FABRICATING CONSTRUCTION COMPONENTS USING LAYERED MANUFACTURING TECHNOLOGY

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Building 3D objects directly from CAD data using purpose built machines is a technique known as Rapid Manufacturing and these processes allow great freedom in the design of the geometry of the manufactured component. These machines build components by selectively depositing or initiating the phase change of a material, bonding sequential layers together. Traditional processes are either subtractive or formative in nature, whereas these methods are additive. Niche markets for these processes are continually developing and they challenge conventional methods of design and procurement. The work presented in this paper reports on recent developments in scaling up these process to create complex construction scale components. The work here discussed the development of the approach and preliminary components have been manufactured with different nozzle diameters. The results to date are promising although increasing the deposition precision will improve the quality of the built parts.

Keywords: construction automation, digital fabrication, freeform construction, rapid manufacturing.

INTRODUCTION

Despite, or perhaps, because of the long history of manual construction methods, conventional construction techniques stifle innovation. Most new methods of production and assembly focus on moving the ‘hand trades’ away from the construction site rather than developing new processes (Gibb and Pendlebury 2003).
In conventional manufacturing and construction, moulds, dies and formwork restrict the geometry that can be realised because of the limitations imposed by (i) casting angles, (ii) non-re-entrant shapes, and (iii) complexity (Hague et al. 2003). Rapid Manufacturing (RM) is now an integral part of modern product development (Hague et al. 2003), having been commercialised over the last two decades. RM has the ability to reduce the waste, costs, and time-scales of component production (Evans and Campbell 2003). RM automates the production of prototyping models for aesthetic and functional testing, greatly reducing the time consuming manual production methods (Sambu et al. 2004).

Rapid Manufacturing

RM is a family of digitally controlled layer based 'additive' processes that have superseded the forerunning Rapid Prototyping (RP) methods. RP techniques were developed for generating models for evaluation in the design cycle (McDonald et al. 2001); whereas RM uses those same process for the creation of end use parts directly

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(Dickens 1999) without the need for tooling (Hopkinson and Dickens 2003). RM processes include; Selective Laser Sintering (SLS), Stereolithography (SLA), 3D printing (3DP), and Fuse Deposition Modelling (FDM) (Wohler 2004).
SLS utilises a laser to partially melt layers of powder, which are deposited over the bed area sequentially, thus the targeted areas are melted and become a layer of the final component. With powder based processes, the support for overhanging sections of parts is provided by the loose material in the build chamber. The printing processes of RM share a common principle with other methods. Firstly, a 3D model is created in CAD, exported as STL (Stereolithography Language) format, and sliced into layers for a sequential reconstruction. The sliced layers are converted as sequential 2D coordinate sets, e.g. inner and outer boundary lines (where the solid material borders the non-solid material) and hatches (which 'fill in' the solid areas between the boundary lines). Then the data of each layer is sent to the machine, and the (process dependant) 'head' either deposits a binder on powder, or deposits the material directly, or activates a laser; in accordance with these instructions. 3D printing, for example, uses inkjet printer technology to deposit a binder on a fine layer of powdered material where the layer is to be made solid.
With the sequential bonding these 2D layers of material, the machine reconstructs a 3D object. SLA is a laser based process as is SLS, but uses liquid photopolymer resin instead of powder and a ultra-violet laser to activate the material set. FDM extrudes a bead of thermo-plastic and deposits it directly where required where it fuses to the previous layer. FDM is one of the most broadly used layered manufacturing systems because it has low costs and can be used with various materials (Zhang and Chou 2006).

