Modelling Behaviour for Distributed Additive Manufacturing

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ABSTRACT

Distributed forms of construction in the biological world are characterized by the ability to generate complex adaptable large-scale structures with tunable properties. In contrast, state-of-the-art digital construction platforms in design lack such abilities. This is mainly due to limitations associated with fixed and inflexible gantry sizes as well as challenges associated with achieving additively manufacturing constructs that are at once structurally sound and materially tunable. To tackle these challenges we propose a multi-nodal distributed construction approach that can enable design and construction of larger-than-gantry-size structures. The system can generate and respond to integrated real-time feedback for parameters such as material curing duration and position awareness. We demonstrate this approach through a software environment designed to control multiple robots operating collaboratively to additively manufacture large-scale structures. We present and report on a novel computational workflow as well as work-in-progress of a digital fabrication environment. The environment combines a centralized system designed to manage top-down design intent given by environmental variables, with a decentralized system designed to compute, in a bottom up manner, parameters such as multi-node rule-based collision, asynchronous motion, multi-nodal construction sequence and variable material deposition properties. The paper reports on a successful first deployment of the system and demonstrates novel features characteristic of fabrication-information modelling such as multi-nodal cooperation, material-based flow and deposition, and environmentally informed digital construction.

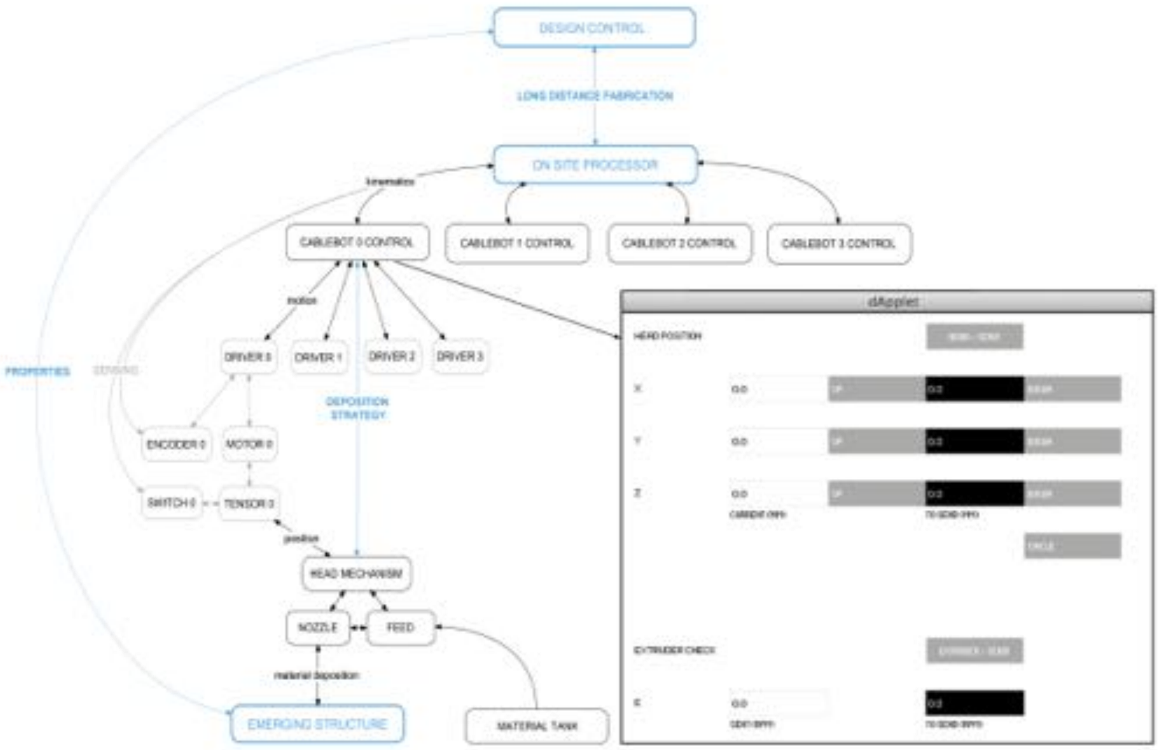

Figure 1: Flowchart and applet setup mode interface capture of the virtual implementation of a large-scale distributed cable-suspended additive construction platform, Mediated Matter Group – MIT Media Lab.

