Responsive Spatial Print

Clay 3D Printing of Spatial Lattices Using Real-Time Model Recalibration

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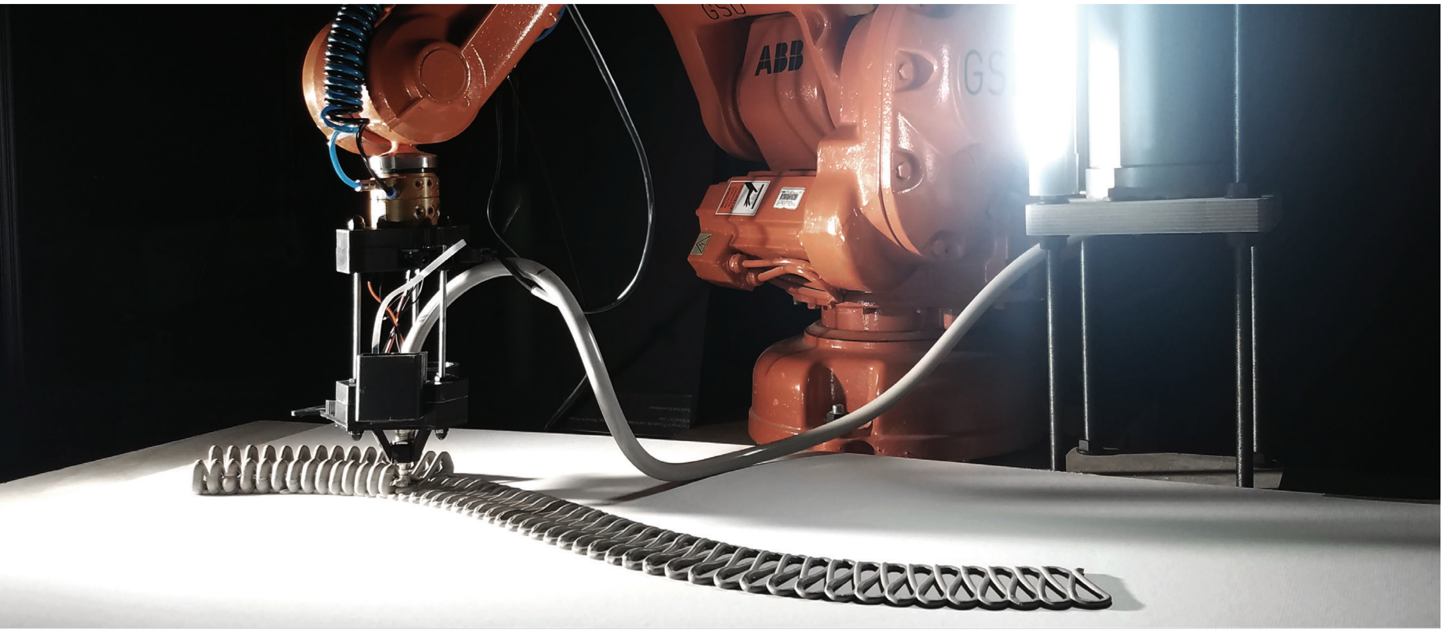

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1 Robotic Fabrication: First zero degree horizonal layer and ninety degree vertical return-loop.

ABSTRACT

Additive manufacturing processes are typically based on a horizontal discretization of solid geometry and layered deposition of materials, the speed and the rate of which are constant and determined by the material stability criteria. New methods are being developed to enable three-dimensional printing of complex self-supporting lattices, expanding the range of possible outcomes in additive manufacturing. However, these processes introduce an increased degree of formal and material uncertainty, which require the development of solutions specific to each medium. This paper describes a development to the 3D printing methodology for clay, incorporating a closed-loop feedback system of material surveying and self-correction to recompute new depositions based on scanned local deviations from the digital model. This Responsive Spatial Print (RSP) method provides several improvements over the Spatial Print Trajectory (SPT) methodology for clay 3D printing of spatial lattices previously developed by the authors. This process compensates for the uncertain material behavior of clay due to its viscosity, malleability, and deflection through constant model recalibration, and it increases the predictability and the possible scale of spatial 3D prints through real-time material-informed toolpath generation. The RSP methodology and early successful results are presented along with new challenges to be addressed due to the increased scale of the possible outcomes.

