The Massachusetts Institute of Technology (MIT) Mediated Matter Group is honing its research into robotic swarm printing by focusing its efforts on material sophistication, or ‘tunability’, and communication or coordination between fabrication units. Here, the group’s Neri Oxman, Jorge Duro-Royo, Steven Keating, Ben Peters and Elizabeth Tsai illustrate this by describing three case studies that investigate robotically controlled additive fabrication at architectural scales.
Architectural design and fabrication methods have historically evolved in tandem. From adobe brick construction dating before 7500 BC to today's 3D printing technologies, fabrication techniques have developed alongside design strategies and architectural styles. New design expressions have advanced innovation in construction techniques, while new fabrication technologies have inspired designers and architects to further push the envelope of design. This historical perspective allows us to distinguish between fabrication technologies that merely make the construction process more efficient, and others that fundamentally transform our way of thinking about building and buildings.

Today, robotic construction methods have the potential to usher in the next era of architectural design. To realise this potential we must question the basic premises of buildings themselves. Will robotic construction merely emulate manual construction, or become the catalyser for novel building processes? The latter approach invites the designer to consider the ways by which to construct a design process to be as meaningful as the product itself.

Additive manufacturing, or 3D printing, is the process by which to fabricate three-dimensional structures from digital files. Successive layers of material are deposited according to predetermined tool paths until the final form is completed. This fabrication method can be classified with respect to two basic attributes: firstly the degree of material sophistication, also known as material ‘tunability’; and secondly the level of communication and coordination between fabrication units. To better understand this distinction, consider two unique structures found in nature: a silkworm cocoon and a termite mound. The silkworm cocoon represents a highly sophisticated material architecture ‘designed’ by a single organism (the silkworm) where the mechanical properties of the silk vary significantly from the outer stiffer to the inner softer shell. The termite mound, however, is composed of primitive material with little or no tunability designed by a highly social community of termites. These two attributes – the level of material sophistication achieved through the ability to control physical properties, and the level of communication or coordination between fabrication ‘nodes’ (termites), can be found and mirrored in the world of digital fabrication.

Manufacturing paradigms to date have been confined to one of these attribute axes, with certain approaches utilising sophisticated tailorable materials, but having limited degrees of freedom and virtually no communication (the silkworm case), and others assembling simple building blocks or prefabricated components in a cooperative fashion with high levels of intercommunication between fabrication nodes (the termite case). The research at the Massachusetts Institute of Technology (MIT) Mediated Matter group aims to combine high levels of communication within and across robotic platforms with high levels of material tunability.

The three case studies here investigate robotically controlled additive fabrication at architectural scales, each representing a unique combination of properties relating to material tunability and communication. First, a robotically layered concrete formwork combining low levels of material tunability with low levels of communication; second, a cable-suspended self-measuring robotic foam-printing platform combining low levels of material tunability with high levels of communication; and third, a templated swarm silk deposition system representing high levels of material tunability with low levels of communication. The article concludes with a brief look at the Mediated Matter group’s planned future research into systems combining high levels of communication with high levels of material tunability and the promise of swarm printing as a new direction in architectural-scale additive manufacturing.

Since the mid-1980s, single-node additive rapid fabrication and rapid manufacturing technologies have emerged as promising platforms for building construction automation at the product scale, but with limited applications at the architectural design and building scales. Characteristic of such technologies are the use of mostly non-structural materials with homogeneous properties, the limitation of product size relative to gantry size, and the layer-by-layer nature of the fabrication process. For these reasons, such methods cannot easily be scaled to large architectural systems. However, the ability to additively fabricate at large scales using robotic platforms can help overcome these limitations. This will involve control of material property and variation (material tunability) as well as establishing sufficient communication within and across fabrication nodes (decentralised robotic fabrication) in the robotic construction of large-scale systems.

Material Tunability in Additive Fabrication

To date, additive fabrication systems have acted typically as assemblers of prefabricated components. In general, such low-level subassemblies are structurally componentised and materially homogeneous. The established approach of constructing pre-manufactured building components stands in contrast to the potential of robotic additive systems to deliver highly customised structural and material forms able to potentially adapt and respond to environmental pressures. The Mediated Matter group’s research has concentrated on developing variable-property printing platforms delivered through single-node fabrication, focusing on high levels of material tunability. An example of the type of structures that

Neri Oxman and Steven Keating, Functionally Graded Printing, Concrete Structural Experiments, Mediated Matter group, MIT Media Lab, 2010–12
Fabracted linear (left) and radial (right) density gradients in concrete samples allow for material distribution to match stress curves. Samples produced in collaboration with Timothy Cooke and John Fernandez of the Building Technology Program at MIT.
can be achieved here is shown in multi-material 3D prints where the different colours denote functionally graded mechanical properties in 16-micron resolution.

