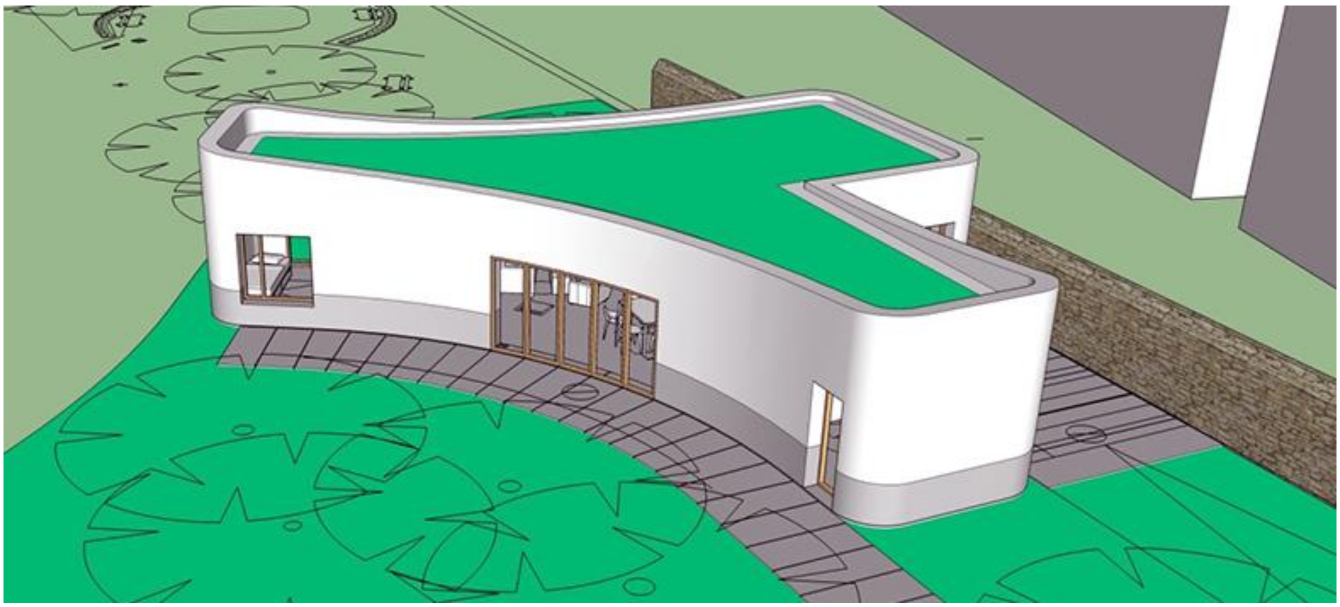
BATIPRINT3D PROJECT REPORT



Source: batiprint3d.fr/en

Institution: University of Nantes
Technology/Project: Batiprint3d
Report issue date: Nov.2017

Issued by: 3D Printhuset A/S
Visit date: 15.Sep.2017
Visited by: Ana Goidea

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.1. Technology overview

Batiprint3d is a patented system using a multiaxis combination of two robots to extrude polyurethane foam that acts as formwork for casting concrete. The process is a FDM (fused deposition modeling) layered deposition system. The extruded material bonds to the previous layer through the process of hardening that initiates once the material exits the nozzle.

Robotic setup (Source: All photos are taken by the author unless otherwise stated)

.2. Institution and development

.2.1. Institution overview

University of Nantes, departments of Laboratory of Digital Sciences of Nantes together with the Research Institute in Civil and Mechanical Engineering have started a research project looking into automated construction systems. They have also been working in collaboration with Nantes Métropole, Nantes Métropole Habitat, and SATT West Valorisation. The construction of the house was done in partnership with Bouygues Batiment – one of the large construction companies in France and Lafarge Holcim.

.2.2. Project overview, size and development

The project aims at building a 95 square meters house on the land of a social housing area in Nantes; the name of the construction is Yhnova House. The launch of the construction was timed to coincide with the Nantes Digital Week event.

.2.3. Target market

The target market is within the construction industry, since Batiprint3D operates under a complete construction system.

