From rapid prototyping to automated manufacturing

Aant van der Zee[1], Bauke de Vries[2], Theo Salet[3]
[1,2,3] Eindhoven University of Technology
[1,2,3] {a.v.d.zee|b.d.vries|t.a.m.salet}@tue.nl

In this paper we present an outline of a newly started project to develop a tool which connects BIM to a manufacturing technique like 3D printing. First we will look some promising manufacturing techniques. We will design a small dwelling and export it into a BIM, from which we will extract our data to generate the path the nozzle has to follow. The chosen path is constrained by the material properties, the design and speed of the nozzle. To validate the system we develop a small VR tool in which we mimic a manufacturing tool.

Keywords: *Rapid prototyping, rapid manufacturing, robotics, automation, Building Information Model (BIM)*

INTRODUCTION

It is good practice in architecture to make prototypes of the design at hand. The reason is often for own usage or presentation to stakeholders. Mostly cardboard or wood is used to make these models. In the 1980s early examples of 3D printing occurred, though the printers then were large, expensive and highly limited in what they could produce. These industrial 3D printers have been used extensively for rapid prototyping and research purposes. In the 1990's the term "3D printing" was coined at MIT when then graduate students Jim Bredt and Tim Anderson modified an inkjet printer to extrude a binding solution onto a bed of powder, rather than ink onto paper.

These rapid prototyping techniques did start research to see if these techniques can be used as a manufacturing technique, in order to automated the building industry. But in order to be useable in the building industry the manufacturing techniques must connect to a BIM.

RELATED RESEARCH

Rapid prototyping is a group of techniques used to quickly fabricate a scale model of a physical part or assembly using three-dimensional computer aided design (CAD) data. The first techniques for rapid prototyping became available in the late 1980s and were used to produce models and prototype parts. Today, they are used for a much wider range of applications and are even used to manufacture production-quality parts in relatively small numbers. These rapid prototyping techniques gave a new impulse in the research to automate the building industry. For mentioned rapid prototyping processes can be divided into two mainstream categories each with a number of techniques:

1. Additive manufacturing process:

- Fused depositing modeling (=FDM)
- Stereo lithography (=SLA)
- Selective laser sintering (=SLS)
- Laminated object manufacturing (=LOM)

- Electron beam melting (=EBM)

2. Subtractive manufacturing process:

- CNC milling:
- Laser cutter
- Wire cutting

We will discuss briefly the above mentioned rapid prototyping processes. It is just an explanation of the process, in order to make a classification of these processes possible.

Fused depositing modeling

FDM works by laying down material in layers. A plastic filament or metal wire is unwound from a coil and supplies material to an extrusion nozzle, which can turn the flow on and off. The nozzle is heated to melt the material and can be moved in both horizontal and vertical directions by a numerically controlled mechanism, directly controlled by a computer-aided manufacturing (CAM) software package. The model or part is produced by extruding small beads of thermoplastic material to form layers as the material hardens immediately after extrusion from the nozzle. Stepper motors or servo motors are typically employed to move the extrusion head.

FDM begins with a software process, developed by Stratasys, which processes an STL file (stereo lithography file format) in minutes, mathematically slicing and orienting the model for the build process. If required, support structures are automatically generated. The machine dispenses two materials - one for the model and one for a disposable support structure.

The thermoplastics are liquefied and deposited by an extrusion head, which follows a tool-path defined by the CAD file. The materials are deposited in layers as fine as 0.04 mm thick, and the part is built from the bottom up - one layer at a time.

Stereo lithography

SLA is a process, which employs a vat of liquid ultraviolet curable photopolymer "resin", and an ultraviolet laser to build parts' layers one at a time. For each layer, the laser beam traces a cross-section of the part pattern on the surface of the liquid resin. Exposure to the ultraviolet laser light cures and solidifies the pattern traced on the resin and joins it to the layer below.

Stereo lithography requires the use of supporting structures, which serve to attach the part to the elevator platform, prevent deflection due to gravity and hold the cross sections in place so that they resist lateral pressure from the re-coater blade. Supports are generated automatically during the preparation of 3D Computer Aided Design models for use on the stereo lithography machine, although they may be manipulated manually. Supports must be removed from the finished product manually.

Selective laser sintering

SLS is a technique that uses a high power laser to fuse small particles of plastic, metal, ceramic, or glass powders into a mass that has a desired three-dimensional shape. The laser selectively fuses powdered material by scanning cross-sections generated from a 3-D digital description of the part (for example from a CAD file or scan data) on the surface of a powder bed. After each cross-section is scanned, the powder bed is lowered by one layer thickness, a new layer of material is applied on top, and the process is repeated until the part is completed. Unlike some other additive manufacturing processes, such as stereo lithography (SLA) and fused deposition modeling (FDM), SLS does not require support structures due to the fact that the part being constructed is surrounded by un-sintered powder at all times.

