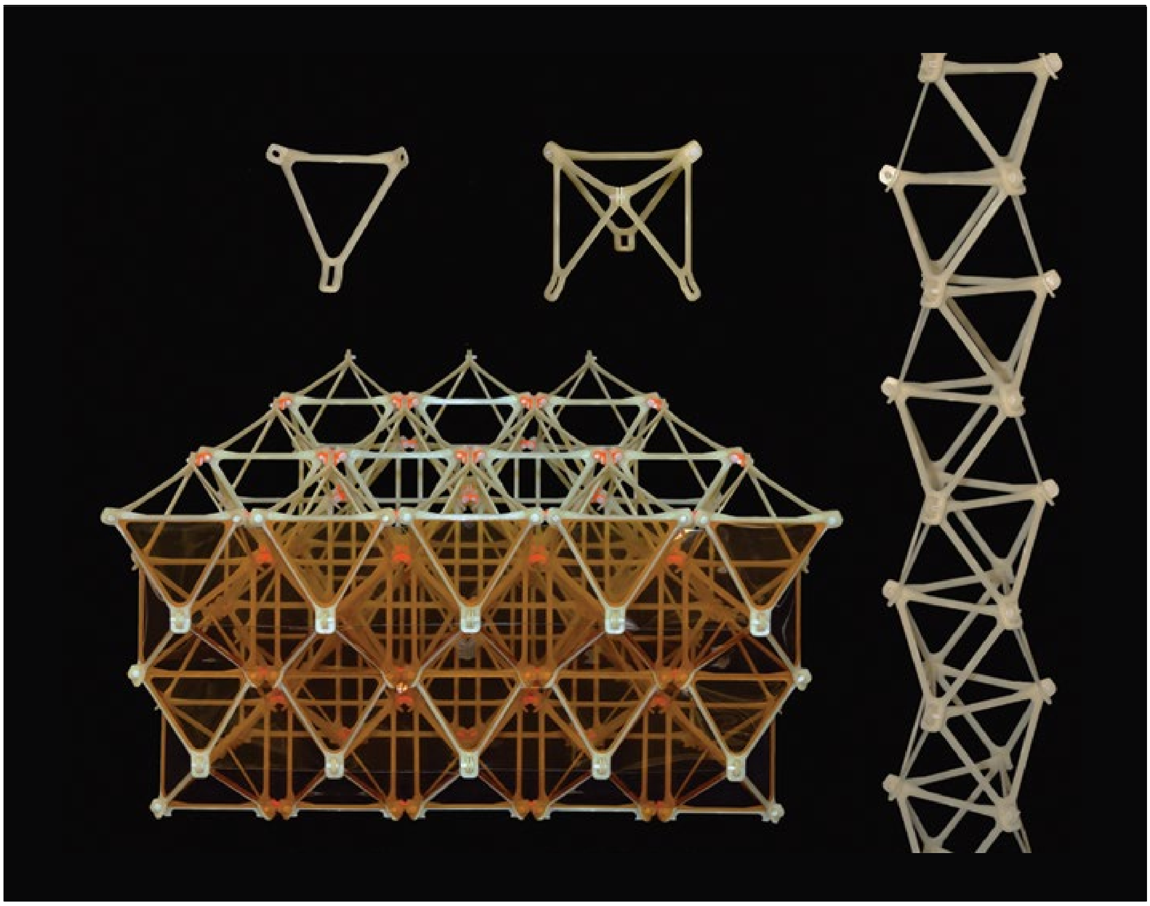


Matthew Carney, Benjamin Jenett, Sam Calisch, Spencer Wilson and Neil Gershenfeld, Digital material structure, MIT Center for Bits and Atoms, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2014

The triangular decomposition of a digital material structure is assembled into a cell, column and skinned volume, shown here using glass-reinforced nylon parts.

