A Digital Design Environment for Large-Scale Rapid Manufacturing

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ABSTRACT
Innovation in architectural design often follows technological innovation. This innovation can often be related to advances in construction techniques or design tools. This paper focuses on the development of a digital design environment for a new manufacturing process that can produce large architectural components. The design environment can be customized so that it incorporates both the flexibility and the constraints of the construction technology, such that the components produced maximize the core concept of the technology.

1 INTRODUCTION
Rapid Prototyping is a mature technology that has been around for 25 years in the manufacturing and product design industries. It is used primarily to speed up the product design cycle time from concept to physical realization for evaluation; it is now gaining a foothold in contemporary architectural practice.

The typical components produced by these techniques are “desktop-sized” architectural models. The combination of the digital CAD environment with the flexibility of the manufacturing process results in almost unlimited geometrical freedom. Practices such as Foster+Partners have taken full advantage of this technology, and it has become an integral, if not essential, part of their architectural design process (De Kestelier and Peters 2008).

A number of protagonists are taking the Rapid Prototyping concept a stage further by developing large-scale processes capable of printing architectural components; there are even claims of the ability to produce whole buildings. These processes will give the architect a new palette of choice in terms of component design, and promise similar levels of geometric freedom as the Rapid Prototyping counterparts.

Rapid Prototyping processes, however, cannot simply be scaled up. There is critical interdependency between material properties, process function, and design objectives that generates specific problems. The increase in scale and print resolution of the built components requires much greater care over how the material is deposited, because the effects of the deposition have a visual impact, as they can be seen on the construction components. Traditional 3D CAD packages combined with the de-facto information protocols used to drive Rapid Prototyping machines fall short of this desired control. A design environment that allows for the design of construction-scale components using the material and process constraints and that provides greater control of the material deposition is required if the impact of the architectural features these processes produce is to be maximized.

This paper is presented broadly in two halves. The first provides an engineering perspective on the background and context, introducing Rapid Prototyping and, in particular, the three principal large-scale construction processes currently under development. One of these processes will be described in more detail. The second part considers the architectural design challenges presented by a new manufacturing process, and the new design environment is described alongside this.

2 RAPID PROTOTYPING, RAPID MANUFACTURING AND FREEFORM FABRICATION

In the manufacturing sector, automation using industrial robots and machines with direct numerical control took hold in the 1960s. CNC developed through the 1970s and 1980s where the computer revolution initiated the development of computer-aided design software (Howe 2000; Kolarevic 2003; Schodek et al, 2005).

In the field of product design, the CAD environment allowed for the digital design of products, but the production of a prototype model for aesthetic and/or functional testing needed to be manufactured by hand. In the 1980s, the first layer-based manufacturing process that made it possible for a physical model to be created directly from CAD data emerged. This significantly reduced the cycle time for the evaluation of product prototypes, and Rapid Prototyping was established.

Rapid Prototyping works through one of two methods: selective material phase change or selective material deposition. There are many processes, all of which operate on the principle of building the object out of sequential layers. Selective Laser Sintering is one technique that uses nylon or metal powder and a laser. A "sheet" of powder is spread over the build area, and the laser is used to sinter those areas that need to be solid. The next layer of powder then fuses to the previous layer. The resultant part ends up encased in a "cake" of unsintered powder, from which it is removed after the build is complete. Some processes fully melt rather than sinter, producing parts that approach 100 percent density and with even fewer defects than conventional casting. A popular process for architectural modeling is 3D printing, which uses a powdered gypsum compound that is made solid by selectively applying a binding agent. Both technologies are examples of selective material phase change.

Techniques such as Fused Deposition Modeling use selective material deposition and involve the continuous extrusion of a thermoplastic that fuses together. A second material is used to support overhanging sections; this is broken off the built part and discarded (Wohlers 2004).

