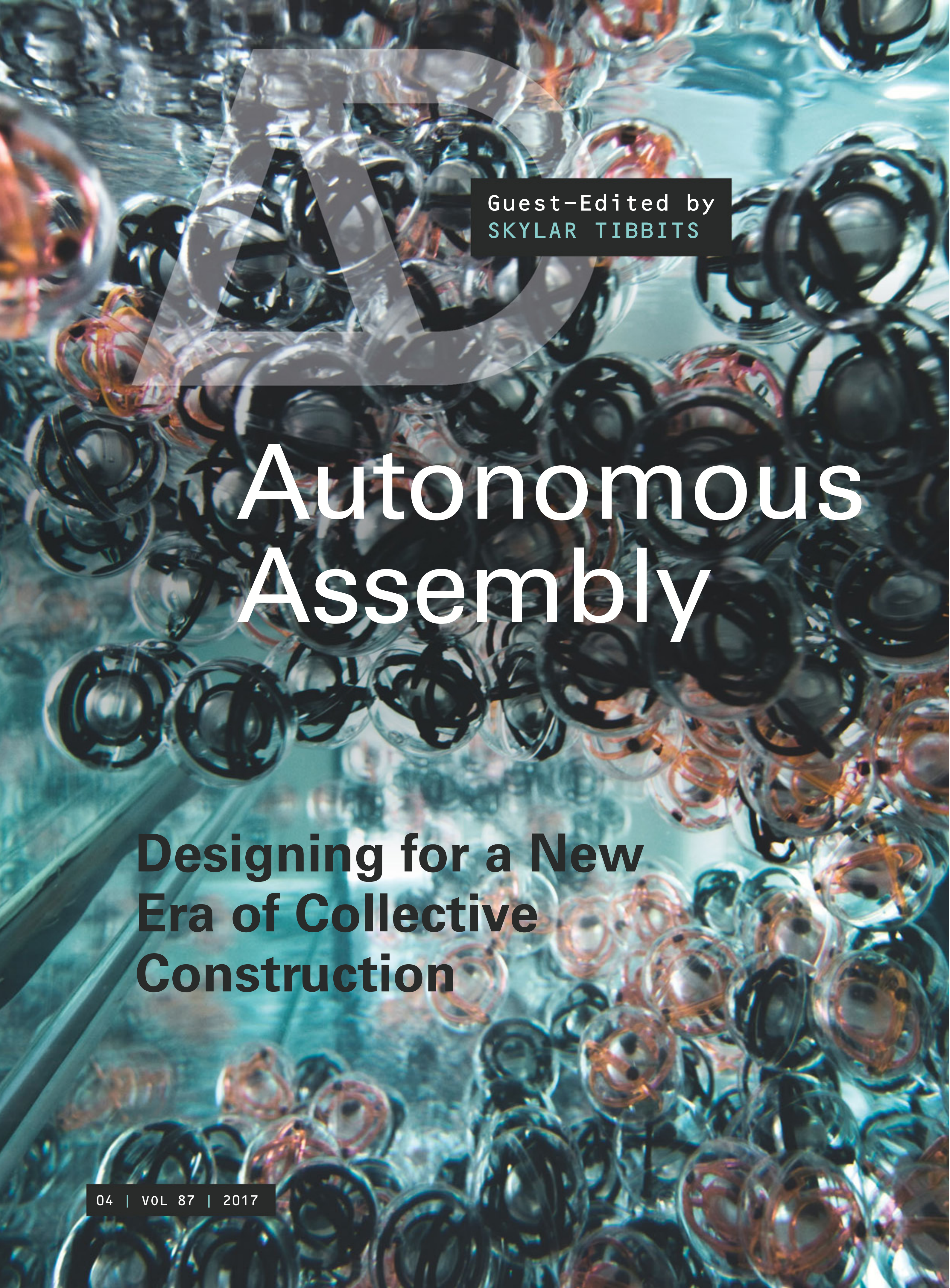

Guest-Edited by
SKYLAR TIBBITS

Autonomous Assembly

Designing for a New Era of Collective Construction

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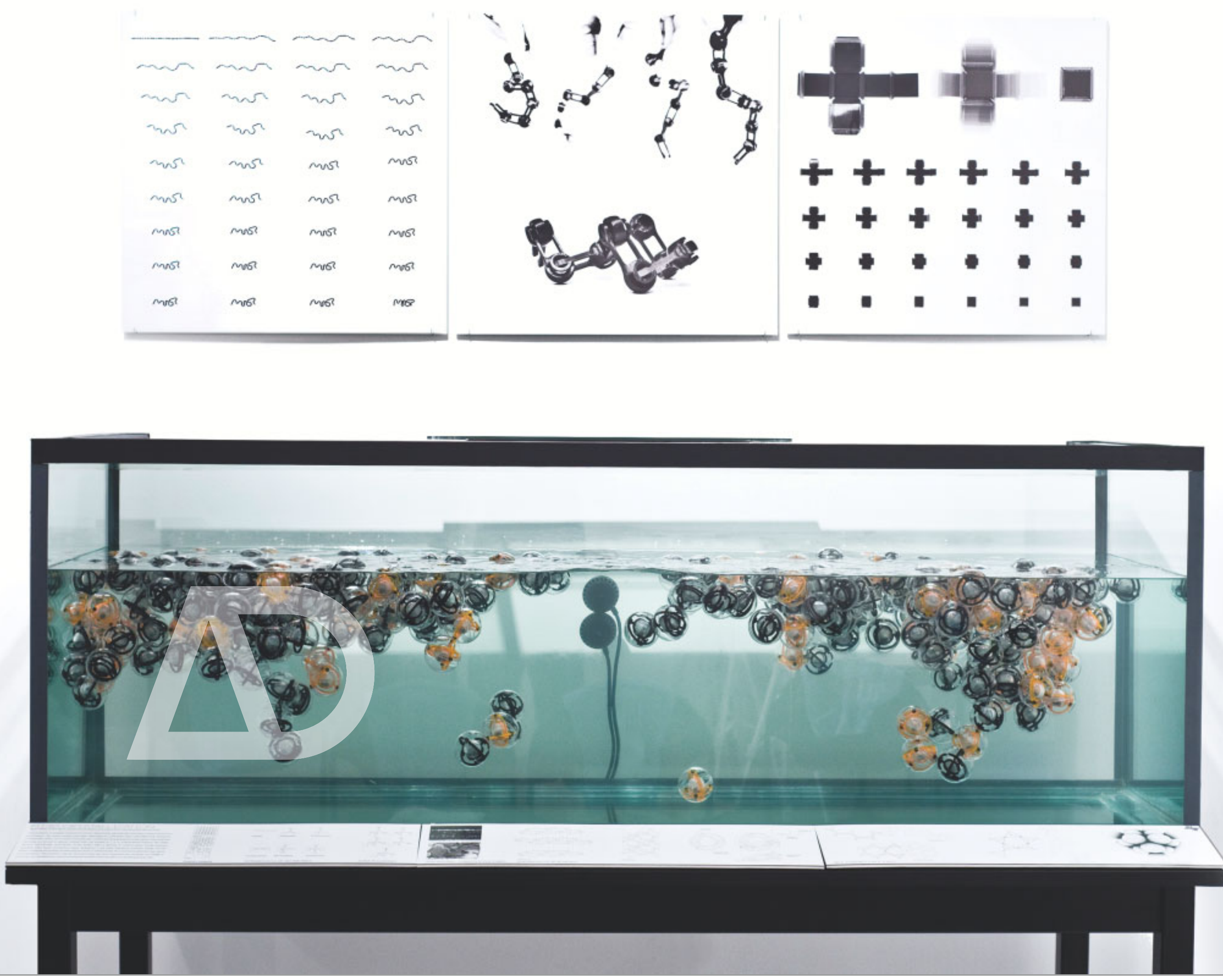

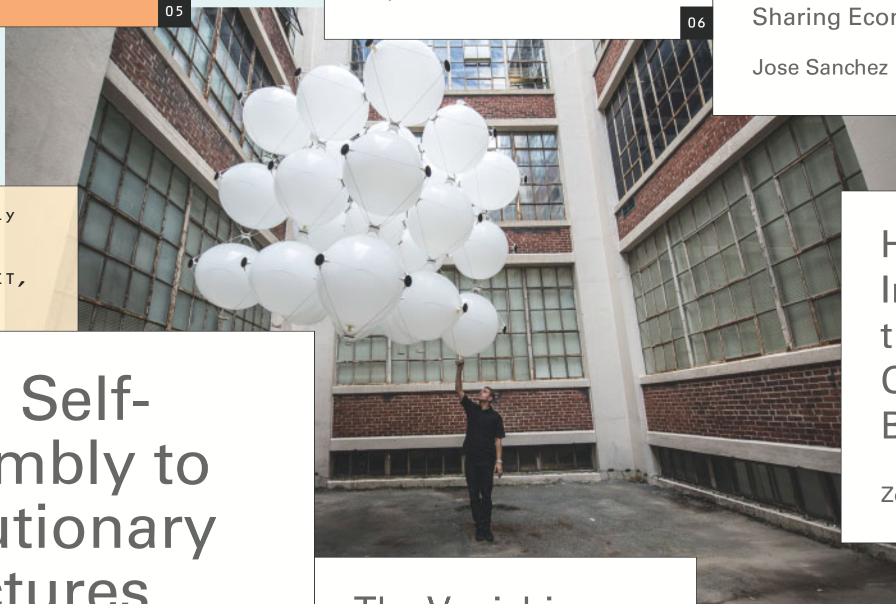

