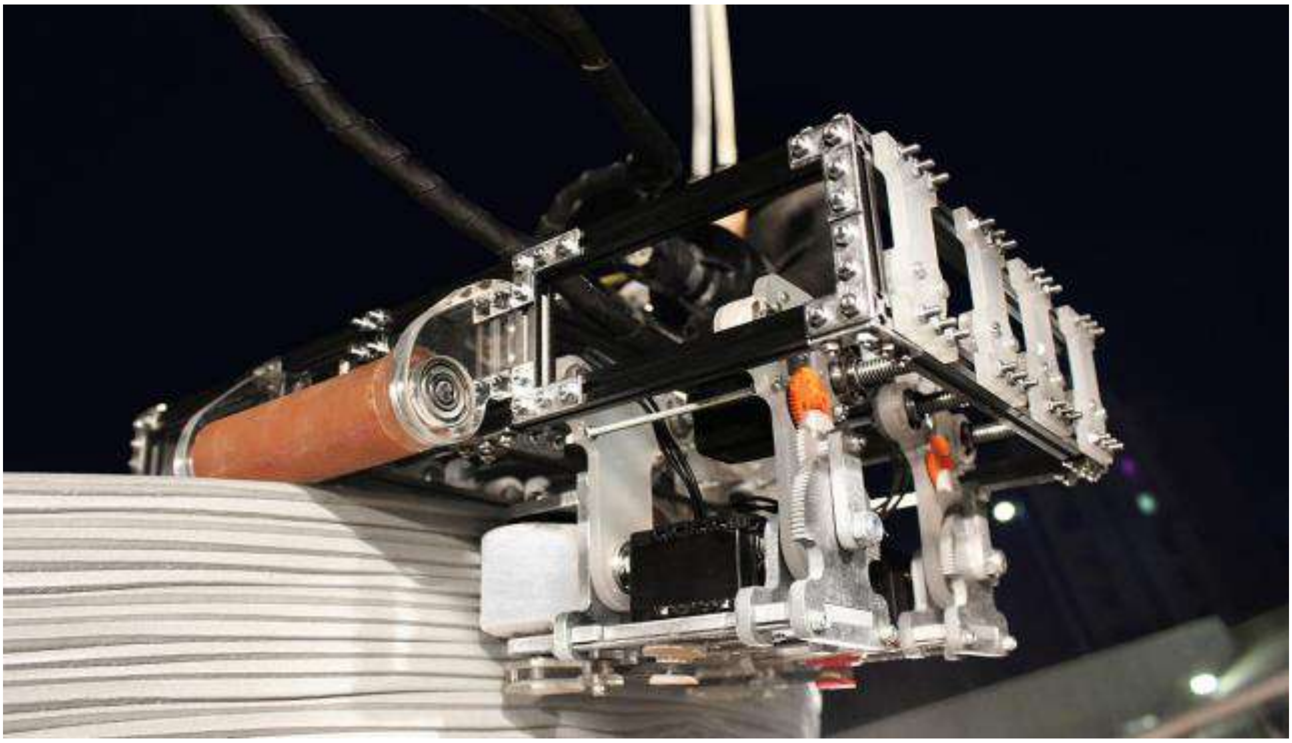
MINI BUILDERS PROJECT - REPORT



Another project emerging from the Institute for advanced architecture of Catalonia (IaaC), which uses a swarm of small, specialized robots that work together to create the whole structure.

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Contents

1. Technology overview

Minibuilders is essentially a layered material extrusion process, where a fused material is pushed through a nozzle and deposited in layer. This technology is very typical and well established both in 3D Printing in general (known as Fused Deposition Modeling or FDM), as well as in its construction-scale variants. But what sets Minibuilders miles away from all other process is a very innovative and completely different approach to actually printing the structure. While other technologies use gantries or robotic arms that move a nozzle around the printable surface, Minibuilders uses a swarm of small robots that work together, and even climb on top of the structure while printing it.

This project was aimed at developing the various specialized types of printer robots.