Over the last 25 years, there have been considerable developments in materials, and this has allowed end-use parts to be created on these Rapid Prototyping machines, hence, the development of the more contemporary name, Rapid Manufacturing. The dimensions of the build chamber limit the part size. Some process work on very small parts to high tolerances. Some specialist machines are quite large, up to 800 mm by 1000 mm by 2000 mm. Some devices are similar in scale to most office items, such as a freestanding photocopier. Typically, however, a built bed up to 500 mm in the x, y, and z directions is used.

Figure 1 Contour Crafting

The principal benefit of Rapid Manufacturing is that it offers "unlimited" geometry at no extra cost, so that components can be manufactured with very complex forms or as complete assemblies or a complete solid object. The production cost has a linear relationship with component volume because the part cost is a function of material cost only. This compares to traditional methods that are required to recoup high tooling costs. In fact, (Hopkinson, Dickens 2003) demonstrated that rapid manufacturing is cost effective for low volume production.

Rapid Manufacturing is finding its niche market wherever customization or personalization is required, and is changing the way products are conceived and designed. Medical reconstructive surgery and dental products such as the Invisalign tool aligning system are examples (Invisalign 2006).

Over recent years, there have been a number of processes developed that take Rapid Manufacturing into the production of construction and architectural components. Probably the first to be developed was a selectively bonded sand and cement process that used an autoclave to harden the material, but the work did not progress any further (Buswell 2007).

Today, worldwide, there are three approaches under development for construction and architectural applications. These are large-scale Rapid Manufacturing, or Freeform Construction processes:

- Contour Crafting;
- D-Shape (formally monolite); and
- Concrete Printing.

Figure 2 D-Shape

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Contour Crafting (fig. 1) has been demonstrated in the laboratory at the University of Southern California. It is capable of producing full-scale, freeform wall structures that would replace the structural concrete block wall similar to that found in UK house construction. The process is based on extruding a permanent shutter that forms the external wall surfaces, which is then back-filled with a cement material. The approach is focused on the ability to rapidly build walls for buildings.

Figure 3 Concrete Printing

D-Shape (fig. 2) is based on the principles of a 3D printer and uses sand as the build material and a binder, which is sprayed onto the surface of each sequential layer. The process hardens over time, and the part is built inside a "cake" of powder, which must then be removed, post build.

Concrete Printing (fig. 3) is under development at Loughborough University, UK, and is based on extruding a bead of material in much the same way as the FDM process. The advantages of this approach are that the control of the extrusion diameter gives the required control over print resolution, and the extrusion process has been demonstrated with different materials. The build process works on the principle of the deposition of two materials, one that is the "build" material and one that is the "support" material, which is deposited as needed to support overhanging sections of the part, and then removed after the build is complete.

3 A DIGITAL DESIGN ENVIRONMENT FOR FREEFORM CONSTRUCTION PROCESSES

This section discusses the relationship between the architecture of CAD/CAM software and manufacturing processes, and then focuses on the development of a new CAD/CAM tool for one of the Freeform Construction Processes: Concrete Printing.

3.1 CAD MODELING AND MANUFACTURING PROCESSES

Digital design environments such as CAD systems have often been developed to emulate manufacturing processes. A substantial part of the manufacturing processes are subtractive (Thompson 2007). The desired product or component is shaped by subtracting (milling, cutting) material from a base. CAD/CAM software has often been developed with this subtractive process in mind. The digital design environment simulates this subtractive process. Typical CAD operations are tapering, chamfering, blending, and shelling. All these operations subtract material from a base volume that subscribes the required model.

CAD/CAM software has been developed not only to design, but also to create the coded instructions used to automate these processes through Computer Numeric Control (CNC) Machining.

CAD/CAM environments are often set up in direct relation to the process of fabrication. Rapid Manufacturing methods are additive processes since they add material to the object until it is complete. Until now, Rapid Manufacturing has adopted the CAD/CAM and digital design environments of the subtractive manufacturing processes.

3.2 WORKFLOW FOR RAPID PROTOTYPING OF ARCHITECTURAL MODELS

Freeform fabrication and, in this case, Concrete Printing, is in its infancy and does not have a standardized CAD/CAM design environment or workflow. The most similar workflow to Concrete Printing is probably Rapid Prototyping of architectural models. This workflow can be used as the start of a design and workflow framework for this new process.