Laminated object manufacturing

LOM is a process where layers of adhesive-coated paper, plastic, or metal laminates are successively glued together and cut to shape with a knife or CNC or laser cutter.

Electron beam melting

EBM is a type of additive manufacturing for metal parts. It is often classified as a rapid manufacturing method. The technology manufactures parts by melting metal powder layer by layer with an electron beam in a high vacuum. Unlike some metal sintering techniques, the parts are fully dense, void-free, and extremely strong.

This solid freeform fabrication method produces fully dense metal parts directly from metal powder with characteristics of the target material. The EBM machine reads data from a 3D CAD model and lays down successive layers of powdered material. These layers are melted together utilizing a computer controlled electron beam. In this way it builds up the parts. The process takes place under vacuum, which makes it suited to manufacture parts in reactive materials with a high affinity for oxygen, e.g. titanium.

The melted material is from a pure alloy in powder form of the final material to be fabricated (no filler). For that reason the electron beam technology doesn't require additional thermal treatment to obtain the full mechanical properties of the parts. The EBM process operates at an elevated temperature, typically between 700 and 1000 °C, producing parts that are virtually free from residual stress, and eliminating the need for heat treatment after the build.

Rapid manufacturing

Advances in the mentioned rapid prototyping techniques have brought about the ability to use materials that are appropriate for final manufacture. These advances in material make it possible to directly manufacturing finished components. Additive manufacturing is defined by ASTM (= American Society for Testing and Materials) as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies such as traditional machining." Additive manufacturing techniques can be used anywhere throughout the production cycle from preproduction (= rapid prototyping) to full scale production (= rapid manufacturing). The advantages of rapid manufacturing lie in the relatively inexpensive production of small numbers of parts, even if they are so-called freeform. This ability to manufacture inexpensive full scale freeform components triggered off research in the building industry to see if they could adapt these rapid manufacturing techniques.

It is our opinion that these additive processes can be subdivided into two main categories:

1. Where material is placed onto a layer of the same material (layered);

2. Where layer-wise material is 'sintered' (sintered).

Both of these categories and especially the 'fused depositing modelling' en 'selective laser sintering' methods are used in by the building industry for rapid manufacturing processes. There are a few promising real life techniques based on the above mentioned categories, which are still under development.

1. Layered.

- Contour Crafting (CC) is a additive layered fabrication technology developed by Dr. Behrokh Khoshnevis of the University of Southern California. Contour Crafting is layered manufacturing system which uses polymer, ceramic slurry, cement to build large scale objects. The extrusion process forms the smooth surface of the object by constraining the extruded flow in the vertical and horizontal direction to trowel surfaces. Attaching the system to a gantry system (see figure 1) the system is capable of "printing" houses.

- Kamermaker: DUS-architects have developed a 3D printer which is able to print rooms with a maximum size of 3 x 3 x 2.5 meter. Using the same technique they are experimenting to print a so-called "grachtenpand" in Amsterdam (see figure 2). The Kamermaker is an up scaled version of the Ultimaker, the 3D desktop printer. In contrast to the filament of the

Ultimaker, the Kamermaker uses a bio plastic granulate which enters an extruder. In the extruder the granulate is heated and pressed together to a homogeneous liquid. This liquid is brought to the printer head which extrudes the melted material along a generated path.

- Concrete Printing Process is developed at Loughborough University in the UK The concrete printing process comprises a printing head which is digitally controlled by a CNC machine to move in X, Y and Z directions via three chain-driven tubular steel beams. A material container is mounted on top of the printing head and connected to a pump to convey the material to the printing nozzle which is activated by the CNC machine. The deposition material, concrete, has been designed to be extruded through a nozzle to build layer-by-layer structural components (see figure 3).

2. Sintered.

- D-SHAPE a 3D printing technique, based on stereo lithography and selective sintering, developed by the Italian Enirco Dini. D-shape uses a a powder deposition process, which is selectively hardened using a binder. Each layer of build material is laid to the desired thickness, compacted and then the nozzles mounted on a gantry frame deposit the binder where the part is to ne solid. Once a part is complete it is then dug out of the loose powder bed. Dini used the technique to build the so-called "Radiolaria" a 1.6 m high architectural art work (see figure 4).