The Mediated Matter group has investigated variable-property printing at multiple scales. Past work developed functionally graded concrete deposition utilising density gradients to reduce mass and improve structural capabilities. Completed work has demonstrated material reductions of between 9 and 13 per cent of the overall mass while maintaining equivalent structural capacity of a fully dense member using radial density gradients in concrete bending samples.2

**Cross-Platform Communication and Coordination in Additive Fabrication**

Progress in swarm construction has typically occurred in the development of sophisticated communication and control protocols to support automated assemblies of basic pre-shaped building components manipulated in predefined paths.3 Deterministic and stochastic approaches in swarm construction have their merits and limitations: deterministic models offer top-down communication templates enabling robustness and reducing error, while stochastic approaches offer bottom-up intelligence providing responsive and adaptive error control in real time.4 The goal of the MIT group design research is the integration of these two strategies to achieve top-down control of large structures combined with bottom-up manipulation of localised material features.

**Robotic Additive Fabrication Case Study: Print-in-Place**

Print-in-Place technology developed by the Mediated Matter group addresses robotically layered concrete formwork combining low levels of material tunability with low levels of communication. It is a construction method utilising fast-curing polyurethane foam as a leave-in-place thermal insulation formwork for castable structural materials. The formwork is designed to be robotically 3D printed on site to allow rapid, custom and efficient large-scale structures. Preliminary research into large-scale 3D printing using this technique has been promising, showing quantifiable benefits in structural strength, construction time, site safety and economic potential.

The technique can be used to additively manufacture polyurethane foam formwork. The resulting leave-in-place formwork is similar to the current construction technology of insulated concrete forms (ICFs), allowing for easier integration into existing site techniques and codes. The spray-foam polyurethane is an ideal material for large-scale 3D printing due to the fast cure time (under 5 seconds), high volumetric expansion rate (up to 40 times), the ability to print double curvature without support material, and the high insulation value of the material.

**Robotic Additive Fabrication Case Study: Cable-Suspended 3D Printing**

The SpiderBot and CableBot, both developed by the Mediated Matter group, are cable-suspended robotic 3D printing platforms that explore high levels of material tunability using a single-node fabrication system, and high levels of communication using a multi-node fabrication system,
By adding external end effectors to the robotic arm and providing a larger gantry, it is possible to 3D print with acrylonitrile butadiene styrene plastic (upper image) and mill the same piece (lower image) within a single/continuous fabrication process.

Print-in-Place technology developed by the Mediated Matter group addresses robotically layered concrete formwork combining low levels of material tunability with low levels of communication. The first system explores the technological challenges of material tunability, and the second high levels of communication via an array of robots that share the same environment and deposit a low tunable material.

The SpiderBot is able to build lightweight but large-scale structures, and is capable of rapid deployment in undeveloped terrains. A simple prototype constructed from off-the-shelf winches yields an impressive working volume of nearly 850 cubic metres (30,000 cubic feet). When fitted with canisters of expanding foam, this parallel actuating device is capable of constructing complex building-scale forms via serial layer deposition. The body is composed of a deposition nozzle, a reservoir of material, and parallel winching electric motors.

above: By adding external end effectors to the robotic arm and providing a larger gantry, it is possible to 3D print with acrylonitrile butadiene styrene plastic (upper image) and mill the same piece (lower image) within a single/continuous fabrication process.
In both the SpiderBot and the CableBot systems, cables from the robot are connected to stable high points, such as large trees or buildings (simulated as a hook system within the installation space in the SpiderBot, and as mounting plates connected to existing structural beams within the installation space in the CableBot). This actuation arrangement allows movement over large distances without the need for more conventional linear guides, much like that of a spider. The systems are easy to set up for mobile projects, and afford sufficient printing resolution and build volume.

Expanding foam or other materials can be deposited by both systems to rapidly create building-scale printed objects. Another material type of interest is the extrusion or spinning of tension elements like rope or cable. With tension elements, unique structures such as bridges or webs can be wrapped, woven or strung around existing environmental or infrastructural features.

The CableBot project uses an array of cable-suspended robots that provides an easily deployable platform from which to print structures that are larger than the spatial envelope of a single robot. The material feed is externalised and reaches the extruder head through hierarchical tubing, in contrast to the SpiderBot where material is carried on the end effector. The motion of every robotic head is set computationally as a rule-based system, exploring the first steps towards the application of swarm intelligence algorithms within the system. The behavioural rules make the robots aware of their envelope dimensions, and of the position of neighbouring robots, so that they can modify their behaviour to avoid collision and hyperextension of the cable system.

The construction strategy explored in the CableBot system is the discrete deposition of soft material drops. This technique enables the emergence of form through robotic node-to-node communication by applying space negotiation rules following each drop deposition. Exploration of this feature is not possible with the continuous layering of material employed in traditional 3D-printing extrusion technologies, such as fused deposition modelling (FDM).