Atypical workflow for the Rapid Prototyping of architectural models is given by De Kestelier and Peters (2008) and covered in brief here. A digital 3D model is made within an Architectural Engineering and Construction (AEC) CAD package. From this 3D model, an STL file is exported. STL is the initialism of Stereo-Lithography, or Standard Triangulation Language, and is a file format that describes the surface geometry of a three-dimensional object as a triangulated geometry. It does not have a representation of color, texture, or other common CAD model attributes. Depending on the Rapid Prototyping technique used, the STL file is then imported into a software package that will translate this file into a format that is readable by the manufacturing device, often manufacturer specific. The software will slice the 3D model in horizontal slices. This slicing will define the horizontal contour lines of the model, and what is inside or outside these contour lines, defining which sections of the part are solid and which are not. This will then define where the device deposits material, or where phase change is initiated.

The machine will typically action the creation of a solid layer in a prescribed sequence; this is often done by first tracing the contours that define the solid/non-solid boundaries and then filling the solid areas within these contours with a hatching pattern. The way a machine hatches or traces contours is related to the detail of the machine process and material properties, and the pattern is created using fairly standard algorithms.

An important feature of any process is the layer depth, since this will define the quality of the surface of the object. This resolution can be around 0.1 mm, so for applications such as architectural modeling, it is not significant.

Figure 4 Digital Test Model for FC Process; and G-Code Generation

3.3 CONCRETE PRINTING-SPECIFIC CAD SOFTWARE AND DATA TRANSLATION WORKFLOW

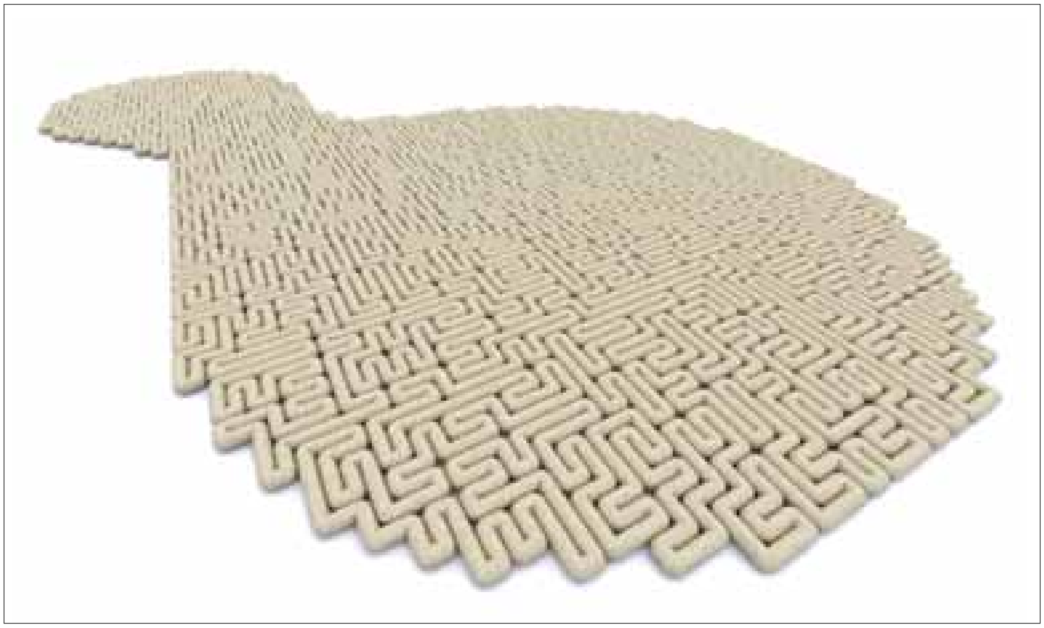
Freeform Construction processes are currently adopting the conventions established in Rapid Prototyping or Manufacturing. A key difference is the relative size of the layer depth or "print resolution." In Rapid Prototyping, the layer depth is approximately 0.1 mm in say a 100 mm high component—a ratio of 1:1000. The Concrete Printing process, however, works between 5 mm and 20 mm in 1500 mm; this is, at best, a ratio of 1:300, an increase by a factor of 3. What this means in practice is that the build resolution can be seen with the naked eye, and this has implications for the design.