Next to the research of developing rapid manufacturing techniques, there is still ongoing research on the implementation of robotics in the building industry, some research is still in its infancy state:

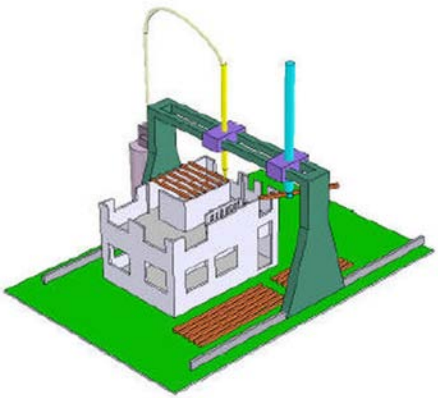


Figure 1
Contour crafting with gantry

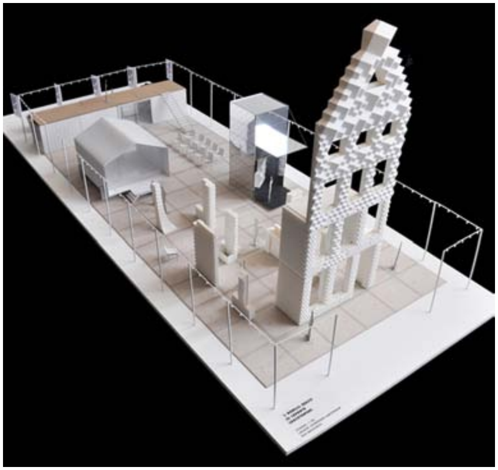


Figure 2
Grachtenpand

Figure 3
Concrete printing

- Assembly robotics
- Drones:
- Exo skeletons

For on-site use of rapid manufacturing techniques systems based on selective sintering have a big disadvantage compare the layered based systems. Selective sintering uses a powder bed, and the finished object has to dug out.

Figure 4
Radiolaria

Each manufacturing technique is capable of deliver building components of significant size. But this means only a step forward in the indoor manufacturing process to personalize prefabricated components.

We can conclude that the research of layered techniques is focused on monolithic constructions, be it adobe or concrete. If we continue in this direction, and developed an on-site 3D manufacturing system which, delivers monolithic buildings, this will raise the question whether clients will accepted those building, or do they prefer houses with a traditional brick or wood cladding. If the clients prefer a traditional look, the advantage of fast manufacturing on site is counter acted by the slow process of giving the building a traditional look. Research had to be done in 3D manufacturing systems with at least 2 materials (nozzles) or a combination of 3D printing techniques and assembly robotics

RESEARCH QUESTION

Compared with the car-industry, the level of automation in the building industry is low. This low level of automation is due to the fact that in the building industry each object is a unique object and each building site is a unique location.

The main reason of this high level of automation in the car industry is a modern manufacturing concept: Computer Integrated Manufacturing (CIM). The CIM systems permit to balance the flexibility in the product with the manufacturing productivity. This relationship is one of the key factors of the success.

The so called platform concept is one of the newest advances of the CIM system. It is based on the use of a number of elements in various models. The same platform design, engine, electronics, etc. are used not only in different models of cars of the same company but also in the cars of other companies. This concept reduces a vehicle cost and makes the automobile companies more competitive (Balaguer, 2008).

It is our opinion that in building industry, now research, development and use of a Building Information Model (BIM) is growing; automation of the building process will become the next main research area.

With BIM technology, one or more accurate virtual models of a building are constructed digitally. They support design through its phases, allowing better analysis and control than manual processes. When completed, these computer generated models contain precise geometry and data needed to support the construction, fabrication and procurement activities through which the building is realized (Eastman 2011).

BIM has a big impact on the design side of the building process and the way stakeholder's communicate with each other. It is our opinion that BIM also will influence the other side of the process, the manufacturing side, be it prefabrication or use of robotics (in the broadest sense of the word). The main difficulty on the manufacturing side is related to the nature of the 'working' environment, which is highly unstructured. Working in this environment involves handling heavy objects, elements made with big tolerances, low-level standardization, and medium level of industrialization and pre-fabrication. The development of a systematized approach to construction using largely dry, prefabricated components delivered just in time has advanced the degree of automation. As a result there is heavy traffic between construction plant and construction site.

Because of the global financial crisis the yearly demand for housing is reduced. De Ridder states "Large quantity is replaced by high quality, small and personalized production units and a focus on added value for the client" (de Ridder 2012). This process will transform the building industry, especially the construction techniques. As stated earlier the automation in the building industry focuses nowadays on prefabrication in closed environments. Few initiatives are realized in the personalisation of the dwelling, see WoonConnect1. With the introduction of 3D printing techniques in the building industry the door is opened to personalized production units be it made in indoor or outdoor environments. It is our opinion that the use of 3D printing on-site is more interesting.

In our research we focus on the Netherlands. The climate in the Netherlands has a big impact on the used materials in the building industry.