.2.4. Past, current and future projects

The 'ferret house' was an early project at the university. It was a small shed used as a test bed for robotic extrusion on a smaller scale. Its construction was how the partnership started one year before. Following a successful result and interest from other actors, the Yhnova house project was initiated.

.2.5. Development stage of printers

The two robots that are employed by Batiprint3d are an articulated robot arm and a guided vehicle; these have been already used in industrial production and therefore readily available on the market. However, the printhead installed on the robot arm as the end effector is custom developed within the project. In addition, a feedback system of positioning the printer on site has been installed. The robotic printing system is developed and fully operational.

.2.6. Development stage of printed materials and largest print to date

At the time of the visit, the construction of Yhnova was undergoing. The foundation was in place, as well as the frames for doors and windows. These act as formwork for the boundaries at the end of the wall, where the polyurethane foam is interrupted. The reinforced steel bars that will be cast have also been installed. Before the current stage, smaller scale tests have been produced, along with a scaled house model bench cast in concrete.

3D

printing and construction progress at the time of the visit.

The whole setup is installed under a temporary tent, which protects the machinery from undesired weather conditions.

.3. Technology

.3.1. Additive manufacturing technology

The process employed in the Batiprint3d construction is of the extrusion based additive manufacturing type. More specifically, FDM (Fused Deposition Modeling) - this is a method of fabrication where each layer is being deposited on top of the previous one, and either through the process of extrusion or soon after, the layers fuse together. This can happen in a variety of ways, as seen in the current printing techniques. In the case of desktop 3d printers, the use of thermoplastics and their fusion through heating and melting as they pass through the printhead is widely used. The equivalent (FDM) technology on the construction scale is seen in materials such as concrete, the fusion between layers is done through the curing in the presence of oxygen. This has been utilized in projects such as Contour Craft by Bekroh Koshnevich, research done at Eindhoven University and more recently, the BOD by 3D Printhuset.

Since the printing material used in the Yhnova house is polyurethane, the fusion between successive layers is done through the very rapid expansion and hardening of the foam after the chemical reaction between the constituent materials.

.3.2. Printing procedure

The construction of the house is done in several steps as outlined below.

1. First, the foundation is cast in place, as even as possible to minimize tolerances. The bottom part of the reinforced bar columns is cast inside the foundation. The rebars are 75 mm and placed

approximately every 3 to 4 meters. The doors and window frames are installed as well. The area of the foundation is just slightly larger compared to the area of the house including the walls. The foundation exceeds the perimeter of the walls mostly where the walls curve in plan; these corners highlight the discrepancies of the traditional construction methods when used in conjunction with digital fabrication. Sewers, water inlet and the electrical wiring system have been brought into the house through the foundation.

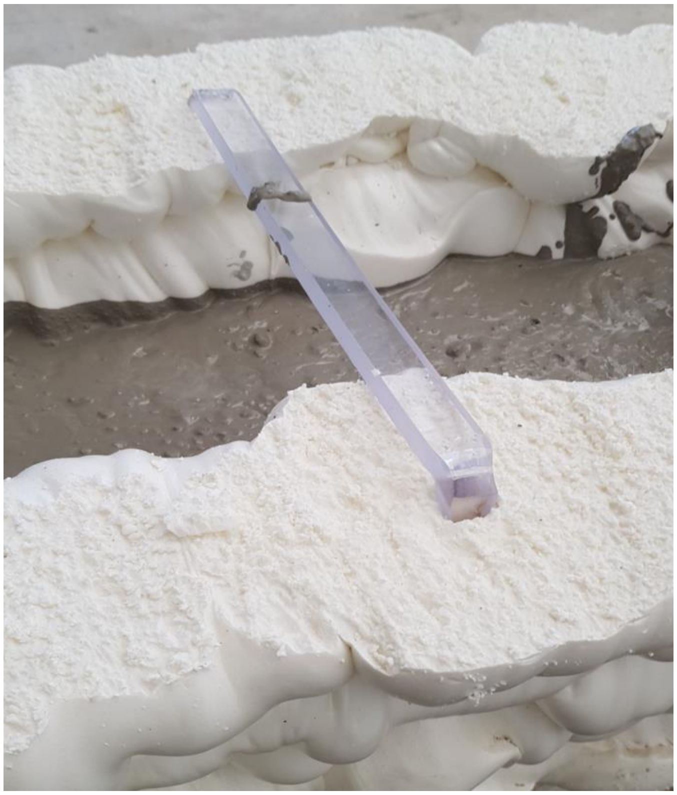
Meeting between the cast foundation and the 3d printed walls.