One of the printer robots in action

2. Institution and development

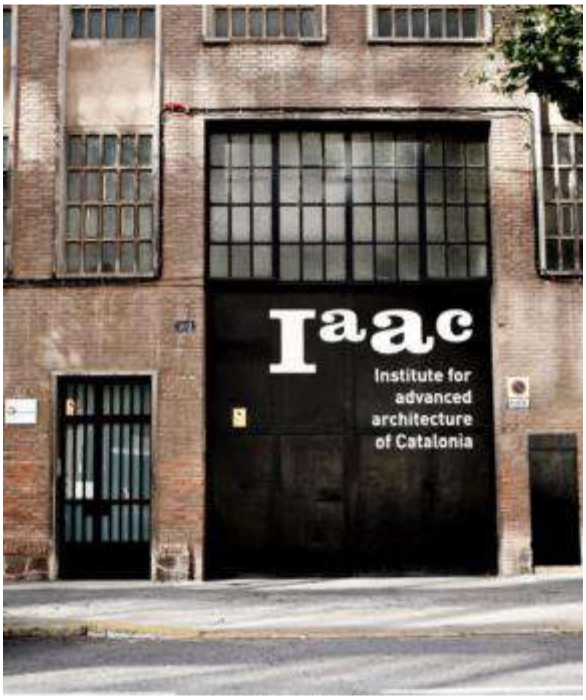
2.1 Institution's overview

The Minibuilders project is under the supervision of the Institute for advanced architecture of Catalonia (IaaC). This educational and research center based in Barcelona sets its main focus on developing architecture to meet the worldwide challenges of the 21st century. It boasts a large digital production laboratory comprised of 3D printers, laser cutters, milling machines, robotic arms, chips manufacturing platforms, and many more. The institute has also various collaborations with other highly recognized institutions, such as the Media Lab of the Massachusetts Institute of Technology (MIT).

This has allowed for a wide array of highly technological ideas and projects to emerge in the last decade.

With a special focus on additive manufacturing and 3d printing on the large architectural scale, it is home to some promising projects on the 3D Construction Printing scene, which helped pave the road for many others. There is a strong collaboration with D-Shape and its founder Enrico Dini, who collaborated in various workshops and projects, and the institute has also designed the first 3D printed bridge printed with the D-Shape technology. Needless to say, Iaac is intended to stay an important player in this emerging field, and has already established itself as one of its early developers.

The Iaac 3d printing projects include Mataerial, FabClay, Pylos, Minibuilders, On Site Robotics, and TerraPerforma. They all share the same knowledge and experiences, tackling various aspects of a 3d printed construction, such as materials, movement of the printer, or the thermal efficiency of a printed geometry. They are essentially all part of a greater picture that is trying to bring 3d printing closer to architecture and construction.



Institute for advanced architecture of Catalonia - headquarters and workshop

2.2 Project overview, size and development

The Minibuilders project is one of the many at Iaac, and it is mostly focused on the research of an innovative approach to 3D Construction Printing. The projects is developed by a team of researchers led by Sasa Jokic and Petr Novikov. The project has resulted in 3 different types of robots being developed, that work in a synchronized way, each with its own specialty within the whole process.

2.3 Targeted market

Since this is only a research project, there is no specifically target market for the moment, apart from construction and architecture in general.

2.4 Past, current & future projects

The Minibuilders project has no direct predecessors within the other Iaac project, as its innovative printing approach stand mostly on its own. However, many positive outcomes and experience from other previous projects, such as FabClay, led by Sasa Jovic, have greatly contributed for this project as well. Mataerial, a project also led by Sasa Jovic, has used the same type of material.

2.5 Development stage of printers

The Minibuilders is mainly focused on the development of the printing technology. It has currently 3 working prototypes of small robotic printers, each with its own specialty. The project has also developed the main unit robot, that acts as a material feeder for the other smaller ones.

2.6 Development stage of printed materials and largest print to date

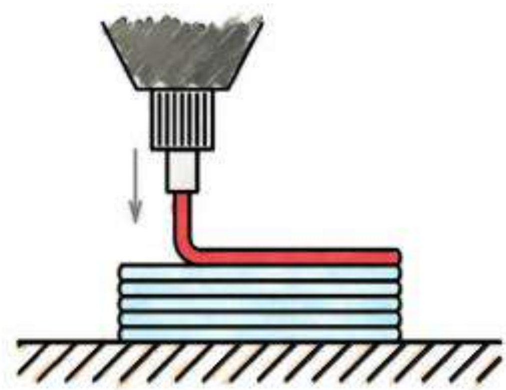
The project is not heavily focused on the development of the material, which has been known from previous projects. It uses a synthetic marble material, which cures fast enough to allow the robots to print fast and print overhanging structures. The largest known print up to date is a large oval wall that increases in size with its height, creating a slightly conical overhanging shape. The structure aims at displaying the potentials of the technology and is approximately 2 meters tall and 1.5m in diameter.