Self-Assembly Lab, Aerial Balloon Assembly, MIT, 2014

Termite mounds, Otjiwarongo, Namibia, 2011

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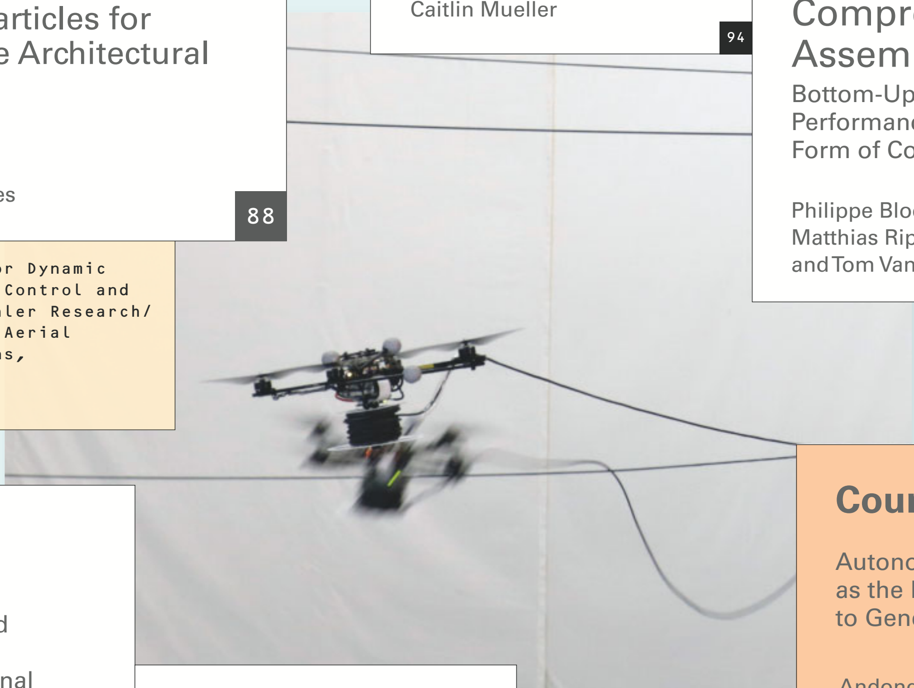
Kieran Murphy, Leah Roth, Dan Peterman and Heinrich Jaeger, Project Z-Form: arch, Experimental Station, Chicago, 2016