2. On top of the foundation the robot system extrudes the polyurethane foam. This is done 300 mm in height at a time, on two wall layers that will act as the longitudinal support for the concrete.

Reinforcement bars and connection with the concrete – together with the first two layers of printing on the foundation.

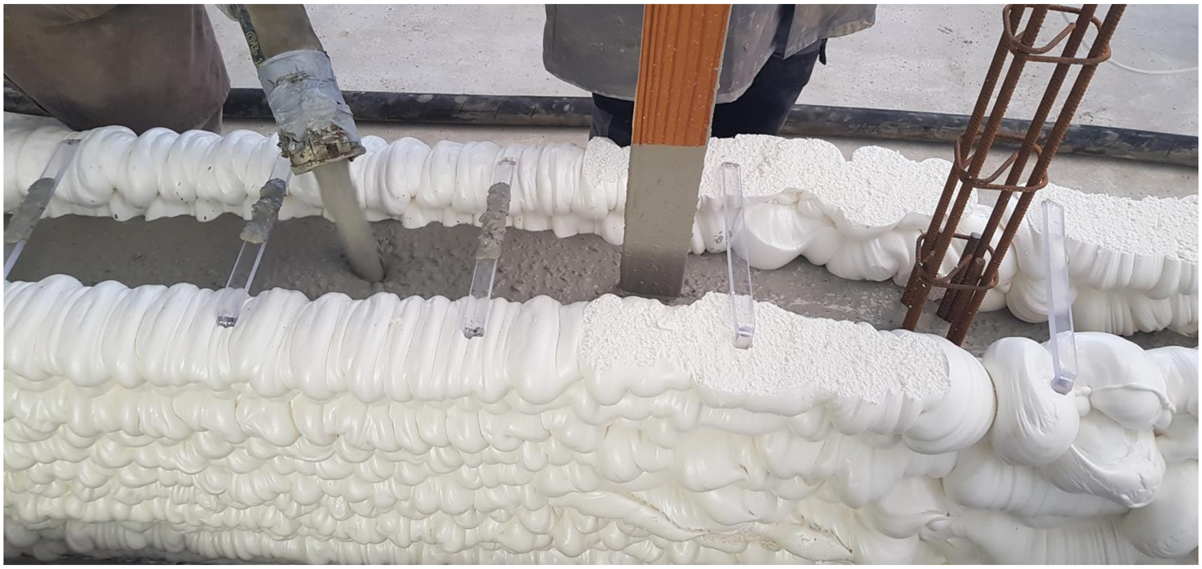
3. After the 300 mm of extruded foam has been laid and hardened all around the perimeter of the house, a row of wall ties are installed. These are made from laser-cut acrylic which was later

thermally bent so that the ends can be inserted in the foam. The ties have the role of holding the two walls together when the casting is made, and during the curing of the concrete. In plan, these are placed at every 250 mm.



Acrylic ties installed on top of the polyurethane foam.

4. The next step is casting the concrete in between the two foam layers. Since the lateral force the concrete exerts on the formwork is increasing with its height, and polyurethane foam is not a strong enough material to support the load of the full height wall, the casting is done in sections. 300 mm is the height that has been established as a good balance of strength and speed of construction.



Concrete pouring in between the polyurethane formwork.

5. After the concrete has been cast throughout the perimeter of the building, another 300 mm of extruded foam is added on top of the existing one and the acrylic ties, securing them in place.