The largest print up to date (2 x 1.5 meters approximately)

3. Technology

3.1 Additive manufacturing technology

The Pylos additive manufacturing technology is a Layered Material Extrusion process. This is an construction-scaled *Fused Deposition Modeling (FDM)* process, a very known desktop printer process where a material in fluid form is extruded through a small nozzle as a continuous stream or filament. The material is then solidified on the printing surface, ready for the next layer to printed on top. Its desktop counterpart uses molten plastic, that melts when going through a hot nozzle and then solidifies by cooling down once deposited on the surface. The construction scale process is quite the opposite. Here a cementbased material, usually a mortar or paste, is mixed right before being fed into the machine. While still fluid, the material is extruded through a simple nozzle, which only helps to shape and channel the material, very similar to adding frosting to a cake. When the material reaches the printing surface it starts to solidify by itself in a chemical reaction with air, which is also known as hardening (first hours) or curing (long term, several days). This process has a considerable level of sensitivity, since hardening should not be completed entirely before the next layer has been printed, in order to ensure a good bond between the layers, but it should also be sufficient enough to sustain the weight of the following layer (or layers).



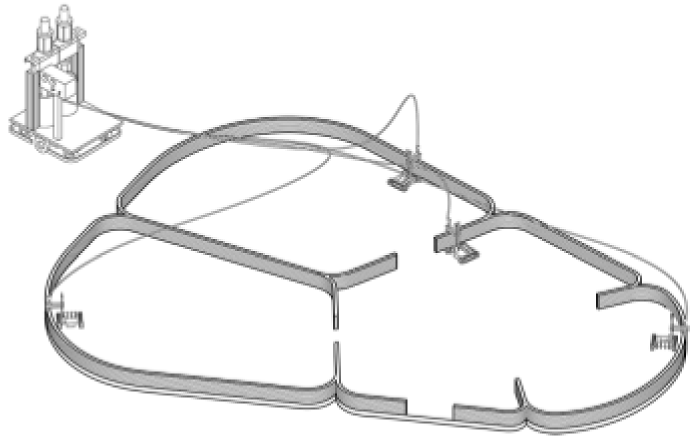
Material Extrusion (layered)

What is also specific for this process is that the extrusion nozzle is mounted on several different robots that are smaller in size and move around or on top of the already printed parts of the structure. While other types of construction scale 3d printers are trying to increase their size to be able to print structures in architectural sizes, this approach has a great advantage of allowing the printer to be smaller than the object it is printing, avoiding the size limitations issue this way.

3.2 Printing procedure

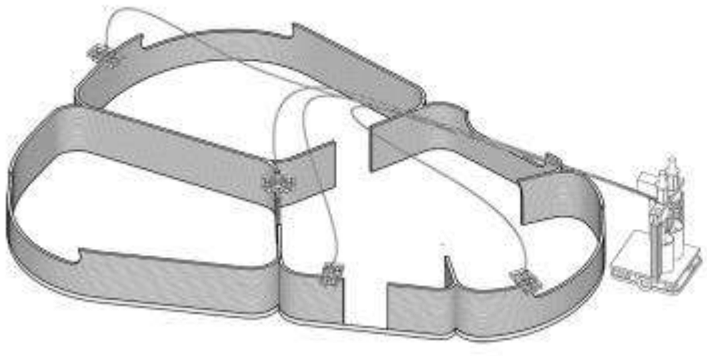
The printing procedure starts with a 3D model design file being translated into the path and the parameters of the specific robots printer during the printing process. This is done through a custom software, which generates a series of curves for each robot to travel along when creating the different parts of the object. These curves that are generated on top of each other are the actual layers of the object. The thickness of these layers depends on various factors, including speed of extrusion and the type of material used, since all materials behave differently under the weight of the layers printed on top. The Minibuilders robots create layers which are approximately 6mm thick, which can also be regulated through the moving speed of the printers. The software translates these curved paths into device control signals that are given to an external controller (a computer or similar device). The controller operates the movement and nozzle for each robot, and deposits the layers according to the curved paths. The printing of the whole structure is divided into three sections, each with a dedicated robot:

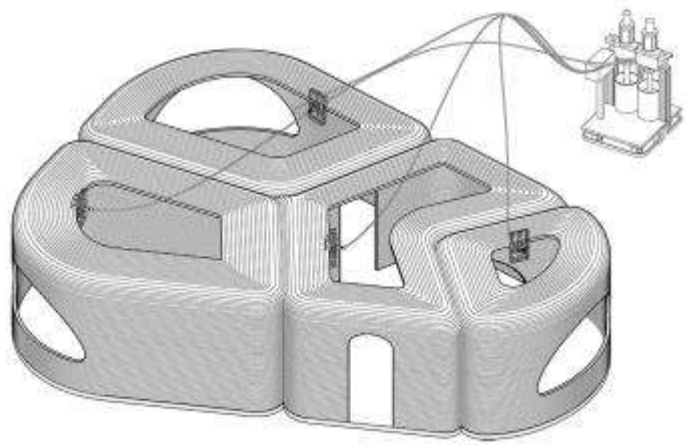
1. The first part of the printing is done by a **Foundation robot**, that lays the first 50 centimeters of printed structure, starting from a flat surface. The printer moves on flat surface and deposits the material through a nozzle located on the side of it.