Institute for Dynamic Systems and Control and Gramazio Kohler Research/ETH Zurich, Aerial Constructions, Zurich, 2013–15

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Front, back and inside covers: Self-Assembly Lab, Fluid Crystallisation, Massachusetts Institute of Technology (MIT), 2013. © Self-Assembly Lab, MIT

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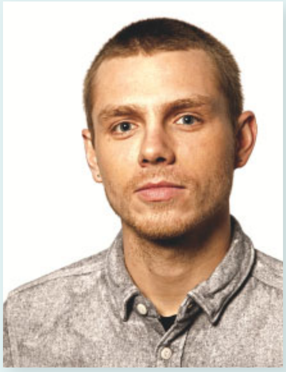
GUEST-EDITOR

SKYLAR TIBBITS



Skylar Tibbits is the founder and co-director (with Jared Laucks) of the Self-Assembly Lab at the Massachusetts Institute of Technology (MIT), and Assistant Professor of Design Research in the Department of Architecture. His invention of 4D printing has established a unique area of design research focused on programmable materials that can sense and actuate in response to internal or external stimuli. From self-transforming carbon fibre to responsive textiles, active printed wood and 'smart' leather, these have a variety of novel material capabilities and industrial applications.

His work on self-assembly has demonstrated the scalability of this natural construction phenomenon with synthetic design and fabrication systems. The research is the first to apply the principles of self-assembly to construction and manufacturing: for example, a cellphone that can build itself, a chair that self-assembles, and the self-construction of aerial balloons. Including symmetric and crystalline lattices, non-homogenous geometries and differentiated complexity, the work has shown autonomous assembly in diverse conditions such as fluid-filled tanks, turbulent airflow chambers and helium-filled environments.

Tibbits has a professional degree in architecture and a minor in experimental computation from Philadelphia University, and a dual-degree master's in design computation and computer science from MIT. He has worked at a number of renowned design offices including Zaha Hadid Architects, Asymptote Architecture and Point b Design, and is the founder of multidisciplinary design practice SJET LLC. He has designed and built large-scale installations and exhibited in galleries around the world, including the Guggenheim Museum in New York. His work has been published extensively, for example in the *New York Times*, *Wired* and *Fast Company*, as well as in various peer-reviewed journals and books. He is the author of the book *Self-Assembly Lab: Experiments in Programming Matter* (Routledge, 2016), and also Editor-in-Chief of the journal *3D Printing and Additive Manufacturing*.

Awards include the LinkedIn Next Wave Award for Top Professionals under 35 (2016), R&D Innovator of the Year (2015), National Geographic Emerging Explorer (2015), an Inaugural WIRED Fellowship (2014), the Architectural League Prize (2013), Ars Electronica Next Idea Award (2013), and a TED Senior Fellowship (2012). In 2008 he was named a Revolutionary Mind by *SEED* magazine.