Figure 5 Resolution of Concrete Printing

Concrete Printing uses an extruded bead (6 mm high by 9 mm wide) to deposit material. The first digital test models for Concrete Printing were created in standard CAD packages such as Solidworks and Microstation (fig. 4). These models were then exported to an STL format and exported to a specialist tool developed for the Concrete Printing process to slice the model in horizontal layers and to hatch the solid sections. These lines are the "tool paths" and can be translated to a set of instructions or G-code that will drive the machine.

Using the Rapid Manufacturing workflow process for Concrete Printing does not take into account the visibility of the layer depth, which is approximately 100 times larger (fig. 5). This resolution has an impact on the aesthetics of the part. In contrast with conventional Rapid Manufacturing, the shape and hatching strategy is essential to the final aesthetics of the part. The conventional design environments have only very limited control over the hatching and contouring pattern, and there are many possibilities such as that given in figure 6.

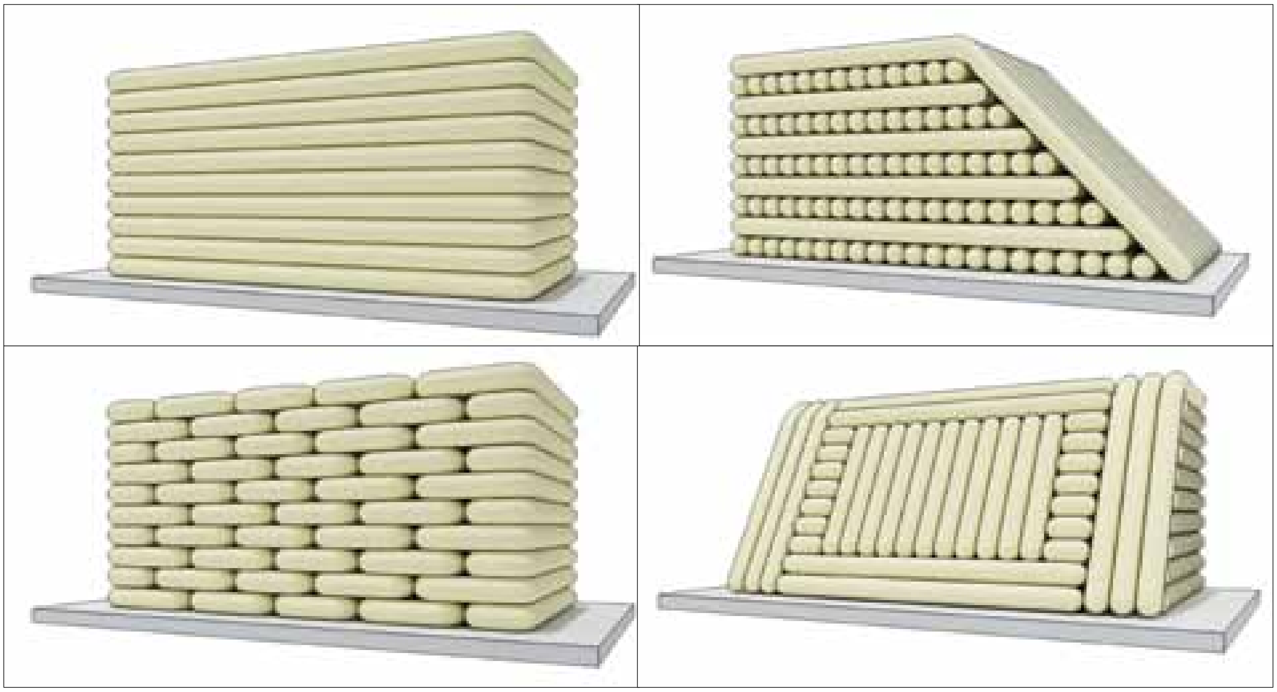
Figure 6
Custom-Designed Continuous Hatching Pattern