1st phase - first 50 centimeters with Foundation robots

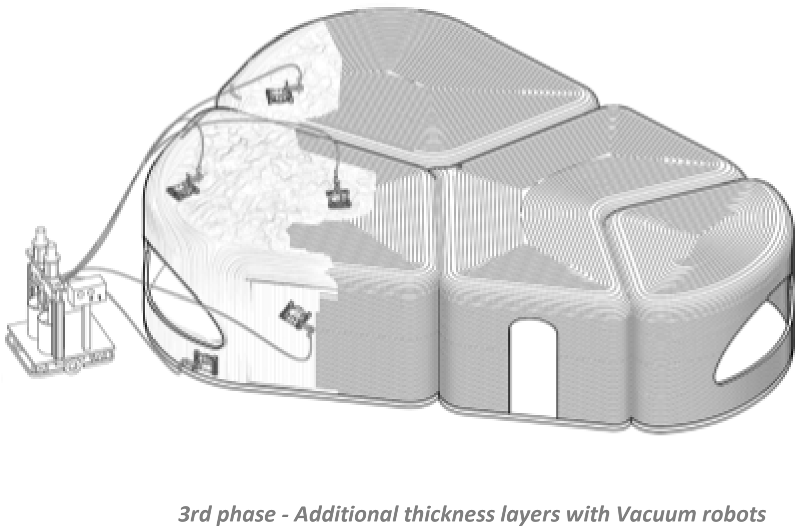
2. The second part of the printing is done by a **Grip robot**, that is fixed on top of these first 50 centimeters of hardened print. The robot grips on the previously printed layers and moves them while printing on top of them at the same time. With each new layer, the printer moves on top of the layers it has already printed, making the printed structure increase in height. The robot can print each layer slightly offset from the previous one, allowing to create gradual inclinations and overhanging structures or ceilings.





2nd phase - Walls and Ceilings printed with Grip robots

3. Finally, once the printed structure is finished, a **Vacuum robot** is attached on of the already printed surface and prints additional thickness layers on top of it. This allows to thicken the printed structure or create additional shapes on its surface.



3rd phase - Additional thickness layers with Vacuum robots

All the three types of robots are attached to a larger master unit, which controls them and provides the material. Once the last part or layer has been printed, the process is finished. The printed object is then left to harden completely.

3.3 Form freedom

The Minibuilders technology can print any shape in the horizontal plane and extrude them vertically, creating a wall. Each layer can also be printed slightly offset from the previous one, hanging over the edge. This allows to create walls with curved shapes by incrementally displacing each following layer. It is even claimed that these walls can be curved all the way to a horizontal plane, and that the printer can then directly print ceilings from that, thanks to the fast hardening properties of the material and the strong grip of the printer. The printer allows basically to print any three-dimensional geometry on any direction, provided that it is a continuation of the initial curve made through gradual changes of the same. The degree of freedom probably lies between 2.5D and 3D, thanks to the material properties and gripping approach.

A few examples of shapes that the Grip robot can create

This type of printing procedure and form freedom is most likely very sensitive to many other external factors, such as wind or heat, that might interfere with the hardening and compromise the bonding between layers, especially when considering the horizontally overhanging parts. Currently, the printer has created a slightly overhanging oval shape, while the printing of horizontal parts has yet to be seen.

3.4 Fabrication location and approach

The printer needs a flat surface, firm enough to print the first few layers with the Foundation robot, which moves around on continuous tracks (also known as crawlers). With layered material extrusion technologies there is also a possibility to print on curved surfaces, making all the layers follow the curvature. Although mentioned in one of their published articles, this approach was not yet seen in use in this project.

The printing process can be compromised with some considerable atmospheric agents, such as heavy wind or rain. Optimally, the printer should be in a covered environment. During the Minibuilders project the printer has only been used outdoors under good weather conditions, using a flat wooden surface as the printer bed.

The printer and the printable surface in outdoor conditions

4. Printer

The main focus of the Minibuilders project is the development of the various robot printers. The fundamental idea behind the project is to create a swarm of different specialized robots that work together, each on its specialized task in order to create the whole structure.