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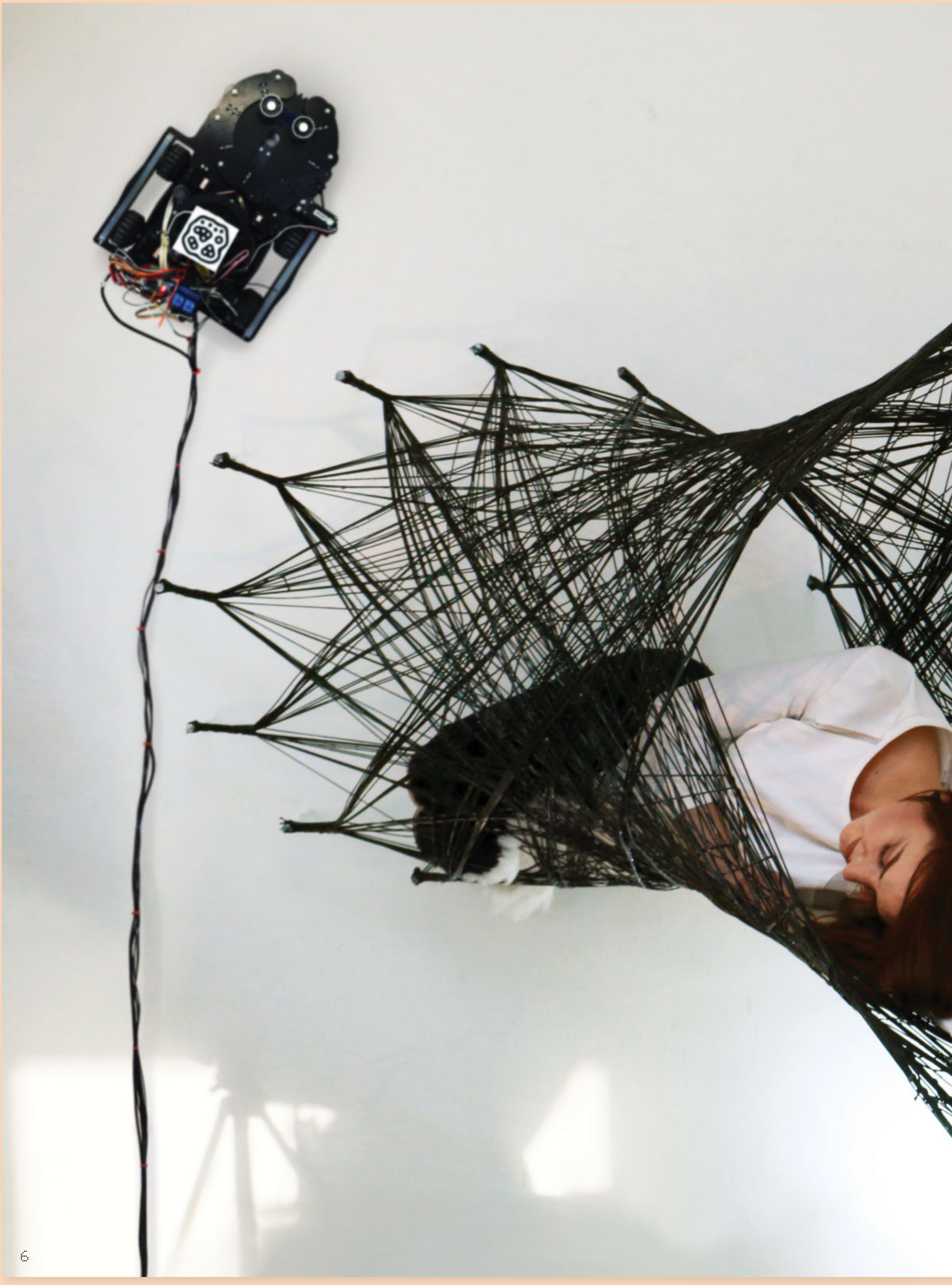
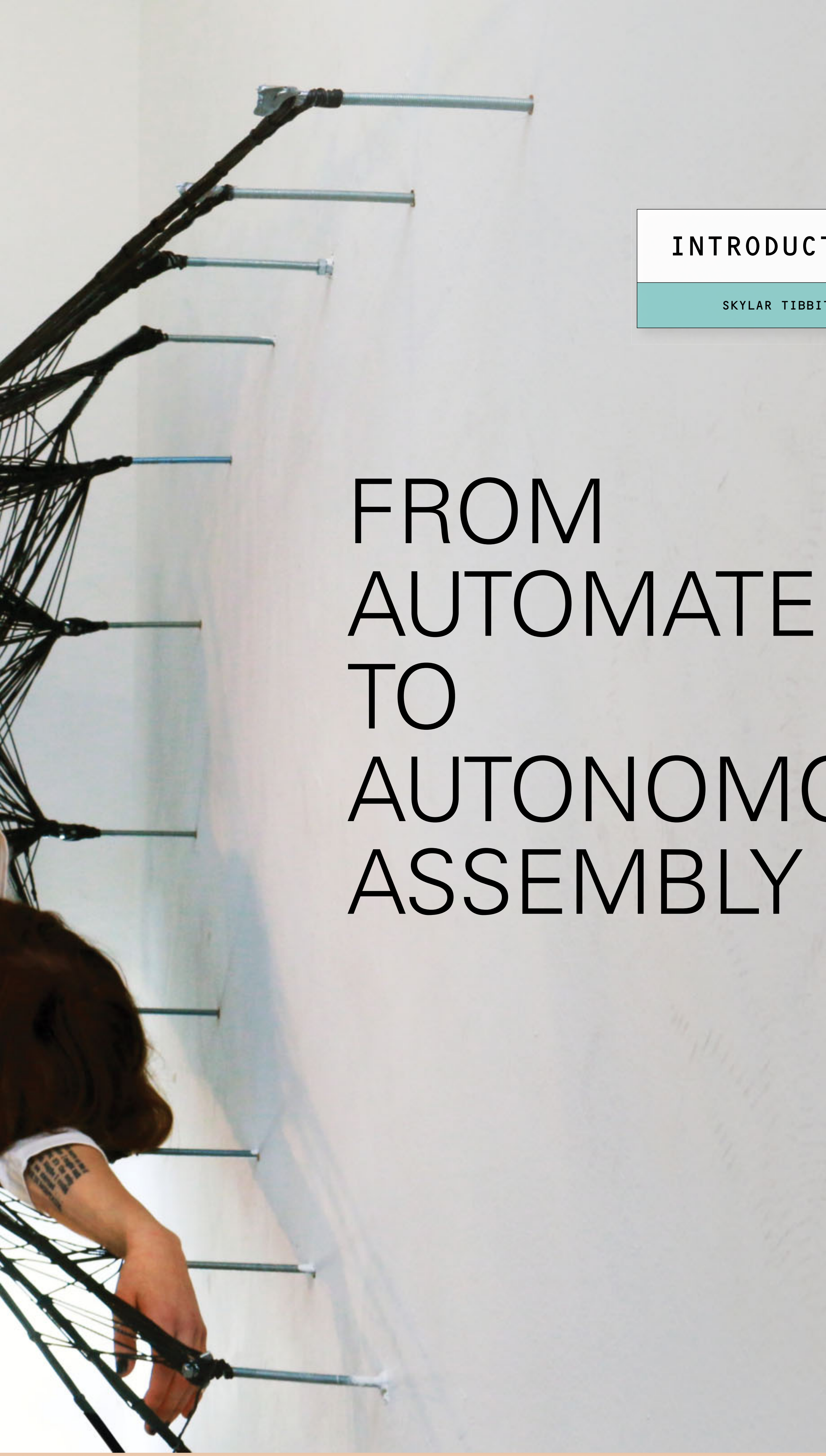