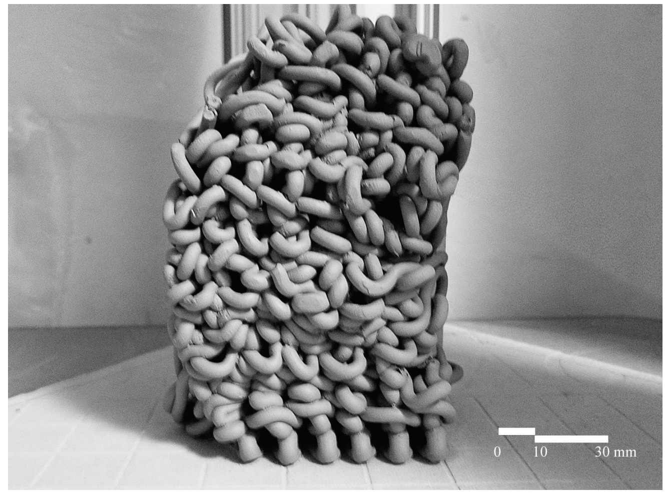
INTRODUCTION

This paper presents an enhanced method for 3D printing complex spatial lattices with clay deposition. The first stage of this research was presented by the authors in "Spatial Print Trajectory (SPT): Controlling Material Behavior with Print Speed, Feed Rate, and Complex Print Path" (AlOthman et al. 2018). SPT constitutes a non-conforming method of spatial clay printing, which takes the malleable properties of wet clay as an affordance. It uses these properties to create porous, self-supporting spatial lattices, enabling the creation of larger-scale ceramic objects while reducing material and printing time. It uses a novel method of non-layered, spatial motion based on the strategic design of volumetric toolpaths, material dragging, and support anchoring. Various toolpath strategies and combinations are discussed in the paper, and prototyped results are presented.

In the aforementioned research, the main challenge identified was the issue of scale. Although the techniques described in the SPT method ensure a higher level of predictability in deposition, a significant degree of uncertainty is still unavoidable. Small differences in material properties and system parameters, such as air pressure or humidity, create local irregularities in the printed form, which in turn become amplified by the accumulated deflection caused in subsequent paths that rely on the printed form for support. Furthermore, material self-weight plays an important role in 3D printing fresh clay. Deposited material compresses the lower levels of still-fresh clay, adding to the global deformation of the printed object relative to the digital model. Figure 2 shows an example of the cumulative effect that material weight and early local irregularities can have on a print's aggregate shape.

In order to enable larger scale printing, the authors identified the need to incorporate real-time surveying of the printed material and a recalibration cycle in the 3D printing framework. This real-time assessment would account for unexpected material behavior and adjust the subsequent printing toolpaths to increase the print's structural integrity. Recalibration of new toolpaths based on the deformation of previously deposited layers would compensate for the inevitable discrepancy in spatial clay printing from the digital model, and would ensure correct material anchoring and curling to achieve complex self-supporting lattices. Figure 3 represents this step toward a more robust SPT method through the addition of a closed-loop self-calibration cycle to the 3D printing framework.

This paper describes the implementation of such system recalibration in the SPT framework and presents some promising early results. Advantages of the enhanced RSP



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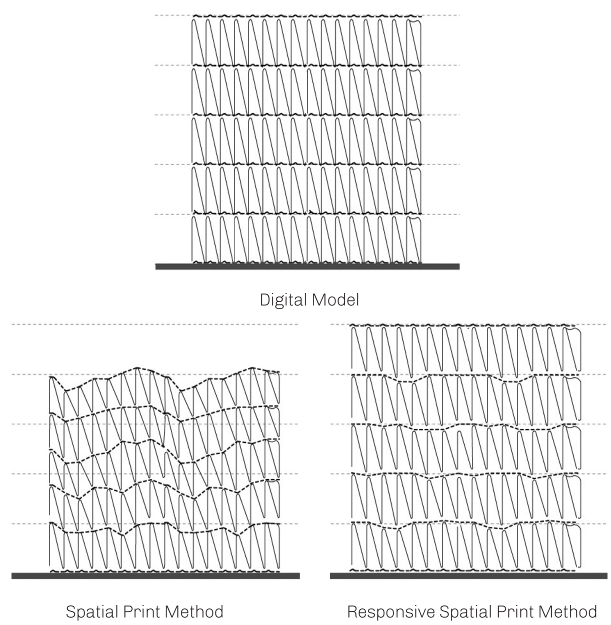