4.1 Robot types

There are fundamentally four robots that have been developed up to now, one main supply unit, that provides the material and three printing robots. These printing robots essentially differ by the way they move around, each with its own degrees of freedom. They are described as follows.

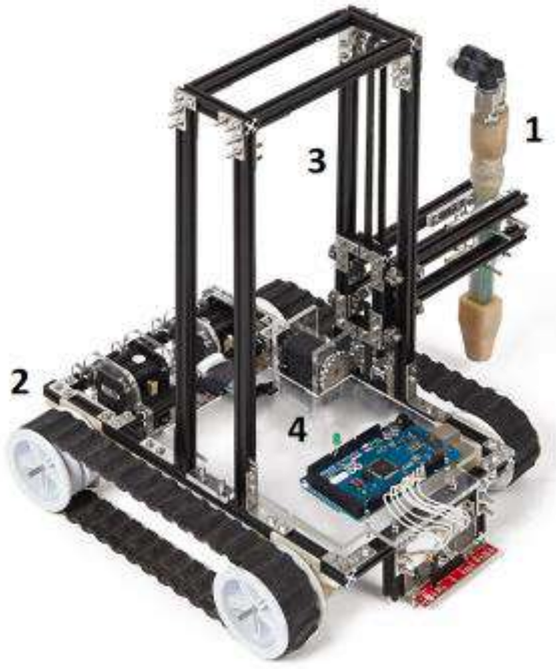
4.1.1 Main unit robot

The Main unit robot is essentially the brain that operates the Minibuilders 3D Printing technology. It is equipped with two material tanks, a two part polymer extruder, a controller (or PC) that coordinates the movements of the connected robot printers, and a set of wheels to allow the unit to move along with the smaller robots. There is also a couple of hoses and cables coming from the Main unit and connected to each robot printer in use, which is mounted on a high steel rod in order to keep them from interfering with the robot.

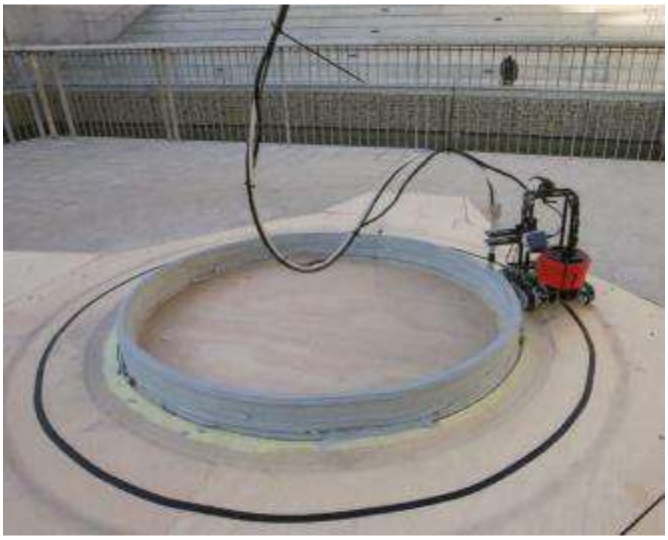
The Main unit controlling front and back view

4.1.2 Foundation robot

The first robot that start the printing procedure in the Minibuilders technology is always a foundation robot. This printer is essentially a small crawler with continuous rubber tracks (**2**-see image below), which is equipped with an extrusion nozzle (**1**) that can move up and down along the side of a small vertical aluminum frame (**3**). This is the only robot that moves on a regular surface, behaving essentially the same as any other Material Extrusion printer. The nozzle extrudes the material while the printer follows the required pattern, by using a sensor that reads a traced line on the surface. This is repeated for each layer, until reaching the height of 15 centimeter, the maximum height the printer can reach. From here it necessary to pass to the next type of printer. The size of the robot is 26x35x37 centimeters, and it weighs 2.05 kilograms.