Freeform Construction Processes

Rapid Manufacturing processes typically produce parts up to (very) approximately a cube with sides with a length of 500mm. In recent years this layer manufacturing concept has being scaled up for architectural and construction applications, called Freeform Construction Processes.
There are some generic criticisms of Rapid Manufacturing such as slow build speed, low accuracy and surface finish, lack of usable materials, and poor mechanical properties (Hopkinson et al. 2006). Scaled up Freeform Construction process has similar issues including:

- Volume of prints; all the RM processes have an inevitable constraint of printing volume, which is restricted by the machine size. Freeform Construction methods are also constrained by the sheer weight and volume of placing build materials and removal of the unused/support materials.
- Printing speed; an object needs to be printed by sequential tool-paths and layers, thus the printing speed of RM is much slower than conventional manufacturing such as casting, but for low volume production, the eliminations of tools and formwork counter balances this.
- Material constraints; Construction is, for the foreseeable future, likely to continue to use readily available mineral based materials such as a cement-based concrete. All materials have natural variations in the constituents and properties and the effects of these become acute in layer based manufacturing. This will be particularly so when creating large parts out of 'conventional' construction materials.

- Design and control of design; a design has to be converted to a specific data format that contains essential instructions used to control the machine. Since the printing path is a set of sequential line segments, the file size of G-code is dramatically increased by complex curvatures. Dealing with very large construction-scale designs will magnify the problem.
- Resolution and precision: the resolution of printing with layered manufacturing techniques is depending on the depth of each layer. The particle size and deposition rate provide a lower limit, countered by the desire to produces detail to a particular level which gives and upper limit. This is key to production speed, function and aesthetics of the printed components.

RM processes do have advantages over conventional manufacturing processes. Firstly, they do not have specific tooling requirements and are able to build customised parts without extra tools or moulds (Hopkinson et al. 2006; Buswell et al. 2007). The cost-per-part of RM-based components are constant, unlike the high initial set up costs for tooling in conventional processes (Hopkinson and Dickens 2003). Secondly, they offer construction automation and the promise of design freedom (Hague et al. 2003; Hopkinson et al. 2006); and thirdly, they have the potential of building in additional functionality into structures (Buswell et al. 2007). Therefore, the introduction of RM can change the designer's method of working and design process (Hague et al. 2003). The research and practice of Freeform Construction is currently limited to three processes worldwide:

- D-shape (Italy);
- Contour Crafting (US); and
- Concrete Printing (UK).

The history of freeform construction research started in 1997. Pegna (1997) suggested the complexity of construction process can be simplified by substitution with a number of fundamental operations, and demonstrated layered fabrication by depositing a layer of reactive material (Portland cement) over a layer of silica to produce 3D form. The argument presented was that many simple operations could be employed to fabricate a complicated shape. The process also resulted in components that had similar compressive strength to regular cast concrete; however, no further research has been reported. Khoshnevis (2004) introduced the next step of developing a process called Contour Crafting (CC). The process of CC mimics the conventional construction process but with some degrees of automation. Firstly, it creates a 20mm high permanent shutter using a special material, which it later backfilled with a cement based compound. Some reinforcement strategies have been demonstrated by hand placing U-shaped tie rods at every 12 inches horizontally and 5 inches vertically (Khoshnevis et al. 2006). Although the CC process is an interesting concept, i.e. the mould is not disposed of and becomes a part of wall, it still requires three separated steps, i.e. moulding, reinforcing and placing concrete and the build layer depth is ~20mm.
Another developer, Enrico Dini (www.d-shape.com) has developed and exhibited the D-shape process at the Civils 2007 exhibition at Earls Court in London, 20 - 22th November 2007. The main concept of his process is based on 3DP, and intended to print architectural artefacts using sand and an inorganic binder with 5-10mm of layer depth. The process is claimed to produce a material with similar properties to marble. Part of the post processing involves removing the unused build powder and grinding

and polishing the surface. The placing and removal of the unused sand is significant since a volume greater than the boxed volume of the component must be placed.
Work at Loughborough University has been developing the third process of Concrete printing. This paper describes the process and reports on progress to date.