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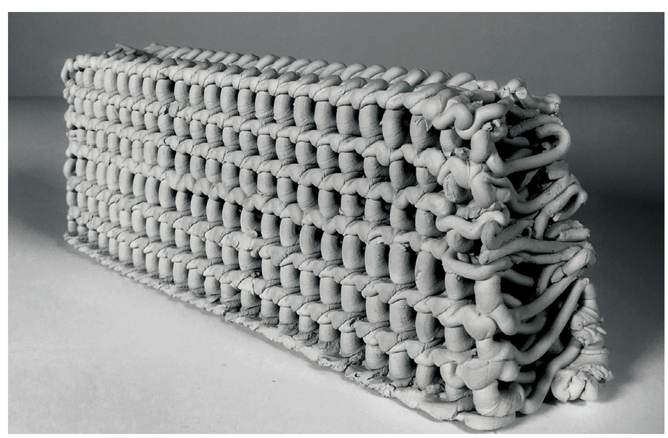

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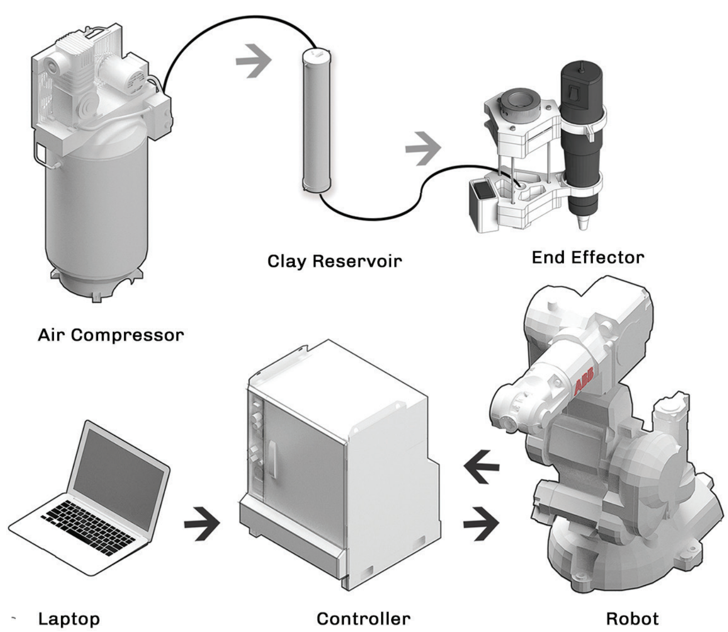
2 Uncontrolled deformation due to deflection and insufficient anchoring.

3 Comparison of Spatial Print Trajectory (SPT) Method and Responsive Spatial Print (RSP) method in relation to the digital model.

4 Outcome of Responsive Spatial Print paths.



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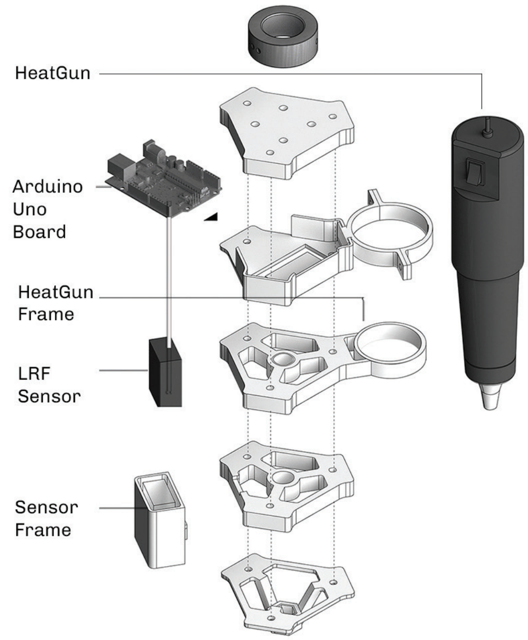

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system are discussed, as well as direction for further research.