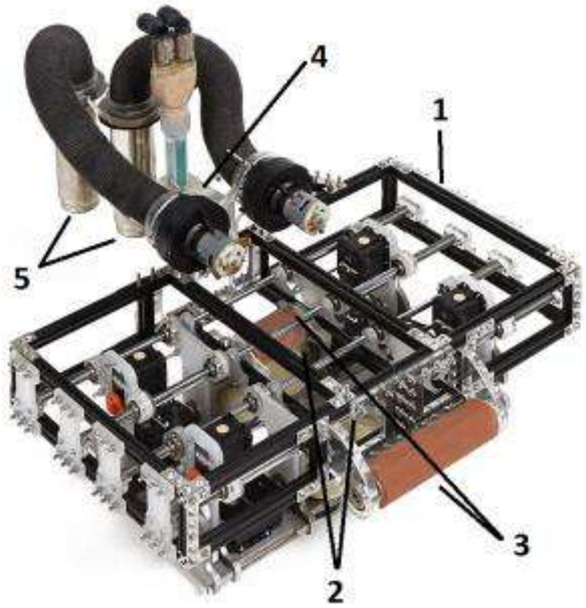
The Foundation robot with nozzle (1), rubber tracks (2), vertical frame (3) and on-board Arduino controller (4)



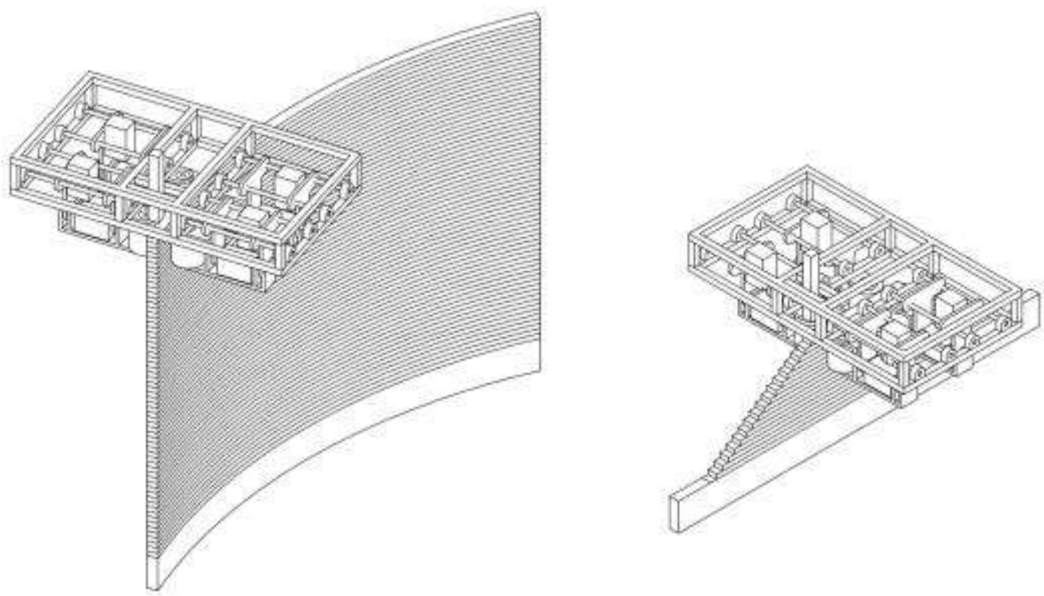
The Foundation robot during a printing procedure

4.1.3 Grip robot

Once the first 15 centimeters are finished and the Foundation robot has reached its limit height, the printing has to be continued with a Grip Robot, the main printer of the technology. This type of robot does what it name says, gripping to the printed layers and printing on top of them. The robot is held in place by four wheels mounted laterally, two on each side (**2**-see image below). There is a spring in each of them, which tends to push them towards each other, and squeeze the previously printed layers into a firm grip. The whole structure of the printer is held together by an aluminum frame (**1**). The four wheels are placed on the bottom part of it, while in the middle there are two rollers (**3)** that help it sit on top of the printed layers and move on them. The nozzle (**4)** is mounted in the back, and features a lateral sliding mechanism, that allows it to offset each new layer from the previously printed ones. Behind the nozzle there are two hot air blowers (**5)** that help the layers harden quicker once extruded. The printer is 40x27x12 centimeters in size, and weighs 4.6 kilograms.