INTRODUCTION

Distributed construction in the biological world enables what is currently lacking in digital design and fabrication: large scale, geometrically complex, materially variable and behaviourally responsive fabrication (Erol 2005, pp. 10-20; Oxman et al. 2015, pp. 1-2). In the biological world, such features are enabled by an organism's ability to respond to environmental cues and adapt to the availability of matter (Wilson 2000; Tan et al. 2013, pp. 18-39). For instance, wasp nests and termite mounts are considered canonical examples for animal- architectures that are coordinated and erected through distributed construction (Wilson 2000). These insects utilize simple communication via sensing stimuli to construct large-scale, highly sophisticated, multi-functional structures that are orders of magnitude larger than themselves (Wilson 2000; Erol 2005, pp.

10-20). In contrast to its biological counterpart, man-made agent-based assembly is generally based on discrete processes, making it challenging to achieve high levels of complexity in agent-to-agent ("node-to-node") communication and material sophistication (Erol 2005, pp. 10-20; Augugliaro et al. 2014, pp. 46-64; Naboni et al. 2014). Higher overlap between material processes, environmental conditioning and fabrication constraints aims to tackle these challenges by increasing the dimensionality of the design space through multifunctional materials, high spatial resolution in manufacturing and sophisticated computational algorithms. In doing so, a holistic vision for design emerges - "Material Ecology" - that considers computation, fabrication, and the material itself as inseparable dimensions of design (Oxman et al. 2015, pp. 1-2).

Distributed Construction: Background

The majority of current research efforts in distributed construction focus on the assembly of discrete components (e.g. blocks or beams) held together in ways that are not readily scalable (e.g. magnetism or friction) (Lindsay et al. 2011; Werfel et al. 2014). These systems are typically developed around specific modular or prefabricated components, which limit the range of possible geometries and applications of the resulting structure (Lindsay et al. 2011; Werfel et al. 2014). From a design perspective, such efforts focus either on duplicating existing rectilinear forms as made by conventional construction methods (Lindsay et al. 2011), or on simulation models that fail to be reproduced in physical environments (Tan et al. 2013, pp. 18-39). Few recent projects, such as the one presented here, explore distributed deposition of large-scale structures with tunable material properties (Naboni et al. 2014).

Additive Manufacturing: Background

Current additive fabrication approaches for digital construction are generally limited by 3 major constraints: (1) the typical use of non-structural materials with homogeneous properties; (2) the dependency of product size in the gantry size, and; (3) the typical need for support material throughout the layered deposition process (Augugliaro et al. 2014, pp. 46-64; Naboni et al. 2014; Oxman et al. 2014b, pp. 108-115). A distributed approach to manufacturing carries potential to radically transform digital construction by (1) digitally fabricating structural materials with heterogeneous properties (Oxman et al. 2012, pp. 261-274); (2) generating products and objects larger than their gantry size (Oxman et al. 2014b, pp. 108-115); and (3) supporting non-layered construction by offering novel fabrication processes such as free-form printing and robotic weaving (Oxman et al. 2013b; Oxman et al. 2014a, pp. 248-255). Building on our previous work, we propose a work-in-progress distributed multi-robot approach to additive construction at architectural scales.