MACROFABRICATION WITH DIGITAL MATERIALS

ROBOTIC ASSEMBLY

Neil Gershenfeld, Matthew Carney, Benjamin Jenett, Sam Calisch and Spencer Wilson

Rapid-prototyping processes are being extended to increasingly large scales, including 3D printing from gantries, and robotic arms for cutting, milling and winding. These all use designs that are digital, but materials that are not: they are continuously deposited or removed. **Neil Gershenfeld, Matthew Carney, Benjamin Jenett, Sam Calisch and Spencer Wilson** of the MIT Center for Bits and Atoms explore the implications of the use of digital materials, reversibly assembled from a discrete set of parts with a discrete set of relative positions and orientations, for applications on scales ranging from aerostructures to geoprinting. Here, they discuss the production of the parts, the modelling of structures made with them, and their automated assembly.

The phrase 'construction worker' is synonymous with manual labour. Building construction is one of the largest industries, with around a trillion dollars in construction spending in the US in 2014, and it is also one of the most labour intensive, with a US payroll of about $300 billion.[1] Whether hammering nails, welding girders or pouring concrete, it relies on large numbers of workers performing repetitive manual tasks. Introducing automation into construction on the scale of the built environment has implications far beyond improving labour productivity. Buildings are largely static, typically requiring years to build and then remaining unchanged for decades; reconfigurability would allow them to respond to changes in internal and external space use. Building intelligence is an afterthought typically added by unrelated trades, rather than being incorporated as an intrinsic part of the construction process. Extreme weather events like hurricane Katrina and superstorm Sandy can cause tens of billions of dollars of damage,[2] but our national technical means to protect against them are bags of wet sand. 'Geoprinting' landscape-scale features would allow protective barriers to be rapidly erected and dismantled. And as we expand beyond earth, automation will be needed to build habitats in space.

Attempts have been made to adapt a range of rapid-prototyping processes to the building scale, but these have had limited impact. Presented here is an alternative approach, based on the distinction between analogue and digital materials.[3] These are assembled from a discrete set of parts, reversibly joined in a discrete set of relative positions and orientations. Unlike either additive or subtractive processes that continuously add or remove material, these attributes allow metrology to be determined locally by the parts, errors to be detected and corrected, materials with dissimilar properties to be used in a common process, and structures to be disassembled and reused rather than disposed. Digitising not just designs, but also materials, has required the development of an entirely new end-to-end workflow for discrete fabrication. The following sections look at alternative methods, the geometry and assembly of the parts, processes to produce them, and their structural modelling.

BACKGROUND

The introduction of robotics into construction has a long history of investigation, but this has not translated into widespread adoption in commercial practice. Existing automation in the building industry has focused on material handling. Examples include the robotic transportation of steel framing, prefabricated modules and wall assemblies.[4] Research robots have been developed for configuration and connection of structures.[5] Automation of earthworks includes surveying, path-planning, and measurement.[6] There are commercial and research applications to excavation, foundation work, and tunnelling, and responses to natural disasters such as landslides.[7] All of these augment rather than replace traditional construction methods.

Large-scale additive manufacturing aims to create buildings through the continuous deposition of material, using industrial-scale gantry systems to move specialised end-effectors. Extrusion of concrete to form walls and enclosures has been developed extensively,[8] other systems use a powder and binder method,[9] fused deposition modelling can create architectural components to 'print' a house,[10] and preliminary research has been conducted on extraterrestrial additive manufacturing using lunar regolith as a base material.[11] However, these approaches have been limited by the cost and performance of machines and materials.