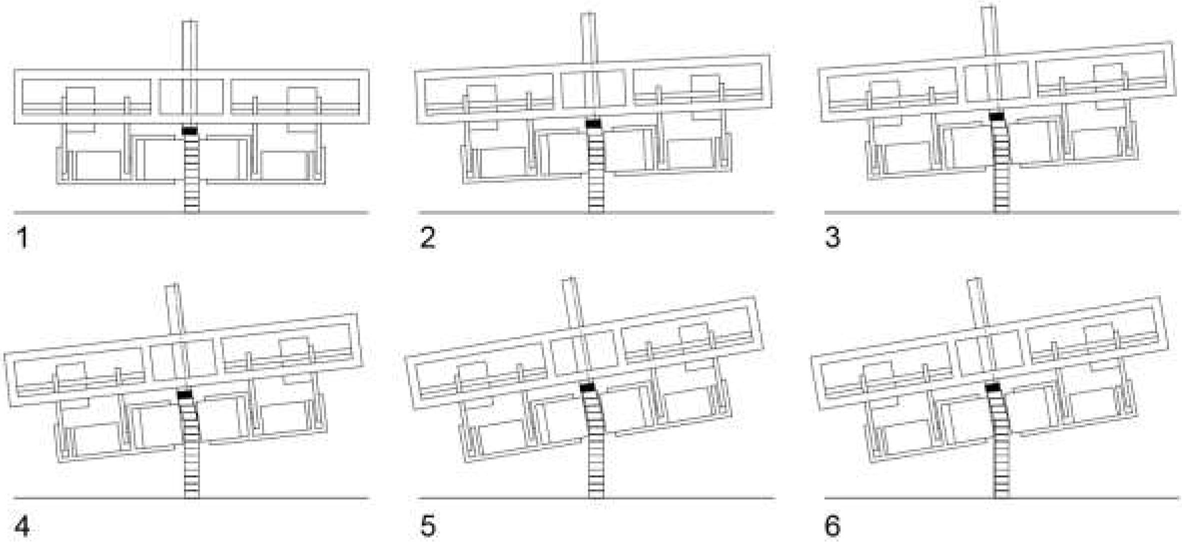


The Grip robot with frame (1), gripping wheels (2), top rollers (3) nozzle (4) and hot air blowers (5)



A sketch of the printing approach of the Grip robot

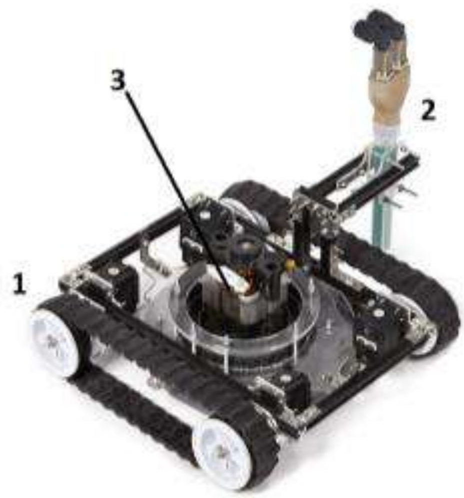
The most important feature of the Grip robot printer is the offset printing of each layer, that allows to create gradual curvatures along the height of the object. This is used when it is necessary to create inclined parts, overhanging structures, or various organic shapes. This is what gives the printer its three-dimensional freedom and allows it also to print ceilings, as a continuation of the walls.



A schematic representation of the offset printing mechanism

4.1.4 Vacuum robot

Once the whole printer structure has been created, the third and last printer is used. The Vacuum robot is placed on the face of the finished surface of the printed object. The Vacuum printer is essentially a Foundation robot with continuous rubber tracks (**1**-see image below) and nozzle (**2**), but with an additional vacuum generator(**3**), which allows it to attach itself through suction onto the vertical walls of the object and all of its overhanging parts and ceilings. By moving around the face of the structure, the robot can print additional layers, and thicken the structure where necessary. The robot's structure is made of an aluminum frame and is 30x27x12 centimeters in size, and weighs 2.1 kilograms.



The Vacuum robot with rubber tracks (1), nozzle (2), and vacuum generator (3)

The Vacuum robot attached onto the vertical face of a printed object

4.2 Movement

All robots use Dynamixel servomotors to power their movements, whether it is for continuous tracks, vacuum generation, nozzle movement, or rolling wheels.

4.3 Material deposition system

The deposition system is made of two parts, which are located in separate positions. The first is the nozzle, which is located on each robot printer, and is essentially two plastic hoses that deliver the material and blend it into single one. The second part is the mechanical extruder that delivers the two components of material through the hoses to the nozzle, and is located on the Main unit robot. The extrusion is therefore controlled on the Main unit, and not on each robot separately. This simplifies the process, and allows the smaller robots to be free of additional weights of the bulky nozzle controllers. But on the same time this makes the control of the nozzle much less accurate. There will always be some residual pressure in the hoses that will create a time lag between the printing command and the actual starts or stops of the printing procedure.

4.4 Material feeding

The material is fed through two containers that are located on the Main unit robot. These are connected with two hoses to the nozzle, and fed through a two part polymer extruder. These are two drum containers, which are not continuously fed with material, but have to be refilled from time to time. This has been created for the purpose of the project, but for actual construction settings larger containers will be necessary.

4.5 Printer electronics and software

The robots use Arduino on-board controllers to operate the printer. The software is written with the Arduino integrated development environment (IDE), and has been specifically adapted for the components used in project.