**Robotic Additive Fabrication Case Study: Templated Swarm Printing**

This project explored a design fabrication approach for robotically controlled additive manufacturing with high levels of material tunability and low levels of communication, inspired by silkworm cocoon construction. It investigates the process of silk deposition by the *Bombyx mori* and

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**Neri Osman and Ben Peters, SpiderBot cable-suspended 3D printing, Mediated Matter group, MIT Media Lab, 2012**

*below and bottom: Extrusion head of a SpiderBot prototype – a cable-suspended, large-scale material deposition platform. The diagrams illustrate the comparison between three-axis fabrication motion and a more sophisticated weblike construction motion.*
proposes a novel fibre-based templating approach for robotic construction that informs its biological counterpart. Characterised as ‘multi-nodal spinning organisms’, with relatively low levels of communication and interaction, silkworms are not bound by social hierarchical structures, but are extremely adaptable to spatial parameters and environmental factors in their immediate surroundings.\textsuperscript{5} By studying their spinning behaviour using a magneto-sensor motion-tracking rig, and determining necessary spatial constraints to control it, the system demonstrates that collective multiple silkworm spinning is a viable method for creating a highly tunable fibrous 3D membrane.\textsuperscript{6}

In this proof-of-concept experiment, a silkworm ‘swarm’ was controlled by spatial scaffolding constraints to alter the spinning behaviour of the silkworms from naturally spinning a cocoon to spinning a flat membrane on a template. The superstructure scaffold was digitally constructed using a computational algorithm based on environmental and biological constraints.

Using basic rules such as the silkworm’s spinning reach, initial steps towards a digitally controlled system were demonstrated by creating a large-scale (3.6 x 3.6 metre/12 x 12 foot) pavilion deploying a biological swarm. Here, the overall design was controlled and constructed digitally, providing a scaffolding for the organisms to crawl and spin on – ‘template printing’ – enabling local variations in density and distribution. The superstructure was made of 15,132 metres

The CableBot project uses an array of cable-suspended robots that provides an easily deployable platform from which to print structures that are larger than the spatial envelope of a single robot.
(49,645 feet) of digitally spun silk thread, while the silkworm swarm deposited approximately 6.5 million metres (21.3 million feet) of silk fibre, creating a highly complex micro-structural membrane.

The task of generating a 3D path for digitally fabricating a single non-woven thread, 6.5 million metres in length with highly tunable material properties, is challenging. In the case of the Silk Pavilion, however, this was accomplished by digitally generating only the overall scaffold strategy and leaving the local control and micro-structural fabrication to silkworms controlled through external factors such as changing space configuration, light and temperature. Furthermore, while the geometrical constraints of the space provided the static control factors for the design, environmental conditions such as light and heat provided for dynamic control factors that can enable real-time feedback between existing and desired spinning patterns.

The global design of the pavilion was derived from desired light effects informing variations in material organisation across the surface area of the structure. A season-specific sun-path diagram mapping solar trajectories in space dictated the location, size and density of apertures within the structure in order to lock in rays of natural light entering the pavilion from the south and east elevations, thereby guiding the movement of the silkworms across the structure’s surface area.

The Silk Pavilion is an initial proof-of-concept behind the synthesis of digital fabrication and biological swarm construction. The Silk Pavilion experiments are a potential path towards the manipulation of ‘biological’ builders in achieving further goals in swarm construction and biological fabrication.
Towards Robotic Swarm Printing

Robotic (Swarm Printing (RSP) – a robotically controlled multi-nodal additive fabrication platform being explored by the Mediated Matter group – could potentially transform the digital fabrication industry by overcoming the current limitations of additive manufacturing. Material limitations could be overcome by enabling automated construction of structural materials; gantry limitations by enabling the construction of large components made of a collective of cooperative small robots; and, finally, method limitations by enabling digital construction methods that are not limited to layered manufacturing, but also support free-form, woven and aggregate constructions.

RSP combines high levels of material tunability with high levels of communication at construction scales that build on the research discussed earlier in this article. The aim is to create RSP structures that include insulation, structural walls, internal reinforcing bars, tubing and wiring. Using a new approach to large-scale digital construction inspired by the biological world, structures could be designed with integrated and continuous functionalities, and fabricated using a distributed system. At the architectural scale, this would allow for production beyond the limits of traditional construction. Through increased footprint, scalability, robustness, efficiency and material tenability, RSP offers advantages over single-node robotic systems and current robotic building platforms. The MIT Mediated Matter group’s future research seeks to unite swarm construction and variable-property additive manufacturing to create complex integrated building systems, inspired by nature, at the micro, product and architectural scales.

Notes