CONCRETE PRINTING

The process starts with data preparation which is similar to a most RP/RM processes. The data of the sliced layers generated from a 3D CAD model are saved as a G-code format. These instructions are read by the machine that operates all the control commands adjusting the nozzle position, movement, and material flow, etc. The prototype machine depicted in Figure 1 is consists of a 5.4m (L) by 4.4m (W) by 5.4m (H) frame and a printing head on a mobile horizontal-beam which moves in the y and z direction while the printing head moves in the x direction only. The printing head is driven at up to 5m per minute depending on the curvature of a printing path. The printing process after the data preparation consists of three steps: material preparation, delivering, and printing.

Figure 1: 3D printing rig.

Mixing (materials)

In our project, two types of materials for printing freeform components are being used. A cement-based material is used for a 'build' while a gypsum-based material is used for a 'support' because of low strength, easy removal and 100% recyclable. The printing process requires highly controlled and constant workability of materials during fabrication. A retarder admixture is therefore added to the materials to secure the required open time for a constant workability. In the printing process, once the fresh materials are extruded out of a nozzle they should have a sufficient load capacity to carry the weight of later layers seated above and also have a suitable plastic state to bond with the surrounding beads and layers. Additionally, the strength of hardened 'build' should be sufficient to carry applied loads.

Delivery

Once the material is mixed, it is placed in the pump located outside of the rig to deliver material to the nozzle through a hose. A small hopper is installed as a buffer zone on the top of the deposition device which in turn delivers the materials to the desired location. In the beginning of printing, the head is located in the recharging position to fill materials into the hopper. When the amount of material in the hopper is reached to the pre-defined low level, then the printing head moves back to the recharging position to refill the hopper (see Figure 2).

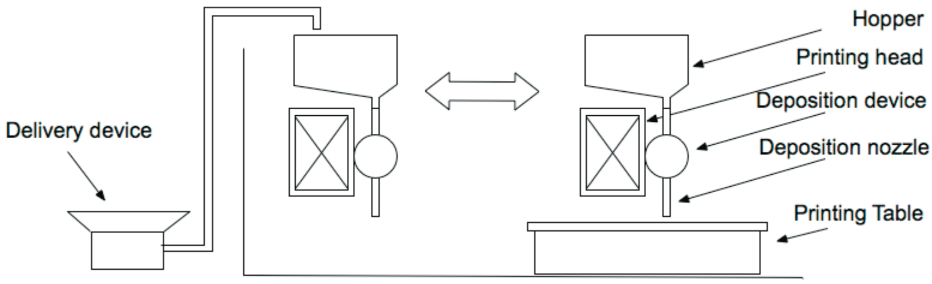

Figure 2: Diagram of the material delivery and refill process

Printing

Conventional construction materials have been selected on the basis of cost and availability, in addition to the ubiquitous familiarity at an industrial level. Extrusion is a good choice to control placement of wet-mixed cement mortar. Currently the build material is extruded through a 9mm nozzle. The support material is printed using an identical system.

PRINTING EXAMPLES

Initially, the proposed approach has been tested with a gypsum-based material using the 22mm (W) x 15mm (H) size of beads. The models for the initial printing were designed to calibrate the nozzle size and surface finishing. The dimensions of the both printed examples are 58mm (W) x 78.5cm (L), and the height is from 4 to 28cm. The printing time of both models is 29 minutes and 23 seconds for the example 1, and 1 hour 6 minutes and 41 seconds for the example 2 (see Figure 3).

Figure 3: Printing examples with 22 x 15mm beads. Left: example 1 and Right: example 2

The results of the initial printing test show the freedom of design without any mould supports; however, the resolution of the surface finishing was not impressive. Thus a further reduced bead size (9 x 6mm) was tested for a comparison (see Figure 4). It was observed that increasing a printing resolution by reducing the bead size also minimise the printing errors such as unwanted dribbles during the nozzle on/off operation and mismatched vertical alignments, etc., although it also increases the printing time.