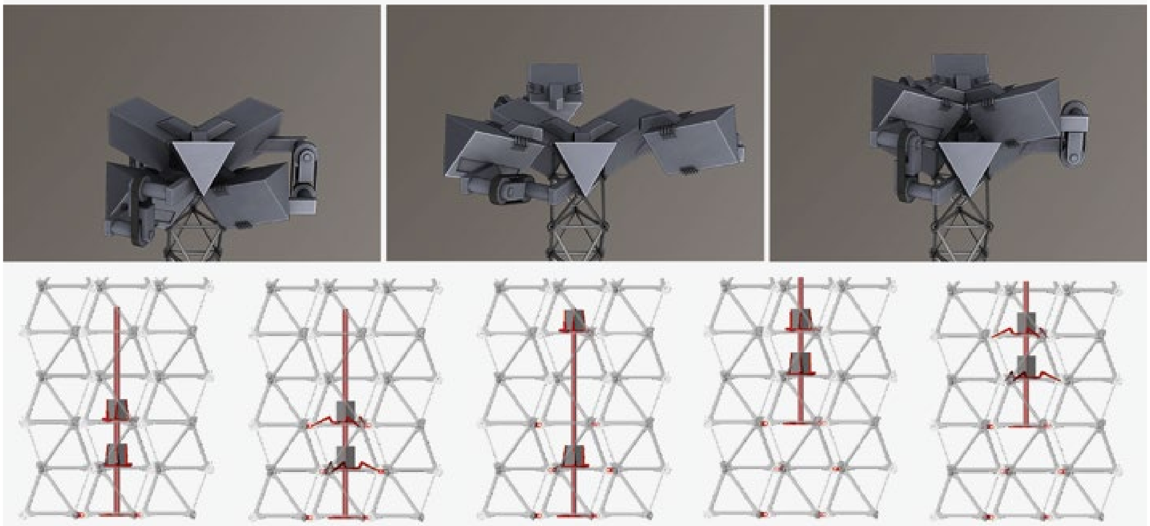
Small, simple robots with fewer degrees of freedom make controls and path planning easier and have modular assembly strategies. Brick-placing robots have terrestrial[12] and aerial[13] applications. The former uses part geometry to define locomotion and assembly, while the latter requires global positioning. Both have been used to demonstrate parallelisation in collective construction, but not yet to make large-scale functional structures. Robotic arms with multiple degrees of freedom have a greater range of motion, but require more sophisticated controls and path planning. Several projects using arms with varying end-effectors have created large structures employing milled wood, wound carbon fibre and knife-cut ETFE.[14] Other projects have used robotic arms to orient and place bricks and wood beams into customised walls and lattice structures.[15]

All of these approaches to automating existing construction tasks seek to decrease the time required by moving more material more quickly, or to increase the complexity that can be achieved by programming motions that cannot be made manually, yet these goals have so far been in opposition. Robotic discrete assembly, however, can simultaneously address both.