INTRODUCTION

SKYLAR TIBBITS

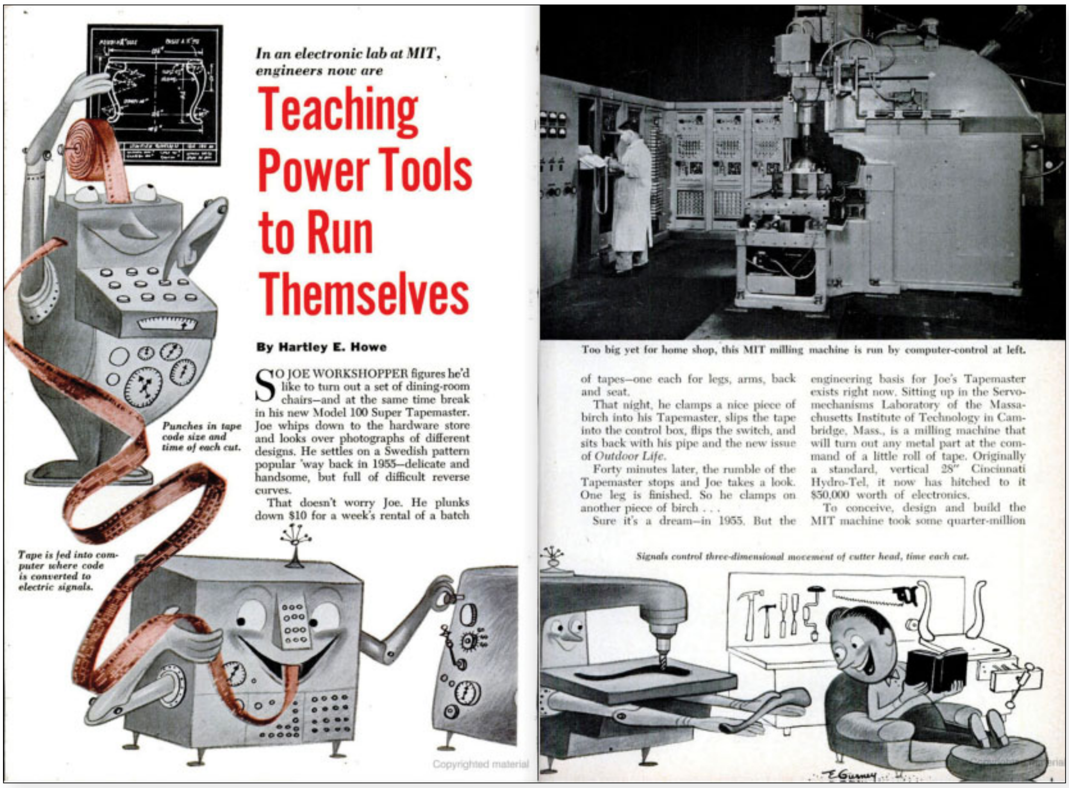
FROM AUTOMATED TO AUTONOMOUS ASSEMBLY

Maria Yablonina, Mobile robotic fabrication system for filament structures, ITECH thesis, Institute for Computational Design (ICD), University of Stuttgart, 2015

The project demonstrates a radically new fabrication process with a carbon-fibre composite system based on the collaboration of multiple semi-autonomous wall-climbing robots.

Construction poses one of the most immediate challenges to architecture as a discipline. With tremendous energy consumption, inefficiencies, cost, timelines, labour shortages and litigation dominating the construction landscape, we urgently need a new perspective on assembly. Since the introduction of computation and digital fabrication in the 1950s and 1960s, architects have been exploring ideas for automation in design and construction. However, rapid advances in these technologies have brought with them a major challenge. Despite the digital fabrication of our new customised and highly performative materials, we are still left with the problem of manual assembly, where humans or machines spend increasing amounts of costly time and energy laboriously building complex structures.

Many have argued for the free complexity and mass-customisation offered by digital fabrication and the efficiency of industrial robotics,[1] an approach that has led to the rise of numerous pavilions and bespoke installations, as seen in MoMA's PS1 in New York and the annual Serpentine Pavilion projects in London. Sophisticated software and digital fabrication technologies have enabled young architects to build experimental structures that test the limits of our digital and physical capabilities. And architects have collectively pushed the boundaries of mass-customised complexities, producing thousands of unique components requiring thousands of connections that demand hours, days, months or even years of manual assembly. The energy input and man-hours necessary to build these structures, however, has generally been overlooked. They have been celebrated with impressive simulations, beautifully nested cut-sheets, videos of CNC machines running 24/7 and stunning photographs, hiding the assembly problem.


