Iridescence Print: Robotic Printed Lightweight Mesh Structures

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Abstract

This article presents a novel robot-based 3D printing technique for the automated fabrication of nonstandard large-scale lightweight structures. The approach offers unique advantages over conventional approaches to 3D printing: It can be performed freely in space, it is scalable, and it enables the fabrication of structures from a filament 3D printing process. A first full-scale demonstration case—the architectural installation Iridescence Print—was exhibited at the Palais de Tokyo in Paris. Based on ongoing research and teaching activities, the installation exemplifies a new area of research in the field of 3D printing: robotically printed lightweight mesh structures.

Introduction

In the spring of 2015, the chair of architecture and digital fabrication at ETH Zurich realized the 1:1 architectural installation Iridescence Print, which was part of the exhibition L’usage des formes—Artistes d’art et artistes at the Palais de Tokyo in Paris. Based on a filament extrusion process, the technique used in the installation builds upon conventional layer-based fused deposition modeling and makes use of an industrial robot equipped with a custom extrusion tool to print 3D continuous mesh structures freely in space. By employing a fabrication method that allows one to print in different resolutions, this process shows great potential for the development of highly informed and geometrically complex architectural structures (see Fig. 1a).

The Iridescence Print installation was digitally pre-fabricated in 12 segments (see Fig. 1b) and assembled at the Palais de Tokyo in Paris. Made from extruded acrylonitrile butadiene styrene (ABS), it required no additional material for assembly or fittings and is therefore in principle fully recyclable. The mesh structure, which is over 8 m² in volume, was adapted to the different parameters of the exhibition space, and accommodated a selection of 24 artifacts and distinct pieces of art in its inner mesh. In order to house the pieces within the structure, the mesh was furnished with recesses and consoles that featured higher density.

Previous Work

The technological basis for the Iridescence Print installation is provided by the research project Mesh Mould, which was initiated at the SEC Future Cities Laboratory and is currently being continued at ETH Zurich in the framework of the National Centre of Competence in Research Digital Fabrication. Specifically, Mesh Mould investigates the robotic extrusion of 3D mesh structures that can act as a combined formwork and reinforcement system for nonstandard concrete elements.

The teaching project Extruded Structures directly refers to the Mesh Mould robotic fabrication process.

*For more information on the project in Palais de Tokyo, see www.palaisdetokyo.com/
*For more information on the project Iridescence Print, see http://gramaziokoehler.arch.ethz.ch/web/ferchungso/0097296.html

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Lightweight robot arms equipped with a custom extrusion end effector perform the ABS extrusion process (see Fig. 2a). This allows students to experimentally investigate the design and robotic fabrication of 3D mesh structures and intuitively test their structural behavior through simplified load tests.

The architectural installation at the Palais de Tokyo builds upon these projects and shows further progress in robot-based 3D printing techniques and the basic design and production process. It also demonstrates novel constructive strategies for life-size realization.

Current State of the Art

Research on robotic fabrication in building construction dates back to the 1980s. The original motivation behind this research was to improve the productivity and economy of building construction, mainly by using the machines' ability to handle an increased payload in contrast to humans. In the course of the recent shift from construction automation to robotic fabrication—and the exploration of novel additive materialization processes—universities such as Harvard GSD (2008), Carnegie Mellon (2009), University of Stuttgart (2010), and Massachusetts Institute of Technology (MIT, 2012) have set up architectural research facilities for custom digital fabrication with industrial robots. Following ETH Zurich (2005), they have fostered promising architectural case studies and prototypical structures, elevating nonstandard robotic manufacturing to the role of a constitutive design and construction tool and resulting in highly versatile and customizable construction systems.

Concurrent to these advances in architectural robotic fabrication is a growing interest in 3D printing among architects, engineers, and designers, who recognize that it is fast becoming a mature technology. When linked with innovative robotic machinery, spatial 3D printing can be more time and resource efficient than horizontally layered material positioning since material is brought directly where it is required in space. Therefore, overcoming 2D layering of material at a fixed resolution, this approach enables the implementation of this additive principle on a tectonic scale.

Important steps into robotic 3D printing were pursued in Mesh Mould. Here, a lightweight industrial robotic arm is equipped with a custom printing tool head for continuous ABS filament extrusion to fabricate geometrically complex spatial meshes. Mesh Mould explores a unification of the two most labor- and cost-intensive aspects of concrete constructions, the formwork and the reinforcement, into one single robotically fabricated material system. Here the mesh structure acts as porous formwork during the process of concreting, and is activated as reinforcement after the concrete has cured. Whereas the first phase of the research focused on the extrusion of polymers, the consecutive second phase focuses on the robotic manipulation of steel wire in order to cope with the large forces acting in a loadbearing concrete structure. The simultaneously launched Material project at the Institute for Advanced Architecture of Catalonia (IAAC) focused on spatial extrusion of two-component thermosetting polymers. Such novel explorations now motivate a number of new approaches to the design and fabrication of 3D printed architecture, and show that the use of robotic technology for 3D printing is clearly feasible. For example, the group of Neri Oxman at the MIT pursued robotic freeform printing without support materials, and more recently, a team at Bartlett School of Architecture (University College London) investigated the possibility of robotic 3D printing to explore highly intricate architectural designs through custom plastic extrusion.

Technology of the Extrusion Process

The fabrication setup for the Iridescence Print installation consists of small-scale six-axis robotic arms with built-in safety features that eliminate the need for additional safety infrastructure. These arms are equipped with custom-built printing heads (see Fig. 3), with the component buildup resembling standard filament extrusion technology.