BACKGROUND

Strategies to address issues related to intensive labor, material availability, and environmental factors have led researchers to exploit the potential of new technologies in building construction. Attempts have been made in the fields of robotics (Bechthold 2010), integrated CAD/CAM fabrication (Braumann and Brell-Cokcan 2011), local resources, and available technologies for materially-informed construction systems (Menges 2012). This effort has led to the emergence of the Liquid Deposition Modeling (LDM) fabrication technique with an extensive focus on clay printing for large-scale construction. The process has been further developed by the World's Advanced Saving Project (WASP) in their Eremo design for habitable construction, which uses the standard technique of 3D printing characterized by depositing one layer over another with constant speed in a stacking manner. However, the current technique only allows a limited degree of control over the geometry to produce variation in patterns, porosity, and other functionalities. The "Clay Bodies" project by Emerging Objects (Rael et al. 2016) takes advantage of clay's malleability to generate blocks with various patterns, by drooping away from the 3D printed surface and returning back again. The success of the drooping is fully determined by the type of clay mix. However, printing clay spatially—printing in the air— is especially challenging due to clay's unpredictable behavior during its wet state, making it difficult to create stable structural forms with voids.

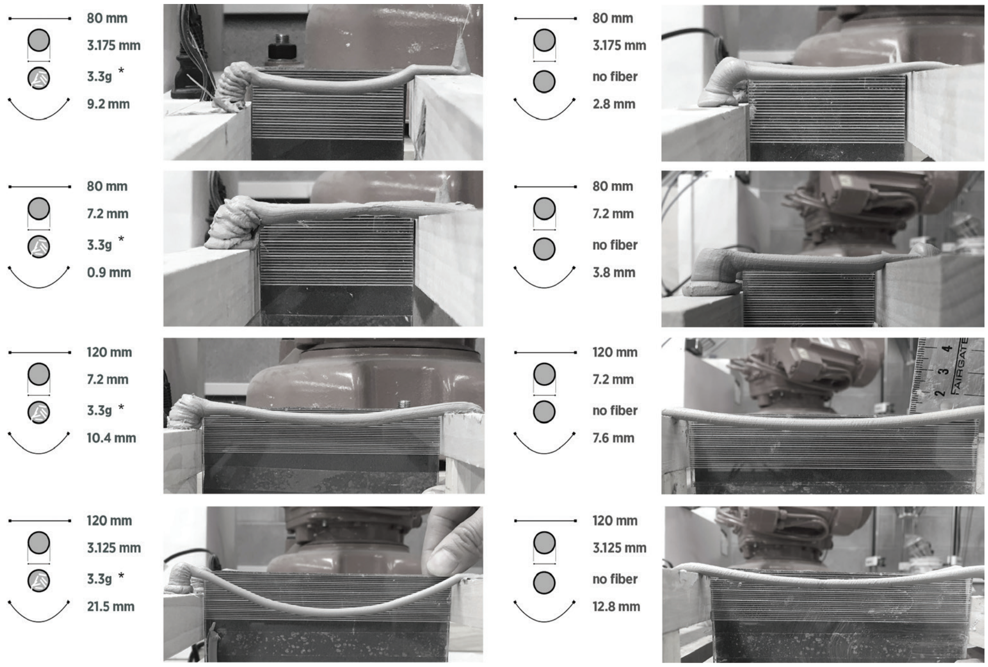
METHODS

Experiment Setup

The experiment was carried out using an ABB IRB 140 6-axis multipurpose industrial robotic arm, with a bespoke end effector. The clay mixture remained the same from the authors' previously optimized research: cone 10 stoneware clay, water, alcohol, and nylon fiber at the ratio of 1 kg clay to 70 g of water, 2 spray shots of alcohol and water, and 5 g of nylon fibers. Hand-mixed clay was loaded in a stationary 5 liter aluminum clay reservoir, which was pressurized with a 65–80 psi air compressor. Clay was pushed through a clear vinyl tube with an inner diameter of 9.525 mm and length of 457 mm to a nozzle mounted on the print head. Nozzles with inner diameter of 7.37 mm and 3.2 mm were tested (Figure 5). A customized end effector (Figure 6) was designed to be compatible with various nozzle tips and allow a plastic tube to be straightened for the consistent extrusion of clay. To expedite the drying process, which is required before depositing the next layer, heat at 650 °F was provided by a heat gun. For recalibration, deflection of the printed geometry was measured by a Laser Range Finder (LRF) sensor. The LRF sensor was chosen from 6 tested sensors due to its stable accuracy (under 1 mm), compatibility with the software control stack, and ease of use as a controlled measuring solution as opposed to a generic 3D scanning one (Vasey et al. 2014).