Almost all Rapid Manufacturing processes work on the basis of horizontal slicing; the height generated by this sequential layering is usually called the z-height (hatching and contouring on a given layer occurs in the x and y directions). With a visible building resolution, however, it is easy to imagine how to create tool paths that occur in all three dimensions (fig. 7). With Rapid Prototyping software packages, all the slicing is done purely horizontally, and the G-code follows that concept.

Each designed feature must be a multiple of the minimum build resolution, and this should be designed into the CAD software so that the design is implicitly achievable in terms of practical machine limitations and resultant aesthetics. In addition, a designer would find great benefit in seeing the object in a more realistic representation that truly represents the manufactured object. An appropriate approach to achieve this is to model the material extrusions explicitly, using the tool-path instructions.

Figure 7
Three-Dimensional Tool Paths



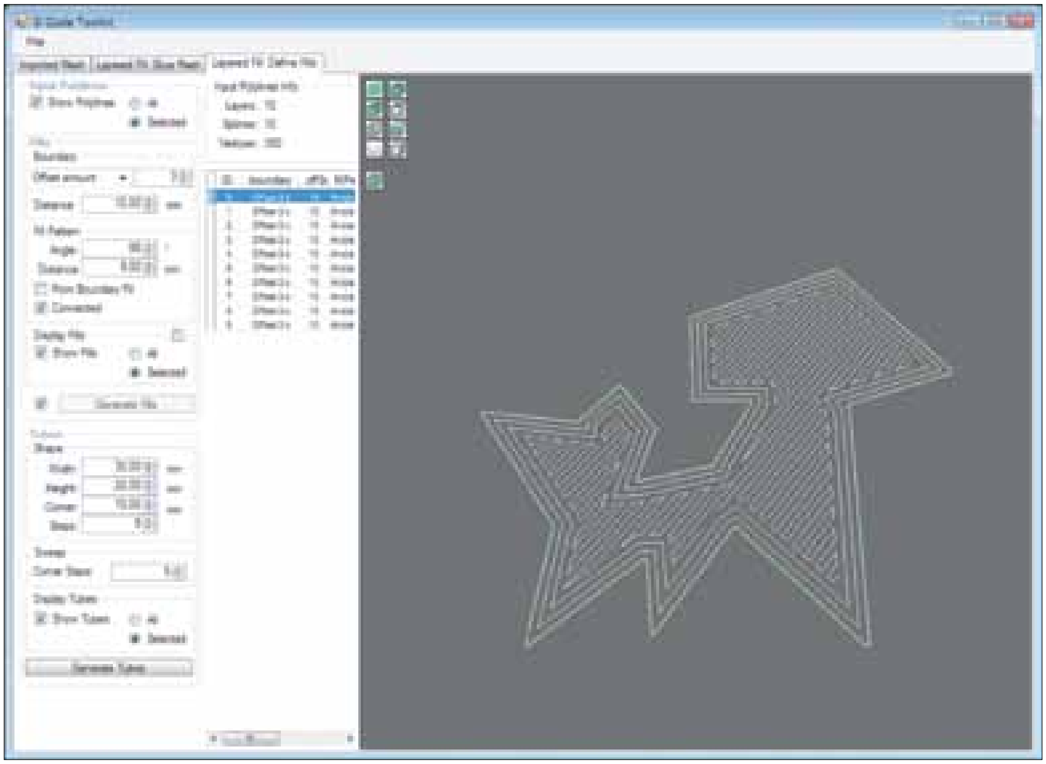
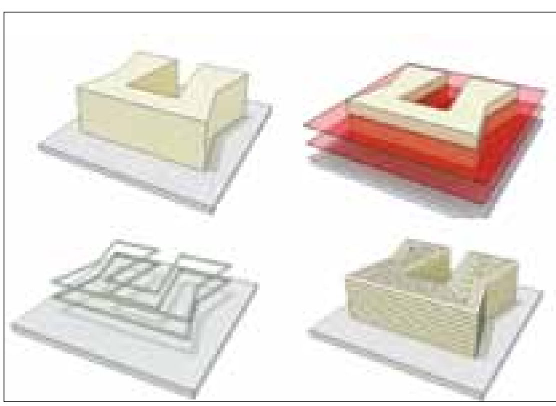