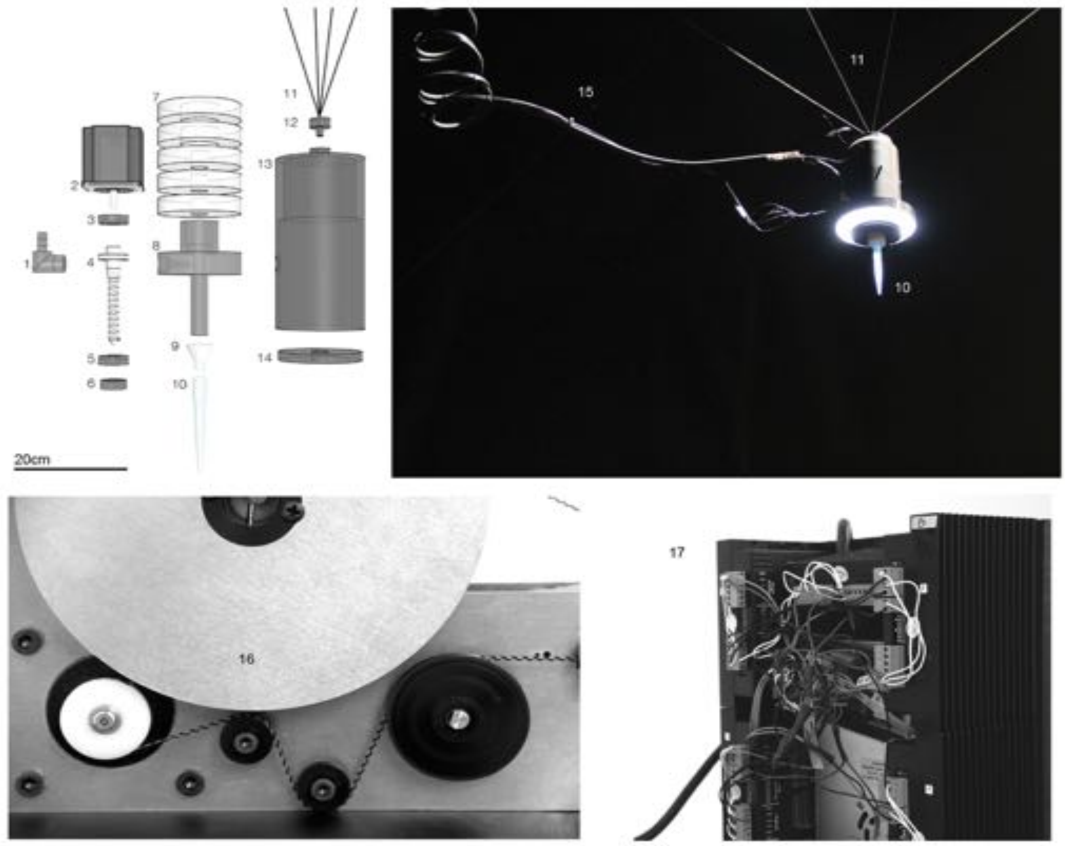

Figure 2: Electro-mechanical implementation for a cable-suspended construction system. The extruder head assembly is composed of material inlet (1), stepper motor (2), rubber seal (3), custom screw (4), rubber seal (5), U seal (6), lead weights (7), screw mixing chamber (8), HDPE custom nozzle (9), pipette tip (10), synchromesh cable (11), cable fixture (12), delrin housing (13), and end cap (14). Material is fed via hierarchical tubing (15). Spring motor assembly for synchromesh cable (16), and electronic control assembly (17). Mediated Matter Group – MIT Media Lab.

Behavioural Model for a Cable-Suspended Robotic Construction System: Implementation Strategy

Hardware:

Machine control firmware was developed in C and C++ language using micro controller boards (Arduino Mega 2560). The boards distribute serial signals to stepper motors (Gecko 6723-400-4) via the Probotix Bi-polar 7.8A drivers. The motors are NEMA 23 in size and are rated for a holding torque of 2.83 newton-meter. The drivers permit a maximum current of 7.8A and are powered separately from the electronic controls with a 48V power supply. Constant force spring motor assemblies (Stock Drive Products/Sterling Instruments, ML 2918) are used to spool up excess cable as well to keep tension on the pulleys. The micro controller receives feedback data from incremental rotary encoders (Yumo, A6B2-CWZ3E-1024, 1024 P/R Quadrature) and custom made zero switches comprised of copper contact and a connecting copper element attached to the cable at the right length. Each agent is suspended via four straight centre stainless steel cables which are encased in a helically wound nylon/polyurethane sleeve (Stock Drive Products/Sterling Instruments, Synchromesh, 1.6mm outer diam.). Each custom-built extrusion head assembly is composed of a stepper motor with a rubber seal and a custom extrusion screw. Lead weights are applied for stabilization of the extruder head; cable fixtures are attached to four incoming cables with machined plastic housing and a material supply inlet Fig. 2. The material feed for each head is composed of a pressure pot containing paste-like material fed to the extrusion heads by narrowing the flexible tubing diameter towards the extrusion head Fig. 2.

Software:

The distributed system is implemented in a Java language customized applet enabling real-time 3D representation of the agents' behaviour. There are two sets of functionalities in the applet relating to two modes, the *setup mode* and the *building mode*.

The *setup mode* takes as input data each agent's envelope dimensions and base. The envelope dimensions of each agent are measured in 3D physical space, where the top corners of each envelope are placed parallel to the construction base plane. The agent's base is an origin point measured in space where the "robot builder" is at rest. With this information at hand the system is able to determine initial cable lengths and to reset motor encoders as a starting point for subsequent construction behaviour. Fig. 3 shows the setup interface where initial data is read from motor encoders, and then used to position extruder head as well as to test the extrusion stepper motors.