Design of Experiment

The aim of this experiment was to understand the effect of clay bead diameter, clay type, and its span on the deflection of a simple extruded bead supported by two points under its own weight. We hypothesized that the aforementioned



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5 Elements of the experiment: ABB IRB 140 6-axis robotic arm, air pressure at 65–80 psi, 3.2 mm inner diameter nozzle, 5 l cartridge, and heat gun at 650 °F (not to scale).

6 The design of the end effector enables the integration of printing, heating, and measuring processes in a closed-loop system.

8 The deflection values of one sample from each of the eight experiment treatments.

Independent Variables	Level [-]	Level [+]
A (Span [mm])	80mm	160mm
B (Nozzle Dia [mm])	3.175mm	7.2mm
C (Material)	no Fiber	3.3g(fiber)/kg(clay)

7 Minimum and maximum values of independent variables in the experiments. 7

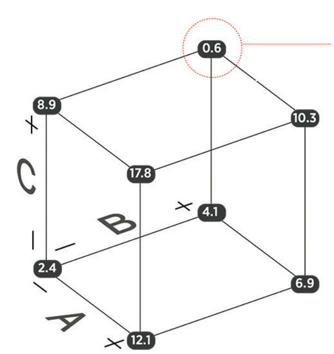
factors greatly contribute to the deflection values under certain set conditions. The experiment's results would inform the process of creating stable and efficient lattice geometries with possible differentiated properties to construct truss-like structures.

The experiment followed a Design of Experiment (DOE) method , in which Full Factorial Design (FFD) with the two-level factor technique was selected to evaluate each factor's dependency or independent variable on other factors in the design experiment, as well as their combined effects on the deflection value (Mee 2009). In the context of FFD where three factors are set with low and high values, eight experiments were required. Each experiment was evaluated with four samples. Each sample of each experiment was realized by extruding a clay bead between two supporting surfaces (Figure 8), one of them being lower than the other, accommodating a sufficient amount of clay at the anchoring location to drag the clay bead without snapping. The anchor speed was set at 3 mm/s, drag speed was set at 20 mm/s, and extrusion speed was constant for all samples.

The experiment showed that the minimum deflection was achieved with a span of 80 mm, a nozzle diameter of 7.2 mm, and clay mixed with fiber (Figure 9). Secondly, by changing only the nozzle diameter in the previous combination to 3.175 mm, the deflection was increased four times, demonstrating that the span and nozzle factors have higher effects on the deflection values than other combinations. The experiment ran with constant air pressure, but it should to be noted that some variance occurred when we switched the pressure on and off while creating each sample. Therefore deflection values were not highly precise, yet they could still be valid at a given constant speed and the set conditions for other factors.