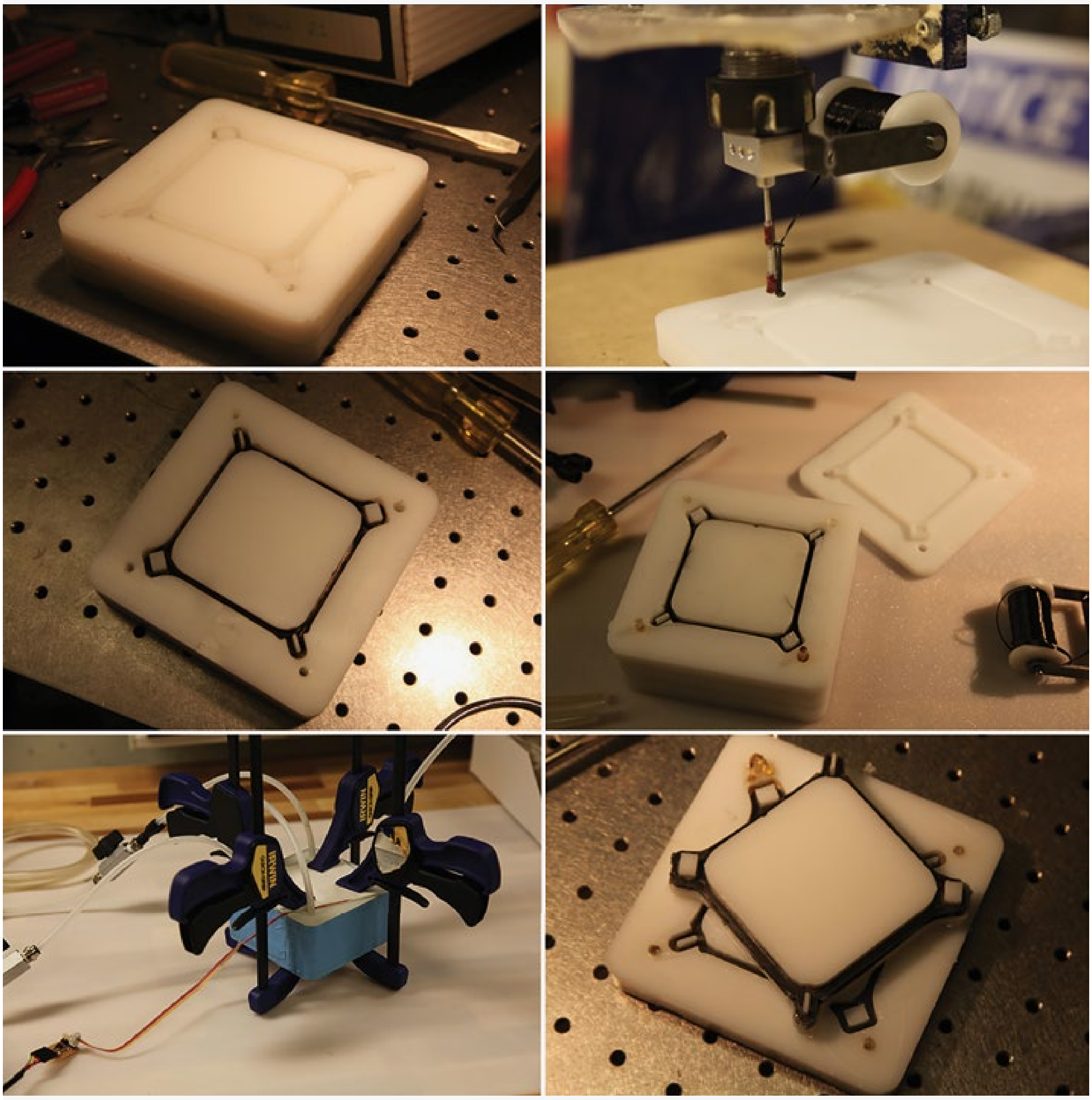
GEOMETRY AND ASSEMBLY

The first question to be addressed is the geometry of the parts to be assembled. In 1864 James Clerk Maxwell identified the trade-off between constraints and degrees of freedom in a framework.[16] If the framework is under-constrained, its mechanical properties are dominated by bending; if it is over-constrained, they are dominated by stretching. The latter uses mass much more efficiently, but that benefit is reduced as further constraints are added. In three dimensions, vertex-connected octahedra are at that boundary, the 'cuboct' lattice.[17] In its digital composites project, MIT's Center for Bits and Atoms has shown that this structure reversibly assembled from oriented carbon-fibre loops has shown the highest reported modulus in the ultra-light regime.[18] Joints are usually avoided in composite structures because they introduce points of failure, but here they serve as links to transfer forces between

Modelling of the cyclical robotic assembly of a digital material structure as a linear column (top) and cross-linking (bottom).



Netshape composite part production is based on ganged resin transfer moulding (GRTM).



the loops. The assembled structure behaves as an elastic solid, and because of the massive internal redundancy it fails incrementally rather than catastrophically.

For aerospace applications, these digital composite structures allow the benefits of carbon-fibre construction to be pushed into a previously inaccessible regime of sparse space-filling structural volumes. And the expensive supply chains to produce and handle parts the size of an airframe can be replaced with automated final assembly of the fibre loops. These same benefits can be extended to building applications, relaxing the extreme weight requirement.

The cuboct digital composite structure was initially assembled from cross-shaped parts. Automation of this process is difficult, because their joints require simultaneously aligning the legs of parts from four neighbouring cells into the centre of a central one. An alternative geometrical decomposition uses triangular faces that can be placed simultaneously. A further simplification for the automation is to divide tasks, so that these are assembled in linear trusses in a fast building direction, then cross-linked into 2D sheets and 3D volumes in a slower build direction, analogous to the secondary and tertiary structure of a protein produced by linear elongation from a ribosome. The discrete construction of these structures can be reflected in an incrementally attached cellular surface skin.