The *building mode* function calculates the trajectories and temporal positions of each agent employing linear trajectories and constant velocity. We use a 3D modification of the Bresenham algorithm (Bresenham 1965, pp. 25-30) to move and track the agents in space via shortening or lengthening one of the four cables that are assigned per agent. The system computes discrete close approximations to linear trajectories from any 3D origin to any 3D target in the agent's envelope. Trajectory corrections are applied to avoid collision although agent envelopes may overlap, allowing for co-construction in specific and designated areas.

Behavioural Model for A Cable-Suspended Robotic Construction System: Rule-sets And Adaptation

Interesting design opportunities emerge when more than a single material deposition node shares a construction space. The implications of robotic collaboration are vast and must relate to challenges such as agent awareness to boundary condition, envelope sharing across agents, real time multi-agent 3D positioning protocols, means for collision avoidance, and distributed preservation of the mechanical cable-suspended system as well as the material deposition feed.

Main rule set:

The main computational rule set encodes five key system functions. Those include three centralized operations - *avoidance*, *storing* and *linking*, and two decentralized operations - *search* and *deposition*.

The *avoidance* function (1) keeps track of each robot's position in space in order to avoid cable hyperextension when agent navigation occurs outside the determined envelope. It also supports collision avoidance either by pausing one of the agents or by modifying its trajectory. The *storing* function (2) saves the position and deposition time of each drop of matter placed onto the structure. The *linking* function (3) ties the emergent structure with design intent rules such that the designer can steer the robots towards building in certain areas and avoiding others. This is achieved by operating the virtual tool through a representation of the physical structure as it is being collaboratively built Fig. 3.

Included in the decentralized operations, is the *search* function (4) designed to enable the agents to explore their envelope spaces and determine an adequate deposition location. During search mode, the robots navigate in 3D by employing bouncing trajectories from their maximum envelope until a z-axis threshold is trespassed; then, the agents verify the possibility of depositing material with the central system. Given a 3D position for additional material - if the relative height of the neighbouring structure and the curing time of the underlying drops are adequate - a new drop will be deposited. During the construction phase, the z-axis threshold is modified in order to adapt to the current height of the construction. Finally, the *depositing* function (5) consists simply of depositing a material droplet in a specific position as well as relaying time and coordinates to the central system.

Adaptation to material conditions:

Material deposition is informed by data embedded in the material itself. Each time a droplet of matter is deposited by a cable-robot agent in the physical environment, the virtual central system stores its data in a clock-based counter. The next agent attempting to deposit a new droplet on top of the stored one, receives information about the structural properties of the existing construct based on expected curing times. If the curing time is adequate, the agent will deposit a new droplet on top of the structure. Else the agent will enter search mode and determine an alternative spot to deposit the stored material. Preliminary results demonstrate small-scale proof-of-concept of structural organization of droplets and proper discrete material bonding. Fig. 4 (top) shows first construction results of a layer of ¼ inch diameter droplets by one of our cable-robot extruders performing rule-based search motion in between depositions. We have tested different droplet-based typology configurations by manually directing an extruder to pre-set positions namely; 4-faced vault, nave, discontinuous wall, and cantilevered continuous wall Fig. 4 (bottom). The material system used is industrial soft putty filler paste composed of gypsum plaster from hydrated calcium sulphate and glue. The virtual and physical systems are currently ready for the implementation of real-time feedback using humidity sensors or thermal cameras reporting to the central program.

Adaptation to design intent:

The construction strategy presented here complies with global electro-mechanical constraints in a rule-based system for the generation of form, while maintaining an adaptation strategy for direct remote intervention. The designer sets up the system to build a structural typology (e.g. a dome, an arch, a column array etc.), and lets the behavioural model initiate its construction in a bottom-up manner. The cable-robots negotiate the construction space without top-down specifications for which agent will build what section of the structure. However, in case of local structural instability or in case of design iteration during the building sequence, the designer can steer the agents toward abandoning an area or focus on completing another. This technique enables the emergence of form through robotic node-to-node communication by applying space negotiation rules for each drop deposition. Exploration of this feature is not possible with continuous layering of material employed in traditional 3D-printing extrusion technologies, such as fused deposition modelling (FDM) (Oxman et al. 2014b, pp. 108-115).