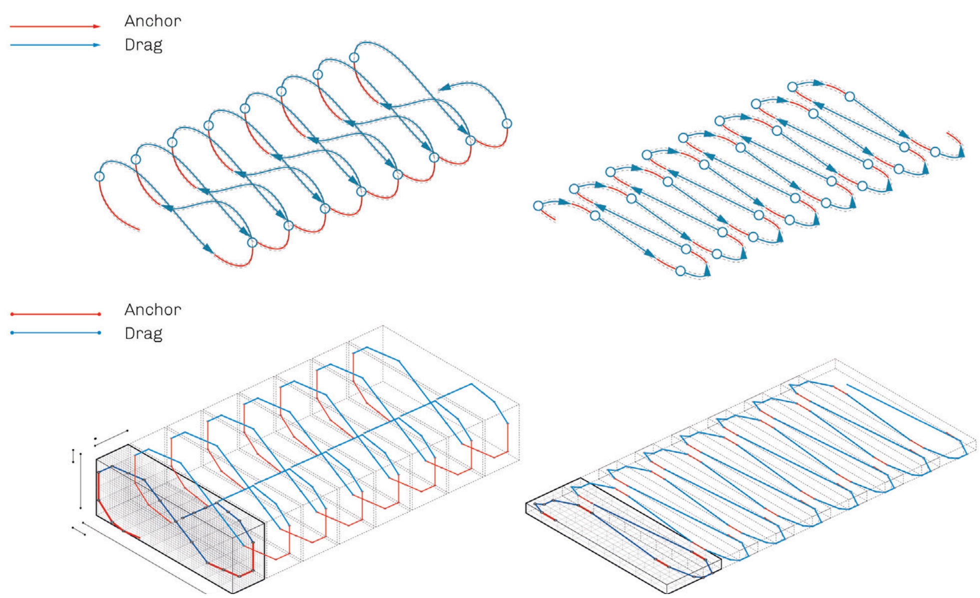
By calculating each factor's linear coefficient and the interaction between them, the deflection value can be estimated by the following regression model:

$$\hat{y} \text{ (yield)} = 7.9 + 7.775A - 4.80B + 3.0C - 1.53AB + 1.49AC - 3.06BC + 1.89ABC \quad (1)$$



Independent Variables	P-Value
A (Span [mm])	0.07
B (Nozzle Dia [mm])	0.11
C (Material)	0.19
AB	0.18
AC	0.49
BC	0.49
ABC	0.22

9 'Cube plot' showing the significance of parameters' effect on the deflection of clay bead.



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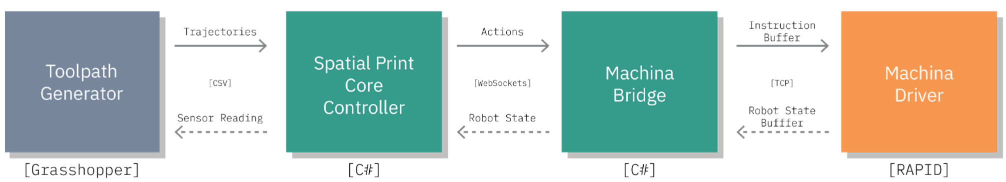

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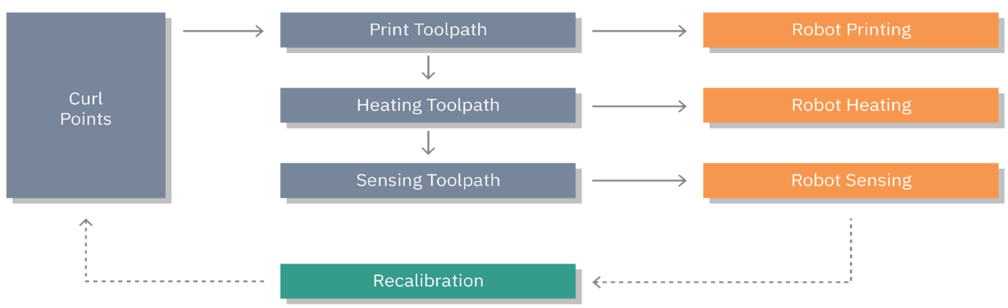

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10 Spatial clay printing parameters based on a 3D discretization logic.