In an electronic lab at MIT, engineers now are

Teaching Power Tools to Run Themselves

By Hartley E. Howe

SO JOE WORKSHOPPER figures he'd like to turn out a set of dining-room chairs—and at the same time break in his new Model 100 Super Tapemaster. Joe whips down to the hardware store and looks over photographs of different designs. He settles on a Swedish pattern popular 'way back in 1955—delicate and handsome, but full of difficult reverse curves.

That doesn't worry Joe. He plunks down $10 for a week's rental of a batch of tapes—one each for legs, arms, back and seat.

That night, he clamps a nice piece of birch into his Tapemaster, slips the tape into the control box, flips the switch, and sits back with his pipe and the new issue of *Outdoor Life*.

Forty minutes later, the rumble of the Tapemaster stops and Joe takes a look. One leg is finished. So he clamps on another piece of birch . . .

Sure it's a dream—in 1955. But the engineering basis for Joe's Tapemaster exists right now. Sitting up in the Servomechanisms Laboratory of the Massachusetts Institute of Technology in Cambridge, Mass., is a milling machine that will turn out any metal part at the command of a little roll of tape. Originally a standard, vertical 28" Cincinnati Hydro-Tel, it now has hitched to it $50,000 worth of electronics.

To conceive, design and build the MIT machine took some quarter-million

Punches in tape code size and time of each cut.

Tape is fed into computer where code is converted to electric signals.

Too big yet for home shop, this MIT milling machine is run by computer-control at left.

Signals control three-dimensional movement of cutter head, time each cut.

Spread from *Popular Science*, 1955

The article illustrated the first CNC machine at the Massachusetts Institute of Technology (MIT). The technology led to today's digital fabrication and mass-customisation capabilities that have challenged traditional labour-intensive construction processes.

Architects have collectively pushed the boundaries of mass-customised complexities, producing thousands of unique components requiring thousands of connections that demand hours, days, months or even years of manual assembly.

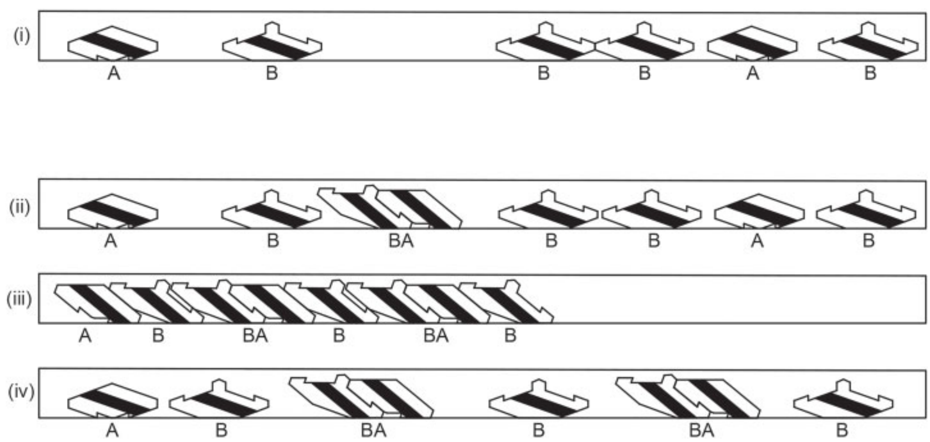
ROBOTICS AND CONSTRUCTION

The introduction of industrial robotics in architecture over the past decade appeared to address the manual assembly problem that mass-customisation created in the early 2000s, if only momentarily, with the emergence of beautiful and intricate robotically assembled structures. From undulating walls to complex pavilions, robots are able to fabricate and build metre-scale constructs. The concept of automation has thus been brought to the forefront of the field, and while certainly upon us as a future scenario for architecture and construction given rapid urbanisation, increasing demands on housing markets and pressure for greater efficiency, purely automated robotic assembly may lead to just another generation of mass-standardised housing or purely efficiency-driven solutions. Autonomous assembly, on the other hand, represents a longer-term vision for flexible and adaptive construction processes where design and assembly coalesce as a means of production; where working from the bottom up with robots, materials and humans provides more agency for components in a process of collective construction.

Outside of academia's recent explorations in industrial robotics, the assembly problem is a much greater challenge that cannot be solved by simply bringing in more robots. The construction of our built environment is becoming a global issue as it contributes 25 to 40 per cent of the world's total carbon emissions; labour shortages are on the rise; and vast inefficiencies are causing increases in the cost of building.[2] In the US, labour productivity in construction has actually fallen over the last 40 years, while in many other sectors such as automotive and consumer electronics, efficiency has risen dramatically. Countries around the world are taking note of these challenges. For example, by 2020 China will construct 30 per cent of its new buildings using prefabricated processes to increase productivity and reduce energy-intensive on-site resources.[3] Similarly, the UK has as its target a 50 per cent reduction in greenhouse gas emissions caused by the built environment by 2025. Novel approaches to construction such as autonomous assembly are thus required to reduce the negative impact on our planet, and to avoid relegating the AEC industries to that of standardised industrial production, or creating a greater divide between design and construction. It is imperative that we find a new model.