Figure 8
G-Code Toolkit

A custom piece of software, called G-code Toolkit, has been developed specifically for the Concrete Printing process (De Kestelier, Bernaerdt and Van Hauwaert, 2009) (fig. 8). This toolkit allows the user to import an STL file and, subsequently, slice this file horizontally according to the printing resolution. The user then has the choice in using contour lines and different hatching patterns. These patterns can be controlled layer by layer. Each layer can have a different hatching pattern. The tool paths that are created through this hatching process can be visualized with the software. In this way, the hatching pattern and the size of the extrusion can be checked for their visual and esthetical implications (figs. 9, 10).



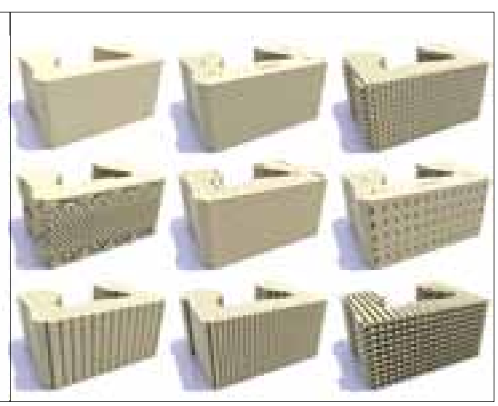


Figure 9 G-Code Toolkit Workflow

Figure 10 Hatching Patterns Generated with the G-Code Toolkit

A second design tool has been developed to generate the machine code that will drive the concrete printer (De Kestelier, Bernaerdt and Van Hauwaert, 2009). This tool is at the moment written as a plug-in for 3D Studio but should soon be implemented in the G-code Toolkit. This script starts from a set of lines that represent the tool path of the printer. The user can now very precisely control the start point and end point, and the order in which the tool paths will be printed (fig. 11). This G-code generator also incorporates a G-code dialect that is specific for the Concrete Printing process.

4 CONCRETE PRINTING A ‘FREEFORM WALL’

Exploring Concrete Printing on a larger scale is the Freeform Construction Group at Loughborough University; they have been developing the design of a large “Freeform wall.” Building a large prototype helps evaluate the hardware and the material development, and serves as a test case for developing a new design environment.

The wall is built up from a central B-spline curve in-plane and has a gradually changing thickness along its length, essentially an extrusion in the z direction (fig. 12). A parametric model was created within Generative Components, which is a parametric modeler built on the CAD modeler, Microstation. Generative Components is mainly used in the AEC industry.