Compared to conventional robotics, the task of this kind of relative robot is significantly simplified. Global positioning is not required because metrology comes from the parts that it is assembling. Continuous control systems are also not necessary because there is only one cyclical motion and errors are bounded by the constraint of joining the parts. Independent locomotion is not needed, because the assembler functions as a part of the structure that it is assembling. And the discrete operation can be naturally divided so that many assemblers can work in parallel. To project the potential performance, a typical repetition rate for the fastest comparable cyclical mechanical processes such as a pick-and-place, sewing machine, or machine gun is 100 Hz. More conservatively, to move larger parts, assuming a 10 Hz cycle time for the example given below of assembling a 3 x 3 x 1,000 metre (10 x 10 x 3,280 foot) levee from 30-centimetre (12-inch) parts, a single assembler would require about 8 hours, or a 3 x 3 array of assemblers could complete it in under an hour.

PART PRODUCTION

To minimise the mass required to make these parts, conventional composite production requires post-processing following curing and compaction to define the part shape. This is acceptable for making small numbers of high-value parts, but not the enormous numbers of identical low-cost parts used in digital materials. However, the dimensional tolerance of the parts is essential, because they determine the metrology of the structure and enforce the constraints on assembly errors.

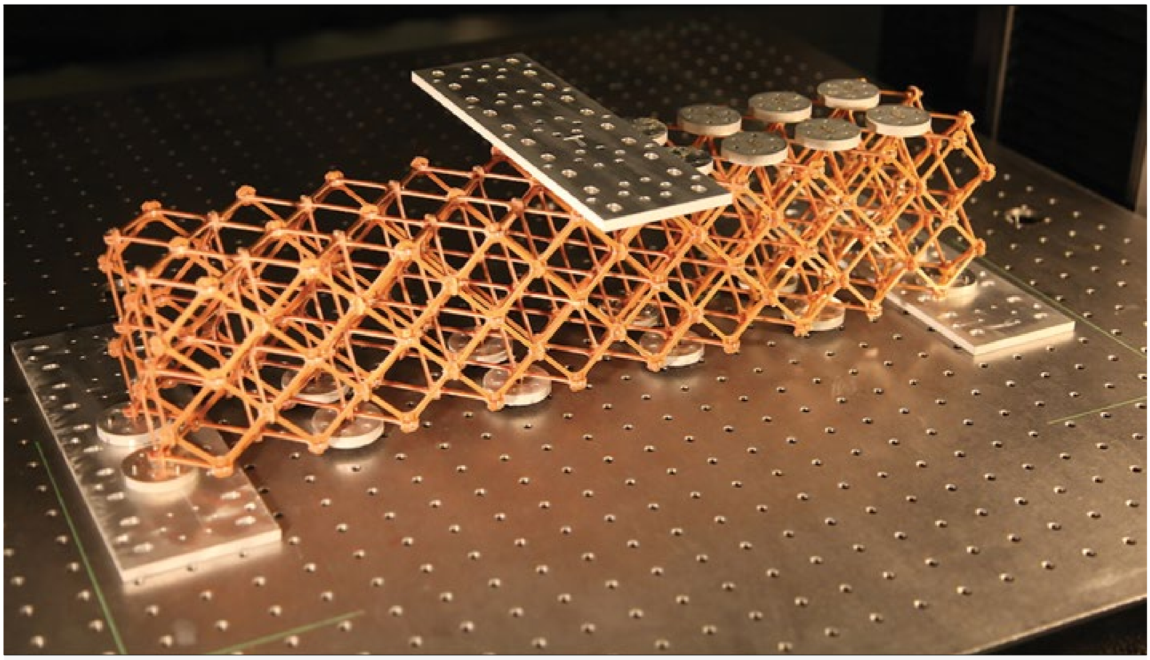
Resin transfer moulding is displacing the use of prepreg and wet layup in the composite production of complex parts. It requires heavy tooling to withstand the hydraulic pressure, and the production rate is limited by the cycle time for resin injection and curing. To parallelise this process, the Center for Bits and Atoms developed a ganged resin transfer moulding (GRTM). Here, a numerically controlled head winds fibres in a part mould following the axial loadpaths in a stretch-dominated structure. Compaction is provided by the next mould face, and this process is repeated to assemble a mould stack. Resin is then pumped through the moulds in parallel; the parts are cured, and released for net-shape production of oriented fibre loops. Modular mould stacks can be added to increase throughout for volume batch production. The parts can then be flat-packed or loaded into cartridges for shipment to robots for on-site assembly.

