas colored meshes offer the advantage of containing all the information on a single entity, allowing the color grading and the mapping to be unambiguously defined on a single editable file. However, the editing of colored meshes is less accessible for end users than editing raster images that can be manipulated using common photo editing software. These principles are compatible with the proposed AMF/3MF file format, which allows the inclusion of color specification and texture maps.

Although this workflow is developed using the Rhinoceros API, the use of scripting allows the method to be adapted to other platforms. A condition for the potential standardization of file formats and workflows specifically designed for 3D printing, the ability to process data at a low level is fundamental for research to be software agnostic.

The printing results show that varying the filament width from a texture mapping is possible, although the effect was limited. Despite the use of an alignment algorithm to restrict the effect of the variable filament width to one side of the print, the applied pattern is still faintly visible from the inside, as shown in Figure 6. This raises the question about the precision of the shifting compensation to the alignment method, which may need further adjustment. Higher variations in traveling speed can provide a clearer variation of the filament width, but higher printing speeds compromise the stability of the print. Likewise, printing at lower speeds favors the strength development of the fresh material, avoiding material failure when the strength of the fresh material is exceeded, most often resulting in the yielding of the first layer. Also, the image texture used in this example represented an extreme case, where sections with thicker filaments were confined to small areas with high contrast. Consequently, the robot lowered the traveling speed for a single control point, limiting the change in filament width achievable. Considering these observations, smoother transitions would be probably preferable to improve the definition of the projected pattern and the overall printing quality.

## 6 Concluding remarks

This paper presented a novel design-to-manufacturing workflow for 3DCP that integrates color information into the model. The method was validated by printing a test object with variable filament width, demonstrating its ability to design parts with extended complexity. The modular nature of this workflow enables the specification of printing parameters independently from the geometry. This allows a vast number of variations to be produced from the same file, which is an improvement from previous methods that required crafting 3D models for every design iteration. These variations can be achieved by manipulating either the geometry or the color information, extending the scope of design for 3DCP.

Integrating all steps within a CAD environment allows for accelerated design iterations, but maintaining the modularity of the process is key to offering versatile tools that are not limited to a particular application. Slicing, color sampling, and code generation modules were easier to develop and maintain as separate scripts.

A prominent feature of this workflow is the capability to apply density maps on existing geometry that can respond to specific structural conditions that use concrete only where required, limiting material use, and consequently reducing their environmental impact. This study opens new ways for creativity and optimization in 3D printing, where the ability to determine material properties as part of the design process enhances the potential for producing customized and complex structures. Further work will investigate process-specific methods for optimizing the material distribution on 3DCP elements according to structural requirements.

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