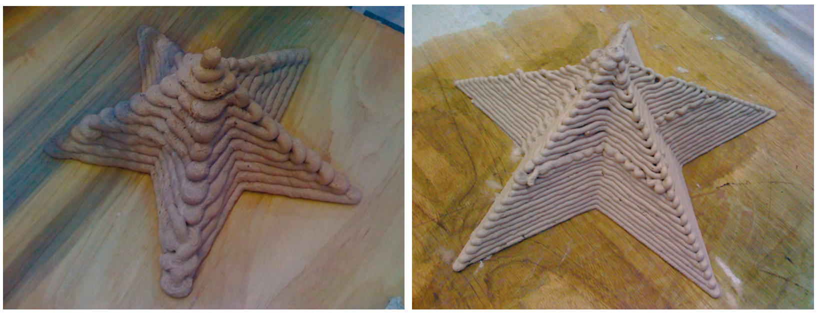

Figure 4: Printing examples two resolutions. Left: 22 x 15mm and Right: 9 x 6mm.

The prototype system has been further improved and tested with more shapes and a cement-based material. The natural surface texture has architectural interest generated by the extrusion process rather than being polished which could lead to novel finishes and applications. Thus, a few more models were designed and tested (see Figures 5 and 6).

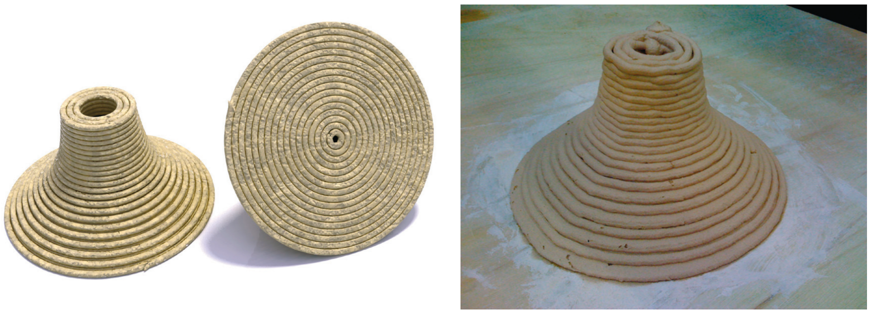

Figure 5: Example - Silo. Left: CAD model and Right: printed model.

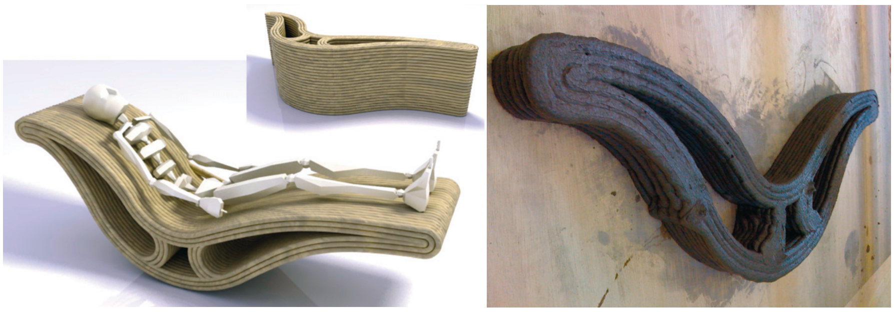

Figure 6: Examples - bed. Left: CAD model and Right: printed model.

Currently at Loughborough a large artefact has been designed in order to demonstrate the scale of the process. The 'freeform wall' is 2m long by 1m wide by 1.2m high. The surface texture is varied, it has an integrated seat in addition to voids that could be utilise by insulation and/or building services (see Figure 7). The estimated weight is around 1.1 tonnes. The requirement of the object to be transportable introduced interesting component integration issues that where solved as part of the design process:

- To place the wall under compression, mainly for transport and safety (toppling, breaking), a process specific reinforcement strategy was developed and implemented.
- For lifting and moving a plywood pallet was fully integrated with the digital design and part manufactured using the CNC machine instructions.

- A design environment that works with the constraints of the process has been developed that output the G-Code to control the machine. The artefact requires more than 10 million lines of instructions to print the entire object (~240MB of file size).