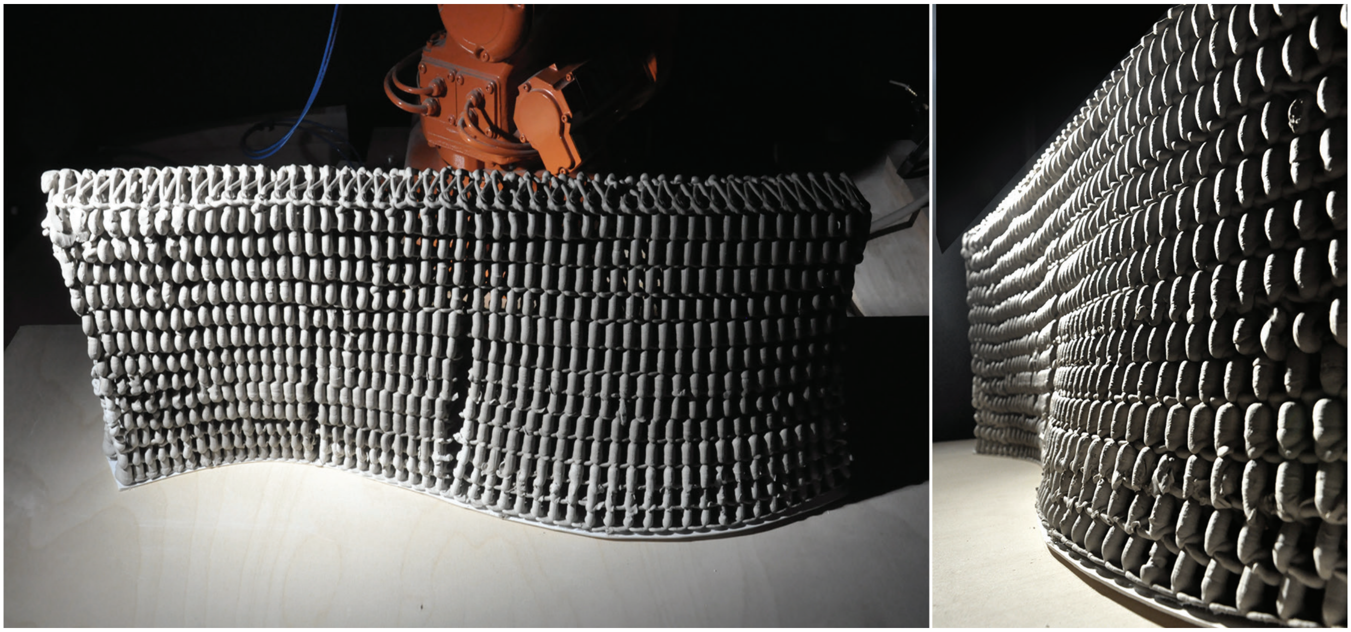
11 Recalibrated Spatial Print system architecture.

12 Spatial Print Procedure.

In addition, the probability values were calculated for all factors and their interaction (Figure 10), and it could be concluded that factors A (span), B (nozzle diameter), and AB are significant to the deflection and are therefore considered signals, while the rest can be considered noise. As a consequence, we can conclude that the addition of fiber in the clay mixture had little effect, but we should note that testing its compression after firing would yield higher structural performance.

Toolpath Generation Based on Non-planar Base

Spatial clay lattices are achieved by a NURBS curve toolpath that combines vertical and horizontal return loops constituting one curl unit. Each path was composed of anchor and drag behaviors with corresponding print speeds of 3 and 20 mm/s. This combination proved able to provide a stable, self-supporting structure with controllable porosity and minimum amount of material (AlOthman et al. 2018). The toolpath was translated into fewer divisions for more controllability and flexibility (Figure 10). This optimization facilitated the readjustment of the digital model during the printing process to ensure proper anchoring for successive layers.



13 Double curved geometry produced by using a closed-loop system. Disconnection in the middle of the geometry due to material shrinkage.

Closed-loop Printing Framework with Ad-hoc Toolpath Generation: Printing, Heating, Sensing and Feedback via Real-Time Robot Control

The digital control system for the SPT framework is designed according to the principles of customization and modularity expressed by Davis and Peters (2013). Instead of a holistic unitary framework, we chose a modular architecture of independent services with data exchange through standard communication protocols. Figure 11 shows a diagram representing the elements constituting the RSP framework.