6. The process is repeated (steps 2-5) until the walls reach the final height.

.3.3. Form freedom

The method described earlier of printing the formwork for casting in an unpredictable material as PU foam have the implication of restricting the freedom of the building form. Each layer has to be printed on top of the previous one without any support. And although theoretically there might be the possibility of incrementally overhanging each layer so that there is variation on the vertical axis, the casting of the concrete impedes this; the force the concrete exerts on the formwork and its weight would not be able to be supported by the PU walls. Therefore printer has a 2.5 dimensional freedom[1] - this means that the plan of the building can have any shape, but the 3 dimensional model will always be a vertical extrusion of the two dimensional form.

.3.4. Fabrication location and approach

The project takes place in a residential area of Nantes, in the garden of a social housing complex. The architectural design was influenced by the trees layout in the garden so that there would be no displacement or cutting of the trees.

[1] 2.5 dimensions used here: planar freedom in x and y axis, while the z (vertical) movement is restricted linearly, which means that each layer needs to be deposited directly on top of the previous one, with no offset or cantilevering possible.

Location of the Yhnova House.

The printing is carried on directly on site. Due to the high versatility of the system, the only requirement for the printer is a flat surface on which to run. Considering the high precision of the industrial machinery, very low tolerances are part of the system, therefore small differences in the non automated parts of the construction have high negative impact. This is the case for the foundation, which acts as the platform on which the two robots access the printing areas. However, the system can compensate for these in the material deposition.

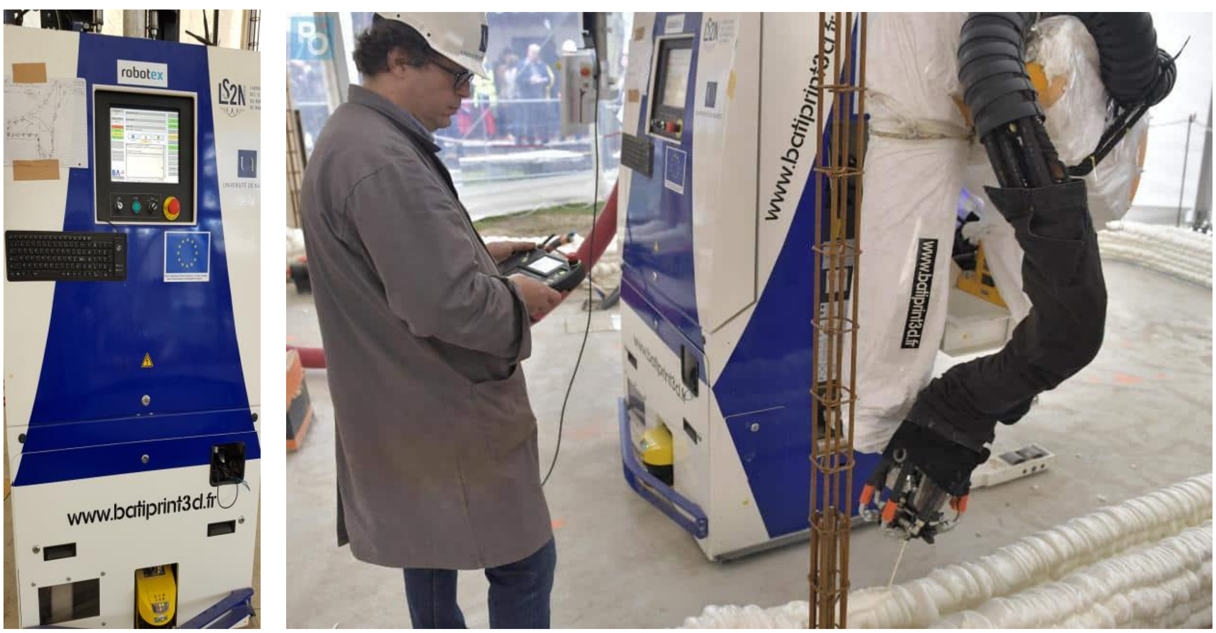
For this to be possible, the robot is constantly evaluating its position in space in respect with the toolpath information received from the central computer. This is done through a laser positioning system. A 360 degrees laser beacon is placed on a pole on the AGV. This sends signals from its location to the photosensors placed around the perimeter outside the foundation at an interval of approximately 3 meters. The signal is then computed and the actual position of the robot is calculated in real time and with high precision.