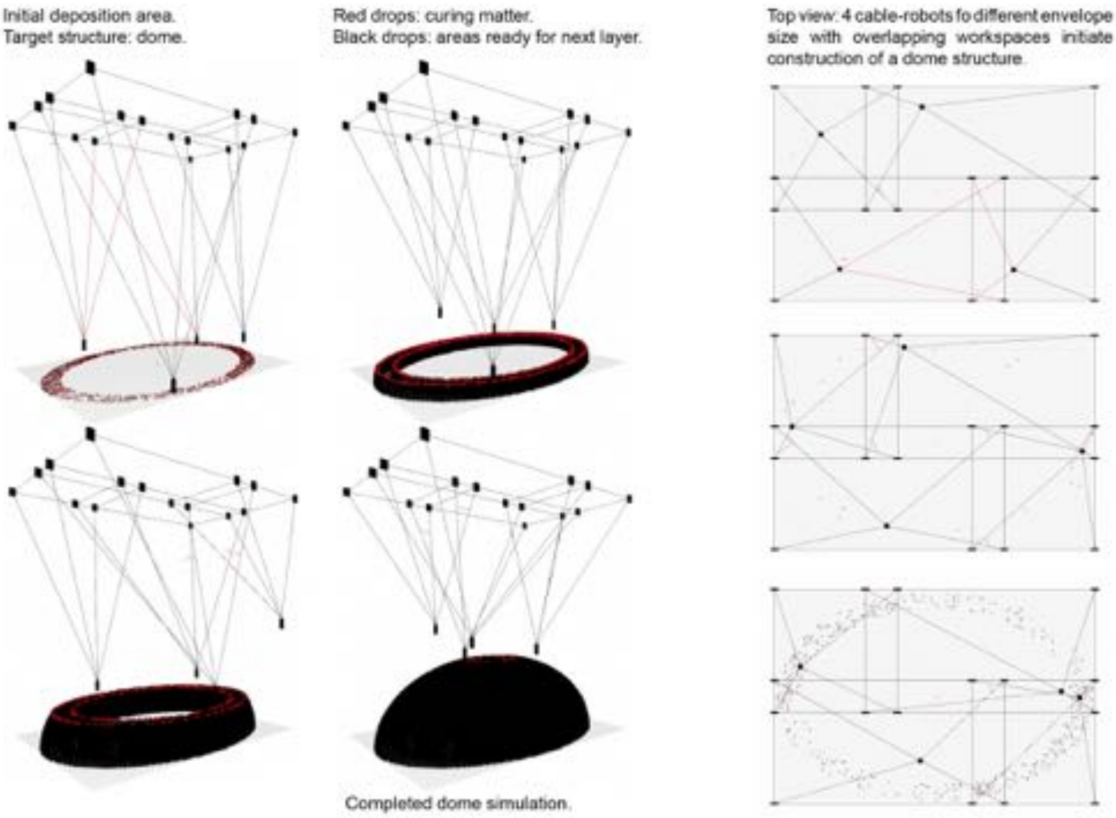

Figure 3: Virtual simulation of a cable-suspended construction system. Robot envelopes are differently shaped and overlap with each other in order to collaboratively build a structure that is bigger than each individual machine's gantry. Mediated Matter Group – MIT Media Lab.

EVALUATION AND DISCUSSION

We designed and built a partly centralized partly decentralized digital fabrication environment of cable-suspended robots. This environment demonstrates the first steps towards the design and construction of a novel fabrication technology made up of multiple fabrication nodes that is designed to support cooperative construction of large-scale structures. The research explores themes of asynchronous motion, multi-nodal fabrication, lightweight additive manufacturing and the emergence of form through fabrication. Importantly, the project points towards a new design *workflow* that is directly informed through fabrication, material and environmental constraints, true to the Material Ecology approach (Oxman et al. 2015, in press) and characteristic of Fabrication Information Modelling (FIM), a novel methodology and framework that we are currently researching (Duro and Oxman 2015, in press). Although the mechanical hardware requires further development in order to achieve a fully functional large-scale implementation, the computational workflow shows promising results in simulation. Indeed, the successful deployment of a small-scale prototype embodies the benefits of combining a top-down centralized approach to fabrication with a bottom-up decentralized approach. Small size proof-of-concept fabrication was achieved using the described computational workflow and hardware, demonstrating that such an approach and system are feasible. Specifically, improvements to the mechanical system such as higher zero-switch reliability to avoid strain on the hardware at failure must be implemented. In terms of dynamic control, the choice of a 1.6mm outer diam. Synchromesh cable proved to be challenging in terms of precision and overall dynamic strength. In terms of material supply, continuous feed via a pressure pot could be replaced by a cartridge approach, potentially providing a more stable print head without any physical constraints or interference from the material feed.