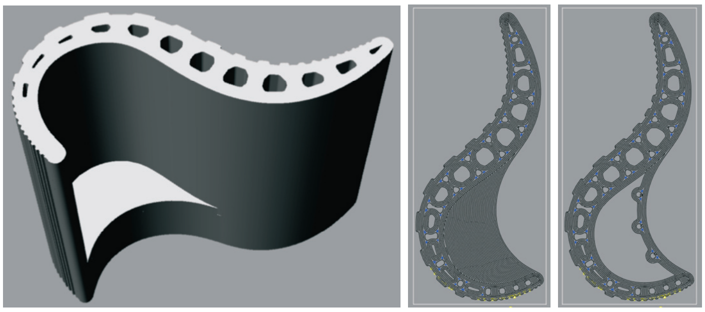

Figure 7: The large artefact. Left: rendered model, Middle: top view, Right: section view.

Production of the artefact is underway and should be completed in the summer of 2009.

CONCRETE PRINTING: DISCUSSION

The work to date is promising and offers a new way of manufacturing construction and architectural components. There are a number of issues. The physical dimension of the rig restricts the printing size because of (i) the cross beams over the frame for rigidness which restricts the height of prints considering the removal of prints, and (ii) the mobile horizontal-beam and the print head which reduce the actual printing area. However, the components that can be printed are substantial and the weight of the finished component quickly becomes the limiting factor of a design when moving it is considered. There are many alternatives for improving the rig design outside the scope of this project, which include the application of robotics.

Typically components produced through layered manufacturing methods have lower compressive, flexural and tensile strengths than counter parts manufactured using traditional formwork processes. For example, the typical tensile strength of FDM parts using ABS P400 were reported between 65 ~ 72% of the strength of injection moulded parts (Montero et al. 2001), which means high strength cement based concretes should be used. In early stage of the project, a pre-bagged commercially available material with a compressive strength of 40MPa was used. However, the printed components are inherently weaker and so new low shrinkage, cement-based 'build' materials are being developed that have the desired workability characteristics required by the deposition process.

The development of a 'lights out' manufacturing process is beyond the scope of the project, but the mixing and delivery of substantial quantities of material is not trivial. A shorter route from mixing to deposition is favourable to reduce clean down time and improve the delivery characteristics and reduce waste. The weight on the rig head is also key, restricting the rate of movement.

The printing process is currently fixed with a single nozzle size and so printing time (i.e. maximum rig traverse speed) and surface resolution are also fixed in constant proportion. Increasing printing resolution by reducing the nozzle size will extend the printing time because it will requires more hatches (less volume deposited per meter) and layers to print.

An important issue is the control of the part 'growth' in z-height: Maximum vertical height is achievable through control over layer thickness consistency. Distortion can occur with the load of the deposited material on itself and can affect the build height and impact on vertical surface alignment. Figure 8 shows the case of rough vertical alignment with different thickness of each layer.

Figure 8: Surface alignment issues.

Concrete Printing is still underdevelopment and the quality of the manufactured parts is improving constantly. A full scale artefact is being produced to demonstrate the technology. It is expected that the approach will initially find applications in the production of doubly curved cladding panels or other high value components. With the design of the component described digitally, before manufacture, the opportunity to add functionality, reduce weight and optimise structurally all become possible when there is a manufacturing process are capable of producing components of 'any' geometry.

CONCLUSIONS

Rapid manufacturing is beginning to have an impact in the design process and the necessity of new processes and materials for construction has been stated in the recent European call (ECTP 2005). In the last few years there have been three large scale processes for construction applications developed based on the principles of RM that offer construction automation. Freeform Construction process has limitations, but the design freedom they offer is unparalleled.
This paper focused on one process underdevelopment at Loughborough University, UK, funded through the UK government, in collaboration with industry. Concrete Printing described in this paper uses conventional construction materials such as cement and gypsum. The process was described, some sample parts presented and some of the limitations and issues discussed. Early results are promising and illustrate the flexibility and potential for component design innovation.

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