Laser beacon on top of the robot (left image) and laser receptors (right image).

.4. Printer

.4.1. Robot types

The printing system consists of two robots which work together synchronized to achieve a large scale coverage required for architectural application, as well as multiple reaching angles.



Back view of AGV robot (left image) and robot assembly during printing (Source:https://www.basystemes.com/en/news/20170915/)

.4.1.1. *Main unit robot*

The main unit robot on which the printhead is installed is a Staubli industrial robot. It is a 6 axis articulated robotic arm, which provides high flexibility in terms of reaching the target point.

.4.1.2. *Secondary access robot*

The main robot arm is secured on an AGV (Automated Guided Vehicle) which transports it. Since the first robot only has a reach of approx. 3 meters around it, it needs to be moved along the perimeter of the house in order to be able to print the walls of a larger structure. The AGV can move the robot arm on the XY plane, as well as in height in order to reach the top part of the walls.

.4.2. Movement

Due to the many axes that the robotic system has in place – six for the main robot arm and three for the AGV robot base – the restrictions on the movement and material deposition are very low. However, due to the material system of polyurethane foam formwork that needs to support in situ casting of concrete, the geometry is limited in vertical freedom.

The printhead can approach the target position on each layer from a high number of angles. In the construction process of the Yhnova house, the steel rebar columns have already been installed in the concrete slab before the printing process. These represent obstacles in the toolpath of the robot, which needs to compensate for them. The many axes of the system are helping overcome this problem, since the robot arm can reach around the columns and extrude in areas that would be hard to reach with a printing system that used less axes.

.4.3. Material deposition system

The two material liquid streams are connected to the printhead of the main robot into a mixing chamber, where they are combined and then extruded. As they get out, the foam expands and solidifies on top of the previous layer. The width of each layer varies between 80 and 150 mm, with a height of 50 mm. The space left in between the two polyurethane walls for concrete casing is also varying due to the unpredictability of the process, but lies in between 100 and 200 mm in width.

Image of a section through the extruded polyurethane foam, showing the variation between different layers.

.4.4. Material feeding

The extruder is connected to the polyurethane canisters of the two material components. These are

pressurized so when the extruder releases the material, it flows out.

Poly-isocyanate and polyol cannisters.

The concrete is cast through a hose that pours concrete from one point at each wall inside the foam formwork. The hose is carried and positioned by the robot arm, so the process is automated. A pump placed outside of the tent is mixing the concrete and feeding it through the hose inside. A truck delivers the concrete to the site.

Pump

mixing station.

.4.5. Printer electronics and software

Slicing and robot control is done in Staubli native programming language, which can be either in VAL robotics language or PLC-IEC61131 language. The robot is connected to a desktop computer located on the site. CS8 controllers effect the command on the robots[2].

.4.6. Printer speed

The maximum printing speed of the system is quite high in the construction printing category, running at 0.2 meters / second. However, this only accounts for the extrusion of the polyurethane foam and not the whole process of erecting the walls. Considering all the other necesary next steps, the overall construction speed slows down compared to the 3d print speed. The time in between the printing of the 300 mm wall sections is that required for the casting of the concrete and placing the ties, as well as letting the concrete cure so that it can support the next section of concrete cast on top of it, without adding more pressure on the polyurethane formwork.

.4.7. Printer accuracy

The robot system positioning and movement accuracy is around 1 mm, which is more precise than the standard tolerance in the construction industry.

[2]https://www.staubli.us/en/robotics/

Approx a meter height of a portion of a wall sample printed in polyurethane.

However, the polyurethane has high rate of expansion and rapid solidification. This means that the final extruded and rigidified deposition has, within an interval, an unpredictable shape. The small scale variability of the material is high, resulting in a surface rugosity of few dozens millimeters. (See photo below)

.4.8. Printer operation, handling and assembly

The printing system can be ran and supervised by one person.