Systems such as the one outlined in this paper can be deployed for large-scale construction by attaching a distributed fabrication system to existing objects in the built environment. Cables from each robot can be connected to stable high points, such as large trees or buildings (Oxman 2014b, pp. 108-115). Such actuation arrangement can enable movement over large distances without the need for conventional linear guides. A cable suspended system is straightforward to set up for mobile projects and affords sufficient printing resolution and build volumes.

In future implementations, sensing feedback can play a key role in the design and development of the agents' rule-based behaviour. By means of 3D scanning and thermal imaging, structural stability and material behaviour can be monitored and fed back into the model. Real-time comparison of virtual and physical built volumes, as well as the aforementioned material property tracking function, can contribute to closing the gap between virtual-to-physical design workflows; as well as opening up new and exciting opportunities for innovative long-distance fabrication environments where the designer provides input from afar.

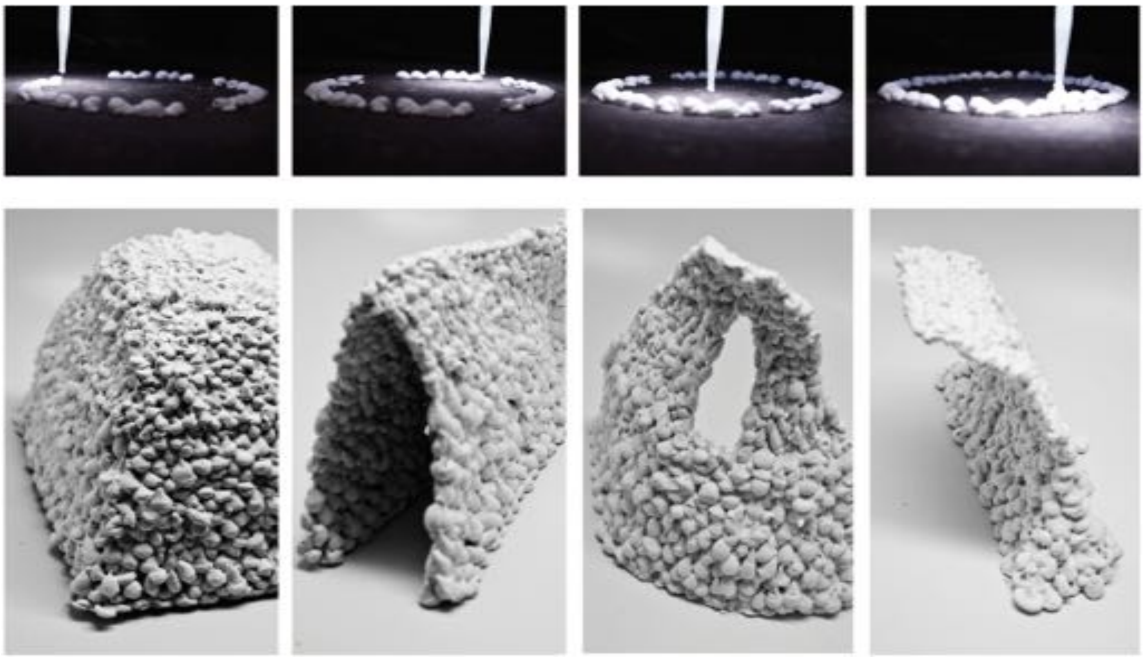

Figure 4: Top: Initial results of robotic deposition of layered droplets performed by one cable-robot extruder. Bottom: Preliminary manual experiments in soft plaster deposition including a 4-faced vault, a nave, a discontinuous wall, and a cantilevered continuous wall. Mediated Matter Group – MIT Media Lab.

ACKNOWLEDGEMENTS

This research was conducted by the Mediated Matter Group at the MIT Media Lab. Ideas, methods, products and techniques were developed to support on-going group research focusing on large-scale distributed fabrication systems. The authors would like to thank Mediated Matter alumnus Jared Laucks for his contributions to the project, as well as the MIT Media Lab and the 2013 Lisbon Architecture Triennial for their support.

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