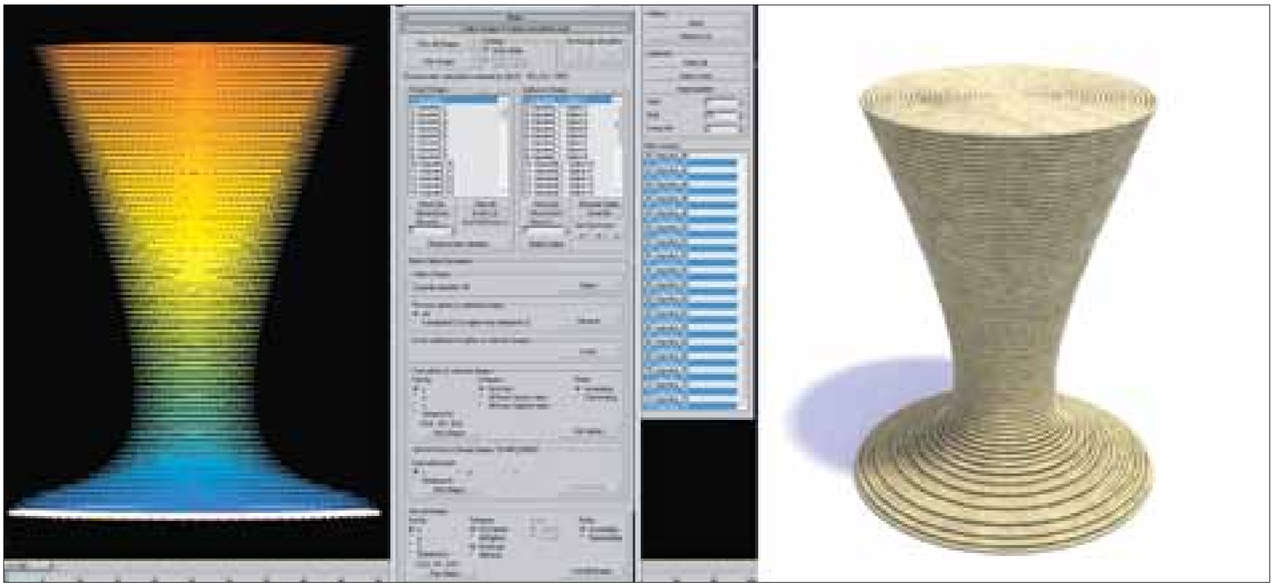


Figure 11 G-Code Exporter Script for 3D Studio

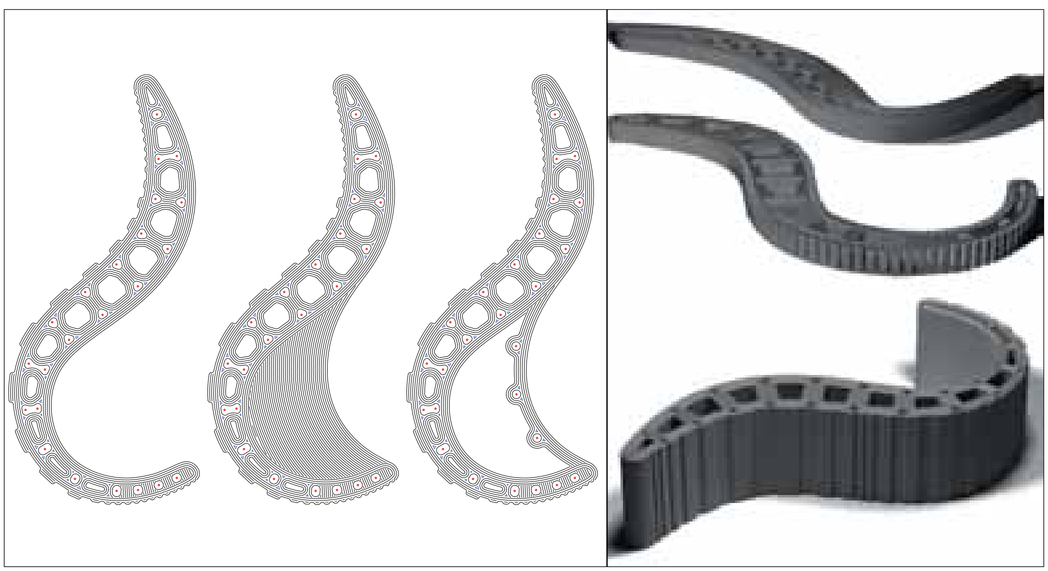


Figure 12 Freeform Wall

Instead of modeling the wall as a volume, the wall is being directly built up out of a set of lines. These lines represent the tool paths or extrusion contours and patterns. A parametric logic is built up so that these lines can be edited and transformed in one go, without the need for editing each tool path separately.

The parametric model of the wall is created in such a way that the following features can be adjusted: a 4th-order B-spline curve controls the central spine of the wall, and a law curve, whose values are limited by a minimum and a maximum, control the changes in the overall thickness (fig. 13).