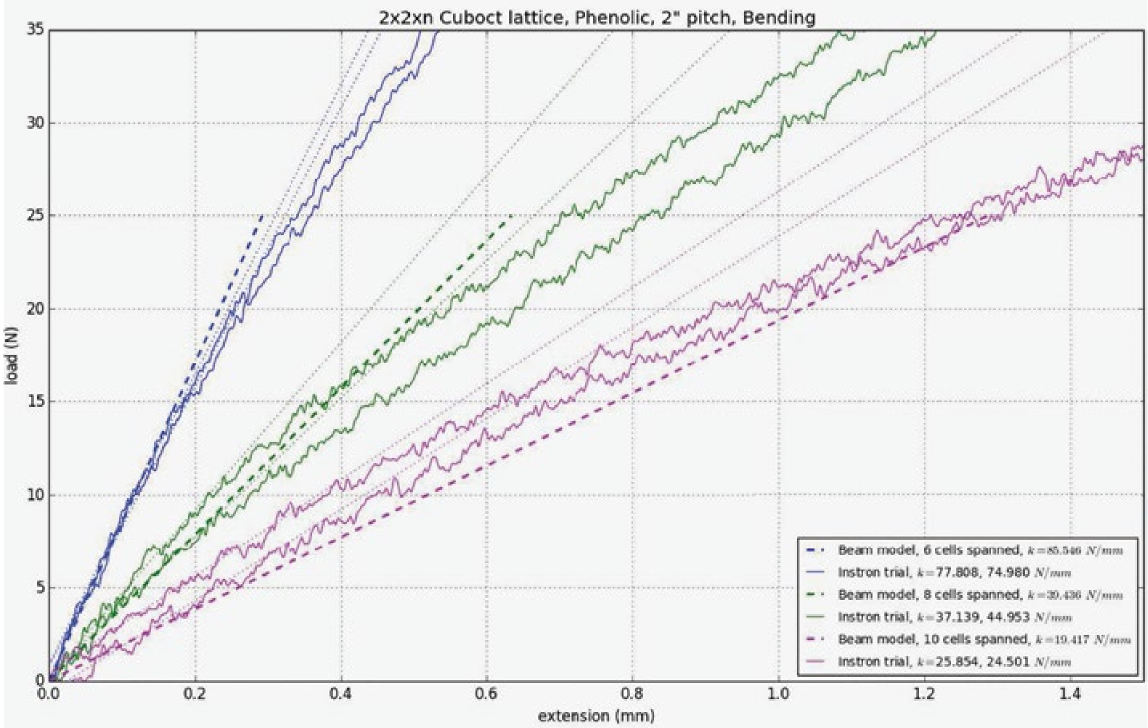
MODELLING

The discrete construction of digital materials provides an equivalence between designs and their mathematical models. In finite element analysis (FEA), the geometry to be modelled is subdivided into many small, easy-to-analyse parts. Equations are derived for the physics to be modelled on these elements, and solutions are specified by the displacements of the element nodes. The same process can be used to model digital materials, by mathematically simplifying their structures to the nodal interactions of their parts. In the case of conventional FEA, the fact that the elements are small is usually used to make approximations to the constitutive equations and transform the partial differential equations into a system of equations to solve. Digital materials elements are not vanishingly small, but they can be analytically simple, so we can turn to solid mechanics models to calculate their behaviour.

A three-point bend test of a digital material structure compared the measured force-versus-deflection curves to those predicted by the hierarchical modelling approach.[19] This offers several advantages over meshed FEA of digital materials in engineering applications. Firstly, there is a huge reduction in the size of the data structures and linear systems used to describe the problem. Correspondingly, the analysis is less costly, and can be iterated more times in the design process. Secondly, this simplification eliminates many opportunities for model mismatch, locking behaviour and numerical instability. This means that numerical predictions can be more accurate, without the need for excessive tuning and validation. Finally, because the representation used to design and simulate is the same, these two stages of the engineering process can be more closely coupled, even occurring within the same interface. In this way, physically meaningful

The flexural modulus testing of a digital cellular solid shows agreement with a beam model.