.4.9. Printer specifications

rinter size (assembled): Roughly 1.5m * 2m * 1m
Printer size (stored): Not available
Print volume: NA[3]
Printing speed: 0.2 m/s[4]
Layer thickness: 50 mm
Accuracy (estimated): Robotic movement: 1 mm; Including material system: few centimeters
Deposition head: Single nozzle, pressurized extrusion
Structure: Robotic arm
Movement: Wheels, tracks and rotation axes
Shape freedom: 2.5
Weight: Not available
Energy consumption: Not available
Required personnel: One person

[3]Since the robot is installed on an AGV, the surface area in which it can run is only limited by the cables and hose length, which can be easily adjusted. Therefore, at least in thoery there is no maximum printing volume.
[4]Note that the printing speed is only regarding the polyurethane extrusion, and not the concrete casting

Price per unit: Not for sale / Not specified

.5. Material

.5.1. General description

Polyurethane foam is a polymer produced by the reaction of poly-isocyanate and polyol. The two materials are fed into the printhead mixing chamber. After they have mixed they react together and then are extruded. The resulting polyurethane expands in the presence of air, increasing its volume by 3000% within the first six seconds of leaving the mixing chamber, after which it quickly becomes rigid.

.5.2. Material properties

The foam is used as formwork for the casting of the concrete. It has a good weight to strength ratio, but considering how lightweight it is, it doesn't have a very high structural performance. In particular, the tensile and shear resistance are the lowest, which is problematic when casting the concrete. The solution for this is to put in place ties that hold the two sides of the formork in place until the concrete hardens. These will also be kept in place, since they will be encased in the concrete. However, this does still not provide enough support, so the concrete casting process is divided into vertical sections of 300 mm.

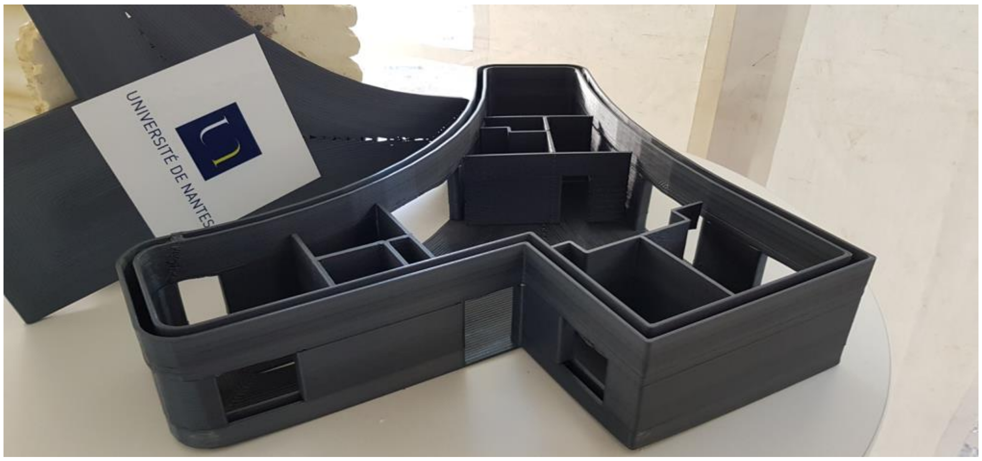
The foam is a very good insulation material, due to the high amount of air trapped within its thickness: 97% of its volume is trapped gas. For this reason, it is being kept in place as the building insulation. In addition, the material is also watertight, acting within the wall system as the water barrier.

Prototype showing the layering within a wall.

.5.3. Material possibilities

Due to the low shear and tensile values, the polyurethane foam limits the number of ways in which it can be cast. The Yhnova project uses it with two dimensional planar (along x and y axes) variation, while the vertical (z axis) dimension is uniform.

The walls will be finished with fiberglass mesh and plastered on both interior and exterior sides, as shown in the image above.



3D printed model of the house showing the plan layout and internal wall partitions.

.5.4. Useful links and sources

http://batiprint3d.fr/en/

Press release: http://batiprint3d.fr/wp-content/uploads/2017/10/NM_YHNOVA_DossierPresse_GB_09-17.pdf

http://www.univ-nantes.fr/partenariat-developpement-/les-chercheurs-nantais-impriment-le-premier-logement-social-a-nantes-1513679.kjsp