The process of on-site 3D manufacturing will have big impact on the design and used materials of dwellings. If we look at the traditional dwelling typology the houses on a row ("rijtjes huis"), we see that now nowadays the main load-bearing walls are perpendicular to the street. As a result the depth of the dwelling is bigger than the width. With a on-site 3D manufacturing system, where the nozzle is attached to a gantry crane the main loadbearing walls will be parallel to the street and as a result the width will be bigger than the depth of the dwelling. This layout will have a big impact on the layout of the new to build neighborhood.

Goal of this research is to connect BIM to automated construction techniques. The research question we like to answer: is it possible to use BIM to automate the construction process on-site and or in a closed environment (pre-fabrication). This research question can be subdivided in to two sub questions:

1. Which type of manufacturing is the most promising in the building industry?

2. Is it possible to use BIM to navigate the "robot", or put it differently is it possible to develop an interface between BIM and the control unit of an automated construction system (= ACS);

RESEARCH APPROACH

It is our opinion that real life 3D printing based on layering is the most feasible on-site 3D printing as manufacturing technique. As explained earlier the nozzle "draws" the walls layer by layer.

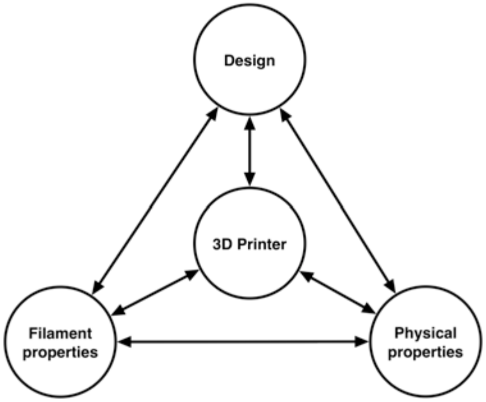
In order to build a interface we need to extract the geometry out of the BIM. More precise we use the IFC code as base for the transformation from the BIM to an 2D layered pathway which the nozzle has to follow.

From the BIM we need to extract the geometry of the walls and the locations of the windows and doors. This information will be used to calculate the x,y,z- movement of the nozzle. The BIM will also be used to generated the required support construction which may or may-not have influence on the path the nozzle has to traverse. But besides to retrieve the orthogonal movement, we have to calculate the shortest, fastest and economic path the nozzle needs to travel. The deposition material constrains the path. 3D printing requires the concrete to have no slump and harden fast. Therefore, the print path and material properties are strongly linked together. If Δt is the time it takes to go from point a on layer i to point b on layer i+1 and point b lies exact on top of point a, we can conclude:

- If Δt is too short the wall will collapses the wall is too wet to bear its own load;
- if Δt is too long the concrete of the previous layer will no longer be wet and the structural properties will be anisotropic.

So Δt is related to the length of the path the nozzle has to go and the speed of the nozzle. The path is related to the design of the building (placing of the walls, windows and door). We can conclude that there is a strong relationship between the shape of the object (building or building component), the demand (physical requirements), the deposition material properties and both manufacturing technique and print path (figure 5).

Figure 5 Relationship between design, material, demands and printer



Research will start to see if the idea to print with multi materials is feasible. With two materials, (lightweight)concrete and an insulation material, efficient sandwich construction can be realised. The second material can also be used to print the required support construction.

CONCLUSION

The research of BIM is nowadays mainly focused on the office-side of the automation in the building industry. For a fully automated building industry we need to connect BIM also to manufacturing side. This research will show that it is possible to map the complex 3D data in a BIM onto an orthogonal movement, which can direct a nozzle in an economic way.

We will design a small dwelling and export it into a BIM, from which we will extract our data to direct the nozzle. To validate the system we develop a small VR tool in which we mimic a manufacturing tool. The VR tools must have the same degree of freedom as the real-life manufacturing tool. Our tool will direct the VR nozzle to draw the dwelling. With this simulation we can conclude:

- If it is possible to use a BIM as control unit for manufacturing;
- Will the nozzle travel the best feasible path.

REFERENCES

Balaguer, C and Abderrahim, M (eds) 2008, *Trends in Robotics and Automation in Construction*, InTech, http://www.intechopen.com/books/robotics_-and_automation_in_construction/trends_in_-robotics_and_automation_in_construction

Eastman, C and Teicholz, P 2011, *BIM Handbook, a guide to building information modeling*, John Wiley & Sons, inc

Khoshnevis, B 2004, 'Automated Construction by Contour Crafting-Related Robotics and Information Technologies', *Automation in Construction*, 13(1), pp. 5-19

Lim, S 2012, 'Developments in construction-scale additive manufacturing process', *Automation in Construction*, 21, pp. 262-268

de Ridder, H 2012, *Legolisering van der bouw, Industrieel maatwerk in een snel veranderende wereld*, Mauritsgroen.mgmc, Amersfoort