4.6 Printer speed

The printing speed of the Minibuilders technology may vary, depending on the robot that is used and how complex is the curve that needs to be printed. Generally speaking, the printers are very slow, capable of extruding no more than 3-5 centimeters of a layer of material per second. That translates to a theoretical speed of 0,03-0,05m^3/hour in best of the cases, which makes the realistic estimate even lower (probably as low as 0,01m^3/hour), which is not suitable for construction use at the current state.

4.7 Printer accuracy

Similar to the speed, the accuracy of the printer is hard to define, since there are no official values given by the project, and since all robots move in a different way. Judging by what has been seen in operation, the Foundation robot is probably the most accurate, since it moves on firm ground. The Grip robot suffers the most, since every error in the printing can affect the correct positioning of the following layer, and there is a risk of accumulating errors and inaccuracies along the way. The whole technology should be within 30mm (Foundation robot) to 100mm (Grip robot) accuracy range.

4.8 Printer operation, handling and assembly

There is no disclosed information regarding the printer operation. The printers seems suitable to be handled by a single person. It is important to note that both the Grip robot and the Vacuum robot require manual assistance when starting to print. They need to placed on top of the structure by a human each time.

4.9 Printer specifications

Printer size (assembled): 26x35x37cm (Foundation robot) / 40x27x12cm (Grip robot) / 30x27x12 (Vacuum robot)

Printer size (stored): Same as above

Print volume: Not limited

Printing speed (estimated): Approx. 0.01-00.3m3/hour

Layer thickness: approx 6mm

Accuracy (estimated): 30-100mm (depending on robot)

Deposition head: Single nozzle, double component extrusion (mechanical extrusion)

Structure: Mobile robotic vehicle

Movement: Continuous tracks or wheels

Shape freedom: 2.5D/3D

Weight: 2.05kg (Foundation robot) / 4.6kg (Grip robot) / 2.1kg (Vacuum robot)

Energy consumption: Not available

Required personnel: 1 person

Price per unit: Not for sale / Not specified

5. Material

5.1 General description

The Minibuilders is not heavily focused on the material it uses, but rather on the technology on how the material is delivered. However, the material still plays an important role in overhanging structures, thanks to its fast curing.

5.2 Minibuilders material properties

The project uses of a particular synthetic marble for their prints. The material is Axson Easymax, a two component polymer, mixed with marble powder. Marble is mixed in both components in a ratio of 60% of marble with 40% of polymer component. The blended components are stored in two separate containers on the main unit, where they can be stored for very long time. When extruded, they go through two separate hoses. They are blended together in the last part, right at the nozzle where the two hoses merge into a single one. Once the two components are mixed together, they start a fast curing process, which is completed in 2-3 minutes, and can also be sped up by using heaters. This fast curing allows the technology to print also in a horizontal or overhanging directions.

5.3 Synthetic marble - material properties

Synthetic marble is a composite material that is a mix of marble powder and various polymers, such as acrylic, epoxy, polyester, polyurethane etc. The materials are mixed together to form a paste, which is then cast into moulds and cured. It is has its own niche in construction, as it is used for kitchen and bathroom countertops that imitate the natural look of marble or granite. The benefits are a good abrasion resistance, shear strength, flexural strength, and impact resistance. It has also a more affordable price, as the variety of shapes and colors that can be achieved would be too expensive and labour intensive if made with natural stone. However, the price of the material is not competitive when compared with other highly available structural materials such as concrete.

A bathroom sink and countertop made with synthetic marble

5.4 Material possibilities

The material is particularly praised for the fast curing properties and the usability time (until the two components are not mixed, the material can stay usable for months). However, the price of such material will probably be a limiting factor, especially in construction, where large quantities are necessary. In any case, it is the actual printing technology that shines through, while an alternative material can be easily picked from a variety of cementitious materials that are readily available on the market. There is proven, extensive and wide knowledge on cementitious materials such as shotcrete, which can also harden very quickly with good mechanical properties. These materials come in large quantities and at competitive prices, so they could be potentially adapted to this process, with some additional research.

6. Useful links and sources

Official website:
http://robots.iaac.net/

Iaac Youtube channel:
https://www.youtube.com/channel/UCM_pHL0Txd32ZE56EZcjqbQ

Media articles on the technology:
https://www.wired.com/2014/06/these-drones-could-3-d-print-your-next-house/

https://3dprintingindustry.com/news/iaac-minibuilders-small-robots-big-ambitions-83257/

https://3dprint.com/6340/minibuilders-3d-print-robots/