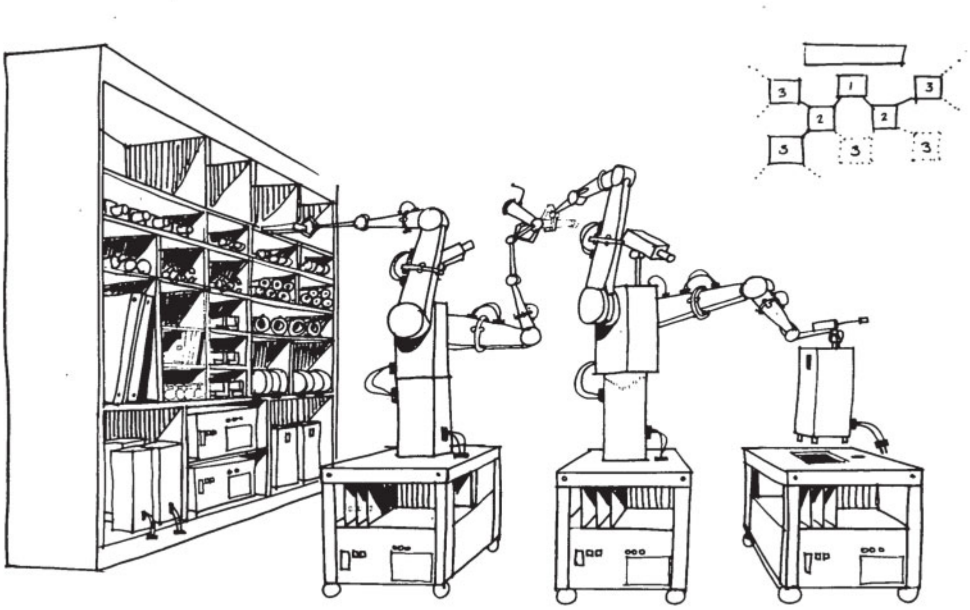
SELF-ASSEMBLY

In 1957, the British mathematician Lionel Penrose introduced self-reproducing non-electronic wooden blocks that could be agitated to promote the passing of information from parent to offspring to demonstrate non-biological replication.[4] More recently, Hod Lipson demonstrated self-replication in robotics, where a number of blocks assembled themselves into a structure that could build another self-similar structure with full capability to assemble another.[5] And in his book *An Evolutionary Architecture* (1995), John Frazer described his Universal Constructor, a working model of an interactive, intelligent environment made up of communicating modules that could 'formulate a coded set of responsive instructions (what we call a "genetic language of architecture")'.[6] All of these examples realised physical and synthetic systems, at the macro scale, that have some degree of autonomy and functionality. However, in biological systems there is autonomy through self-assembly at nearly every scale, from cellular division to human growth and repair. Physical components interact with one another as well as with their environment, and come together to build higher-order structures in which functionality and design emerge autonomously. This process has great potential for the assembling of small- and large-scale structures, yet is hardly utilised in current construction models.



Drawing representing Lionel Penrose's self-reproducing wooden blocks of 1957

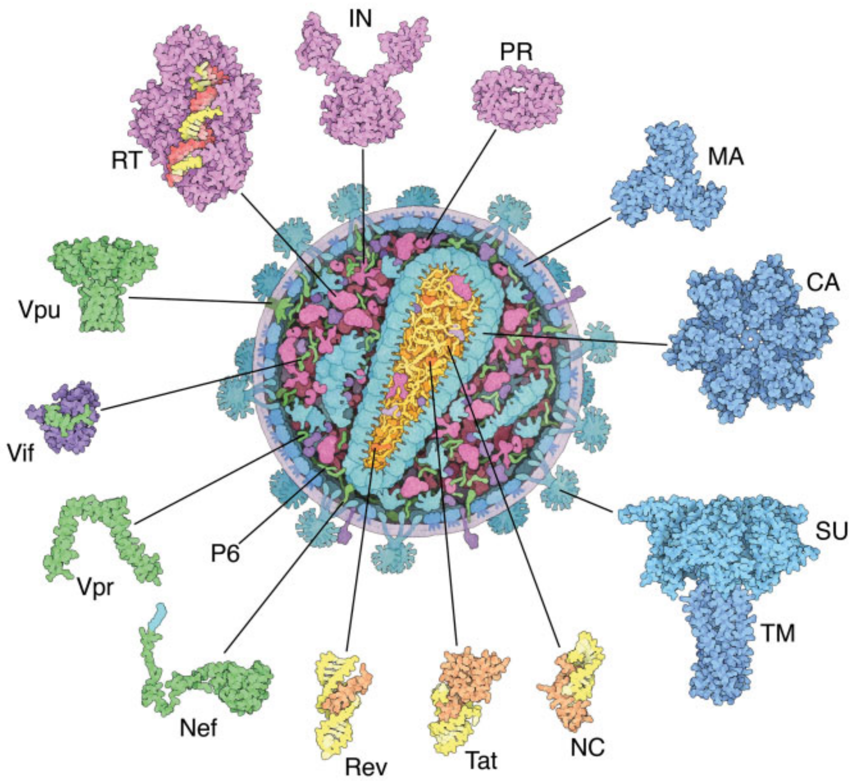
Starting with an initial pattern, when the blocks are agitated and bump into one another they pass information and promote the assembly of other pairings based on the original. Adapted by permission from Macmillan Publishers Ltd: *Nature*, Vol 179, 8 June 1957.



NASA, Proposed demonstration of simple robot self-replication, 1980

Drawing depicting robots assembling other robots from a library of parts, one of the first concepts of self-replicating robots as a future scenario for manufacturing in space.

This issue of AD looks at an alternative model, of autonomous assembly and collective construction whereby components can assemble themselves, working together with humans and robots.



David S Goodsell, Structure of HIV, RCSB Protein Data Bank, 2015

Artist's representation of the various components that assemble to form the HIV virus. This biological principle of self-assembly can be translated to small- and large-scale structures as a new model for construction.