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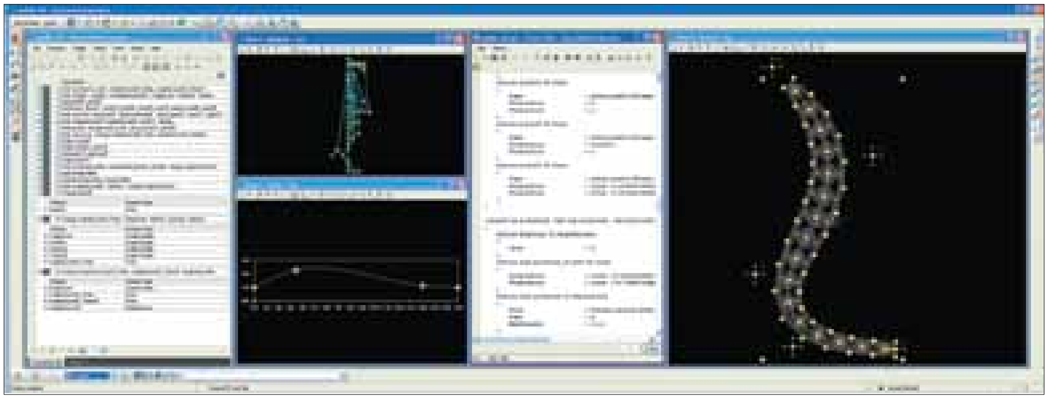

Figure 13 Parametric Model for Freeform Prototype Wall

The model is set up by polylines and B-spline curves. All polylines and B-splines are in a constant parallel offset, equivalent to the extrusion diameter. The concept is to build the construction method into the parametric model; rather than building a geometric volume, the wall is build up by its tool paths. These tool paths can then be "tubed" to render a visual representation of the printed object. These tool paths can be exported to a DWG format, which is then the import data for the Concrete Printing G-code generator script.

CONCLUSION

The use of Rapid Prototyping has inspired different industries to research the possibility of using these layered manufacturing processes for actual production, and not only for prototyping. In the last few years, different universities and companies have developed a few experimental processes to test the possibility of applying Rapid Manufacturing in the construction industry. By designing prototype objects for the Concrete Printing process in particular, it became apparent that new ways of designing are necessary. There will be the need for different CAD environments that are fine-tuned towards Freeform Construction methods. These design environments will need to have the notion of the fabrication process embedded in its modeling tools. The data translation workflows will also need to be adapted towards a design environment where the actual tool paths can be manipulated. There seems to be the need to shift to designing with collections of parametrically controlled tool paths, rather than with explicit geometrical volumes.

ACKNOWLEDGMENTS

THIS WORK WAS CARRIED OUT AS A COLLABORATION BETWEEN THE DEPARTMENT OF CIVIL AND BUILDING ENGINEERING AT LOUGHBOROUGH UNIVERSITY, UK, THE SPECIALIST MODELLING GROUP FROM FOSTER+PARTNERS, UK, AND THE ARCHITECTURE & URBAN PLANNING DEPARTMENT OF THE UNIVERSITY OF GENT, BELGIUM, WHERE THE SOFTWARE WAS DEVELOPED.

THE CONCRETE PRINTING PROCESS ON WHICH THIS PAPER WAS BASED IS AN ONGOING RESEARCH PROJECT BETWEEN THE DEPARTMENT OF CIVIL AND BUILDING ENGINEERING AT LOUGHBOROUGH UNIVERSITY AND UK INDUSTRY, INCLUDING FOSTER+PARTNERS, BURO HAPPOLD, AND SHOTCRETE. THE WORK IS FUNDED THROUGH THE UK'S ENGINEERING AND PHYSICAL SCIENCES RESEARCH COUNCIL, INNOVATIVE MANUFACTURING AND CONSTRUCTION RESEARCH CENTRE AT LOUGHBOROUGH.

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