Relative cost and fill fraction of part materials

Part material	Cost for 3 x 3 x 1000 metre levee ($)	Fill fraction (%)
Concrete	85,136	0.63
Birch plywood	89,828	0.91
Glass-reinforced nylon	176,500	0.69
Carbon-fibre composite	339,950	0.28
Burlap composite	360,540	1.10
Sandbags	597,800	100.00

design parameters can be pulled through the simulation loop more easily, offering better handles for structural optimisation.

ECONOMICS

To estimate the relative cost of construction by discrete assembly, the building of a 3 x 3 x 1,000 metre (10 x 10 x 3,280 foot) levee was taken as a benchmark task to estimate the relative cost of construction by discrete assembly. A beam-bending model for a 9-metre (30-foot) hydrostatic load was used to determine the required Young's modulus of the structure. For a prescribed 0.5 per cent deflection, this modulus is 2.35 MPa. An experimentally derived power–law relationship with an exponent of 1.76 between the Young's modulus and material density for sparse lattice structures was used to determine the density of the lattice for a given material.[20] Cost was then calculated using the Ashby cost equation:

$$C(n) = (Cm * \rho * V) + \frac{1}{n}(Ct) + \frac{1}{r}(Coh + P * CE)$$

C(n) is the cost per unit part being manufactured with *n* the number of parts produced; *Cm* is the cost of materials; ρ is the derived lattice density; *V* is the lattice volume; *Ct* is the cost of tooling; *r* is the production rate; *Coh* is the cost of overheads including labour; *P* is the power required in the system; and *CE* the cost of energy per unit time.[21] For this calculation, a 30-centimetre (12-inch) unit part was assumed, and five candidate digital materials were compared to sandbags. The total approximate cost and density are tabulated opposite. These figures suggest that for the geoprinting application of rapidly erecting large-scale flood barriers, robotic assembly of digital materials can offer significant reductions in both cost and mass.

IMPLICATIONS

Many of the attempts to automate construction have effectively applied modern technology to traditional construction practices. Explored here are the implications of revisiting those assumptions, by discretising the materials as well as the designs. Macrofabrication with digital materials will require a new kind of relative robot that replaces global positioning and continuous control systems with discrete motion within a structured environment. The implications of local metrology with error detection and correction enable significantly increasing the information content in a structure by placing many more individually addressable volume elements. These robots, plus the materials they assemble, are best viewed as a combined system. By retaining the assembler as a part of the structures that it assembles, they can be continuously reconfigured for adaptive online architecture. And by extending assembly to geological scales, landscape architecture takes on a new literal meaning.

Ultimately, introducing computation into reconfigurable construction will allow structural design to be declarative rather than prescriptive. Goals and constraints, such as carrying loads and saving energy, can be specified so that the system of a structure and its assemblers can perform a distributed computation to dynamically maximise these. This is similar in both spirit and implementation to the natural optimisation that is carried out in the 'unbuilt' environment – the rest of the ecosystem. Realising this vision will require development and certification of new workflows to design, model, produce and assemble digital materials. Although there are potential benefits across construction, early adoption is likely be driven in domains that are currently infeasible, including producing landscape-scale features on demand for emergency response, and augmenting humans to build habitats for the colonisation of space. ◬