Since the Industrial Revolution, humans have become particularly adept at building complex structures like cars, planes, consumer electronics and even buildings. However, nearly all of our human-scale structures are designed and built from the top down, whereby the design is passed to humans or machines to rationalise and force materials into place. As the size and complexity of our structures increases, a top-down, energy-intensive and time-consuming method no longer works. Self-assembly, on the other hand, emerges from the bottom up, and can be found in extremely large-scale systems such as weather patterns, the formation of geological features and even whole planets, as well as in nature and synthetic systems, all of which can help us rethink the construction of our built environment.[7]

With the introduction of any new tool, we inevitably ask the question of whether it will replace humans. Will computer-aided design (CAD) replace draftspeople? Will computation replace architects and designers? Will industrial robotics replace construction workers? Sophisticated software and computational programs now include optimisation capabilities that are leading to design solutions that outperform human concepts.[8] Similarly, robots can build 24/7 without getting tired, placing components with extreme precision and repeatability. In nearly every manufacturing sector, products are being assembled with industrial automation. However, manufacturing remains expensive and energy intensive, and manufacturers are thus continually chasing two possible solutions: cheaper labour, or more precise and lower-cost robotics that can replace human tasks. This issue of AD looks at an alternative model, of autonomous assembly and collective construction whereby components can assemble themselves, working together with humans and robots, to build structures that would not otherwise have been possible.

AUTOMATION IN CONSTRUCTION

Construction is still one of the least automated industries, a technological lag often blamed on issues of regulation, scale, complexity, lack of funding or litigation. However, these constraints are often just as severe in other industries. The medical and automotive industries, for example, have stringent safety regulations. And the aviation industry can produce planes of extreme size using building-scale robots and people swarming around the factory to assemble them with unheard-of efficiency in construction. Whatever the reason for its current lack of automation, given the incredible resources, time and cost associated with construction today it is important that the sector finds the incentives and mechanisms to innovate in this area. But automation should not be the only goal; design freedom with customisation and greater material performance needs to remain paramount.

Airbus A380 assembly, Toulouse, France, 2014

The process of assembling an Airbus A380 with building-scale robots, people and structures moving around the plane during construction.

One of the fundamental challenges in automated construction is the one-off, highly customised nature of architecture compared with industrial manufacturing. Mass-produced, self-similar products are manufactured with amazing speed and accuracy, utilising the precision and repetitive capabilities of industrial robotics. However, if every product were unique, the robots would need to be reprogrammed in between each product change, and the affordance of speed or efficiency would drop dramatically. Similarly, when unknown conditions arise, robots would have difficulty adapting to these on-the-fly changes as quickly as humans can.

Another major challenge with robotic construction is limited scalability. A single, very large robot could be deployed to build a structure, but it would be restricted by its reach or dexterity for minute details. A more scalable approach could use robots that have autonomous mobility, but these would need to be sophisticated enough to navigate complex construction sites, communicate with one another, and have the ability to adapt to changing environments, unknown conditions and many other technical challenges. An alterative method currently being explored is 3D-printed buildings with large gantry-style machines; however, this lacks scalability due to the 'skyscraper problem': it is not practical to build a machine that is the size of a skyscraper to then print a one-off building. Gantry-style machines that print buildings or objects smaller than themselves are a challenging solution for full-scale architecture unless relegated to mass-produced homes or smaller-scale components that are then assembled manually. Neither industrial robots nor printed buildings therefore truly address the scalability demands of architecture's highly complex conditions and unstructured environments. A more distributed and less centralised approach to assembly is required that also provides robustness to failure and adaptation when unknown conditions arise.

Institute for Advanced Architecture of Catalonia (IAAC), Minibuilders, IAAC, Barcelona, 2014

Small robots work collectively to print large structures. This model proposes a more distributed and scalable alternative as a method of 3D-printing architecture without gantry-style machines.

AUTONOMOUS VERSUS AUTOMATED

This issue of AD proposes an approach to construction that is not about automation or replacing a specific human/robot task, but rather focuses on autonomy, the ability of materials, components or even processes to come together independently and have agency. This does not only mean autonomous robots assembling buildings; the future of construction might include insect fabrication, smart components that can assemble themselves, or collaborative structures with swarms of people and new material phenomena. This suggests a completely new model, that of autonomous assembly and collective construction by humans, robots and materials. It paints a picture of material coalescence rather than top-down component construction processes, where the materials come together autonomously not just to be faster, better or cheaper, but rather strive for scalability, adaptability, reconfigurability and any number of the life like qualities found in our bottom-up world.

In their articles, Jose Sanchez (pp 16–21) and Zorana Zeravcic (pp 22–7) introduce new digital tools and simulation possibilities needed to design for autonomous assembly. The principles of self-assembly are shown through Robin Meier's work on insect light patterns (pp 38–43), which forms the basis of Kirstin Petersen's and Radhika Nagpal's work on swarm robotics (pp 44–9), and the MIT Self-Assembly Lab's research on macro-scale self-assembly structures (pp 28–37). Marcelo Coelho then demonstrates interaction and pattern formation with human crowds at the stadium scale (pp 50–59). Mariana Ibañez and Simon Kim focus on digital-to-physical feedback loops in interactive human and material systems (pp 60–65), while Benjamin Aranda and Chris Lasch highlight the reconfiguration of material geometries and crystallisation patterns for architectural design (pp 66–73).

Mediated Matter Group, Silk Pavilion, MIT Media Lab, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2013

Top view of the pavilion as approximately 1,500 silkworms construct the fibrous composite. This insect-based construction method utilises self-organising principles to grow a structure without traditional human or robot assembly.