The core of the framework is a bespoke application written in .NET that coordinates data exchange between all modules in the system and queues the requests for robot motion on the model. The application receives the printing, heating, and sensing toolpaths from a generative modeling application written in Grasshopper via a common set of Comma Separated Values (CSV). The core application translates these toolpaths into robot actions using the Machina robot control framework (Garcia del Castillo 2016), which are then staged via WebSockets for streaming to a bridge application. The bridge application buffers all the incoming requests and establishes a TCP/IP connection with a server module written in Rapid code, ABB's native language, streaming these actions in real-time to the controller. The bridge application listens for completion messages coming from the controller and passes them to the core application. The core application then uses the sensed information to request a new batch of printing, heating, and sensing toolpaths, hence closing the loop. The data-flow diagram can be found in Figure 12.

RESULT

The printed double-curved geometry was produced by the use of a closed-loop system that proved successful for calibrating toolpaths to accommodate the discrepancies between the digital print path and the physical print (Figure 13). However, limitations still exist. The process of measuring individual points by using an LRF sensor is time-consuming, and calibrating the print path based on the changed Z axis values provides limited accuracy. In the current experiment scale, the X-Y's movements were negligible and mostly adjusted in the next layer. However, as a geometry scales up, it will be challenging to print the intended geometry without calibrating for the lateral movements. Future improvements to the developed system could include a sensing method that could detect lateral shifts by scanning the entire geometry speedily and accurately, calibrating the location of each succeeding level for proper anchoring. Additionally, printing clay takes time to dry and dries unevenly, creating stresses in the overall geometry and resulting in cracks and warpage (Figure 13). This issue only becomes exacerbated by increasing the scale of the printed geometry. At a larger scale, it would also be necessary to design an optimized print path to accommodate shrinkage, which could be done by integrating a traditional construction technique such as expansion joints. Improving the clay mixture's ingredients with additives to minimize cracking and warping could also be explored.

14 Light penetration through the printed geometry.

CONCLUSION AND FURTHER DEVELOPMENT

This paper proposed a computational framework for a closed-feedback system to improve the efficiency, geometric accuracy, and the stability of 3D printing clay lattice structures. The workflow integrates a live sensory feedback system to collect coordinate information for each printed geometry and correctly compensate for deformations when printing succeeding toolpaths. Within this workflow, a customized application written in .NET facilitated the exchange of data between collected coordinate information, the toolpath recalibration algorithm, and the robotic platform for clay printing. The process proved its effectiveness for precise 3D mesh-like printing of clay, a wet material with unpredictable behavior when printed in non-solid form. Therefore, the developed workflow can be capitalized to accommodate other materials with similar properties for spatial 3D printing, in particular, concrete. However, it has to be pointed out that collecting information using the laser range sensor can be very time-consuming with large-scale structures and only provides information about the Z-value coordinate. Additionally, upon extruding and dragging, the clay bead could shift along the X- and Y- coordinates, thereby causing the sensor to miss a few locations. In this context, future work will investigate the use of high resolution scanning devices that would minimize the time for the recalibration of geometries and increase the accuracy.

In a material context, the design of the experiment showed that the clay bead's diameter and its span length contributed significantly to the deflection values upon performing the anchor and drag procedures. This material knowledge informed the domain of curl dimension to ensure that the dragging of the clay bead induces sufficient tension between vertical elements. This procedure can potentially be implemented in the closed-feedback system workflow, where curl sizes can serve as another parameter that can be varied according to specific design and structural functions.

Furthermore, the digital nature of this closed-loop feedback system makes it possible to store all projected toolpath information and correspondingly sensed deformation. Information gathered in multiple printing runs could be used in the future to train machine learning models, which could in turn be used to anticipate deformation in clay 3D printing.

Finally, the workflow demonstrated its potential and applicability for remote construction of large-scale structures and can be adapted to accommodate certain site conditions. In this regard, the recalibration process would require more than just positional feedback, and could extend to integrate live structural and environmental data in the proposed system for better design decisions.

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IMAGE CREDITS

All drawings and images by the authors.

NOTE

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