Notes

1. United States Census Bureau, 'The Value of Construction Put in Place at a Glance: February 2015': www.census.gov/construction/c30/c30index.html.
2. NOAA – National Climatic Data Center/National Oceanic and Atmospheric Administration, 'Billion-Dollar Weather and Climate Disasters: Table of Events': www.ncdc.noaa.gov/billions/events.
3. George A Popescu, Neil Gershenfeld and Tushar Mahale, 'Digital Materials for Digital Printing', DF International Conference on Digital Fabrication Technologies, Denver, Colorado, 2006.
4. Alan M Lytle and Kamel S Saidi, 'NIST Research in Autonomous Construction', Autonomous Robots, 22, 2007, pp 211–21, and Pentti Vähä et al, 'Extending Automation of Building Construction: Survey on Potential Sensor Technologies and Robotic Applications', *Automation in Construction*, 36, 2013.
5. Franz Nigl, Shuguang Li and Hod Lipson, 'Structure – Reconfiguring Robots', IEEE Robotics & *Automation Magazine*, September 2013, pp 60–71.
6. Sung-Keun Kim et al, 'Construction Robot Path-Planning for Earthwork Operations', *Journal of Computing in Civil Engineering*, 17, 2003, pp 97–104.
7. Tadashi Kanzaki, 'Prospects for Automation and Robotics Revolutionizing Ordinary Construction Systems Through Advanced Information Technology', International Symposium on Automation and Robotics in Construction, 2003: www.iaarc.org/publications/proceedings_of_the_21st_isarc/prospects_for_automation_and_robotics_revolutionizing_ordinary_construction_systems_through_advanced_information_technology.html; David A Bradley and Derek W Seward, 'The Development, Control and Operation of an Autonomous Robotic Excavator', *Journal of Intelligent and Robotic Systems*, 21, 1998, pp 73–97; and Rezia M Molfino, Roberto Razzoli and Matteo Zoppi, 'Autonomous Drilling Robot for Landslide Monitoring and Consolidation', *Automation in Construction*, 17, 2008, pp 111–21.
8. Behrokh Khoshnevis et al, 'Mega-scale Fabrication by Contour Crafting', *International Journal of Industrial and System Engineering*, 1 (3), 2006, pp 301–20.
9. Sungwoo Lim et al, 'Developments in Construction-scale Additive Manufacturing Processes', *Automation in Construction*, 21, 2012, pp 262–8.
10. Hod Lipson and Melba Kurman, *Fabricated: The New World of 3D Printing*, John Wiley & Sons (Indianapolis, IN), 2013.
11. Giovanni Cesaretti et al, 'Building Components for an Outpost on the Lunar Soil by Means of a Novel 3D Printing Technology', *Acta Astronautica*, 93, 2014, pp 430–50.
12. Kirstin Petersen, Radhika Nagpal and Justin Werfel, 'TERMES: An Autonomous Robotic System for Three-dimensional Collective Construction', *Robotics: Science and Systems VII*, 2011.
13. Jan Willmann et al, 'Aerial Robotic Construction Towards a New Field of Architectural Research', *International Journal of Architectural Computing*, 10 (3), 2012, pp 439–60.
14. Steffen Reichert *et al*, 'Fibrous Structures: An Integrative Approach to Design Computation, Simulation and Fabrication for Lightweight, Glass and Carbon Fibre Composite Structures in Architecture Based on Biomimetic Design Principles', *Computer-Aided Design*, 52, 2014, pp 27–39.
15. Fabio Gramazio, Matthias Kohler and Jan Willmann, 'Authoring Robotic Processes', in Fabio Gramazio and Matthias Kohler, *◬ Made by Robots: Challenging Architecture at a Larger Scale*, May/June (no 3), 2014, pp 14–21.
16. James Clerk Maxwell, 'On the Calculation of the Equilibrium and Stiffness of Frames', *Philosophical Magazine* Series 4, 27, 1864, pp 294–9.
17. Kenneth Chun-Wai Cheung, 'Digital Cellular Solids: Reconfigurable Composite Materials', PhD thesis, Massachusetts Institute of Technology (MIT), Cambridge, MA, 2012: http://dspace.mit.edu/handle/1721.1/78199.
18. Kenneth Chun-Wai Cheung and Neil Gershenfeld, 'Reversibly Assembled Cellular Composite Materials', *Science*, 341 (6151), 2013, pp 1219–21.
19. Sam Calisch, 'Physical Finite Elements', Master's thesis, Massachusetts Institute of Technology (MIT), Cambridge, MA, 2014: http://cba.mit.edu/docs/theses/14.08.Calisch.pdf.
20. Michael F Ashby, 'Process Cost', *Materials Selection in Mechanical Design*, Elsevier Science (Burlington, MA), 2010.
21. *Ibid*.