A 3mm filament made out of a thermoplastic polymer ABS was fed from a material spool through a geared system powered by a single stepper motor into a printing head containing an array of four resistors. An Arduino controller

11See www.bartlett.ucl.ac.uk/architecture/programmes/postgraduate/units-and-showcases/march-architectural-design/date/4/2015
12Some components of the first-generation extruder head, such as its structural parts and gear wheels, are made out of 3D-printed elements. For more information, see http://portabee.dprinter.com/support/portabee-kits docs/
regulated the temperature of the resistors by reading the actual temperature through a small thermistor built into the brass drum holding the resistors, maintaining it at a constant temperature of 210°C. In reality, this specific temperature varied ±5° depending on (1) the individual ABS filament batch, (2) the humidity to which the spool was exposed, (3) the printing head that was used, and (4) the temperature calibration parameters. The pressure from the still-cool filament being fed from above inside the extruder head pushed the melted ABS through the nozzle on the tip with a diameter of 2 mm, after which an air stream from a compressed air system immediately cooled it. Although the cooling air was at room temperature, the convective cooling effect was powerful enough to reduce the temperature of the extruded melted filament so that it solidified, enabling spatial extrusions without any additional supports.

Bridging distances horizontally requires a different construction approach than when building normal segments because the added length and weight of the extruded material causes significant sagging. More intensive pulling, which was achieved by increasing the robot’s speed while keeping the extrusion speed constant, enabled horizontal connections with a length of up to 70 cm within an acceptable 5 mm deviation in the middle. To correct the sagging, the cooling was turned off during the extrusion process to allow the ABS to harden more slowly and extensively, and to take advantage of shrinkage (see Fig. 4).

Using the fabrication setup described above, it was possible to extrude on average approximately 12 mm of plastic filament per second.

The Architectural Installation

The Iridescence Print installation is a 12-m-long undulating structure with a height variation between 1 and 2.8 m and a thickness between 0.25 and 0.5 m. It was composed of two dense outer mesh layers that periodically connect and disconnect from one another. Where the two dense meshes open up, the resulting cavity was connected with “hammock” layers made from long printed strings. These hammocks were designed to display a set of objects inside the structure (see Fig. 5).

To preserve full-scale production, the robotic arm was mounted on an external two-axis system, which featured a vertical axis of 3 m length and a horizontal axis of 1.5 m length. This combination of a lightweight robotic arm and an extended external axis system allowed the structure partitions to be fabricated inside a maximum building volume of 1.5 m × 1 m × 3 m (length × width × height). The installation was therefore divided into 12 separate sections, each measuring approximately 1 m in length and comprising 50 layers.

The individual sections of the structure were assembled directly on site and connected through standard cable binders. Those were easy to remove for disassembling the structure after the exhibition.

The number of layers was fixed and did not vary along the length of the structure, but as the layers had different heights, it was possible to vary the height of the whole structure and still have continuous patterning.

Each layer of the individual sections was further divided into three horizontal parts, which the robot reached in different discrete positions of the horizontal external axis component (see Fig. 6). The average length of the robot path was around 2.7 km per section, totaling 32 km for the entire structure. The cell side lengths of the structure vary between 5 cm for the smallest and 10 cm for the largest, with the whole structure containing around 288,000 cells. The final weight of the structure amounted to only 75 kg, as measured from the amount of raw material that was used for the production process.

The sequencing of the printing process was heavily influenced by the thermal properties of the ABS filament. The speed of the extrusion has to be matched with the speed of the robot in order to achieve a consistent printed mesh thickness. Faster robot movement produces thinner mesh for the same extrusion speed, as the material is being pulled from the extruder. Therefore, a separate fabrication logic was developed for every fabrication direction (see Fig. 7).

To encode the fabrication sequence as part of the installation design, the color of the filament changes gradually throughout the pieces. The 3 mm filament was produced out of ABS granulate and small amounts of pigment (white, or blue and/or yellow) to create very lightly saturated color transitions. The blue-and-yellow combination enabled us to achieve transitions between blue, green, and yellow, with recurring white parts in between.
For the filament production, a standard filament extruder was used. Instead of an elaborate laser measurement system for controlling the diameter, a gravity-based method to automatically create filament rolls was deployed. This also meant that the filament varied in thickness by ±0.5 mm, which was absorbed by the robustness of the fabrication system.

The installation runs its way as a continuous loop through the exhibition space, creating a new introverted space that encompasses the interconnected exhibition areas. Here, the constructive and phenomenological relationships between resolution and transparency, between material and its visual appearance, and between information and aggregation are all brought to equilibrium among a multitude of diverse aesthetic and functional requirements (see Fig. 8).

Conclusions

This project demonstrates the feasibility of robotically printed mesh structures, and radically extends the traditional spectrum of 3D printing toward novel, possibly geometrically extreme and internally differentiated lightweight structures. It places 3D material manipulation at the center of the process—from the design and construction through to the object’s final form—and thus enables a paradigm shift from layer-based approaches, which are often limited to 2D positioning of material at a fixed resolution, to spatial techniques, where the design and fabrication process is orchestrated by dynamic manufacturing attributes. This technique enables the production of highly complex 3D structural geometries that make optimum use of material in space. This is key to exploring the full potential of 3D printing in real-world architecture applications, where preservation of scale is essential. An adaptive manufacturing approach, which incorporates sensor feedback to react to occurring fabrication tolerances and unmodeled material effects, would further improve the overall robustness of the fabrication process, production speed, and precision. However, as a first experimental setup and prototype, Iridescent Print successfully illustrates how this approach makes 3D printing tangible to architectural construction and addressable by robotic machinery. In so doing, it simultaneously exemplifies a new vision for digital fabrication in architecture, and challenges us to expand our perception and understanding of it.

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