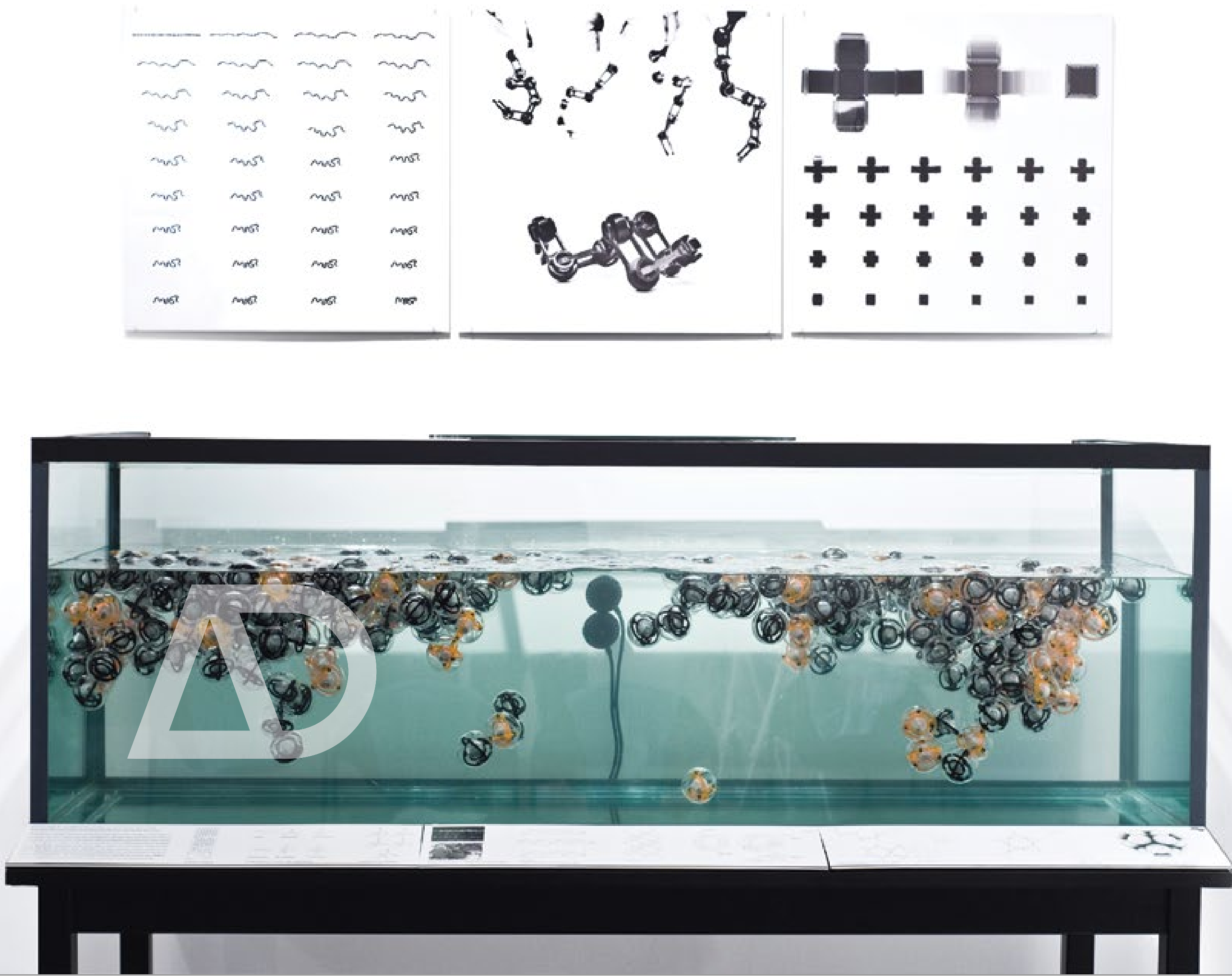
Guest-Edited by
SKYLAR TIBBITS

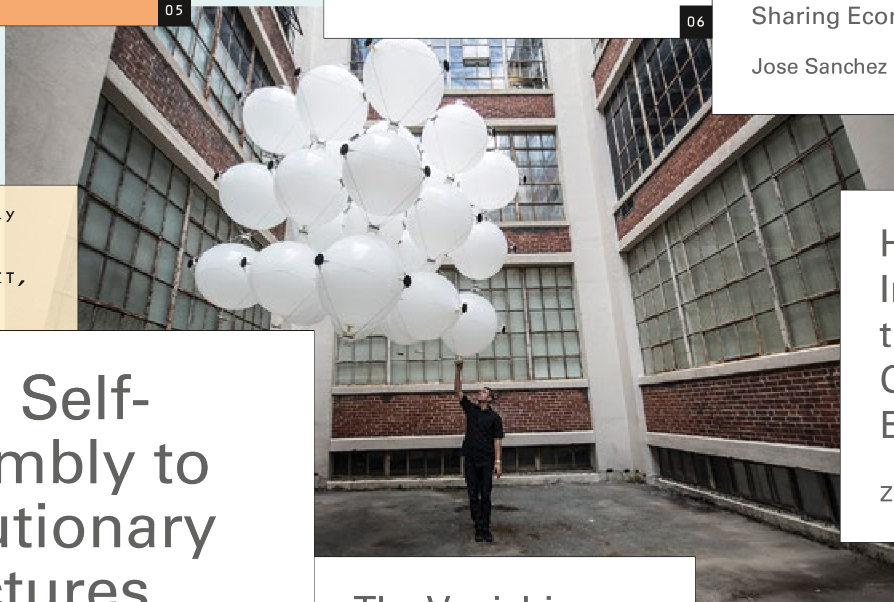
Autonomous Assembly

Designing for a New Era of Collective Construction

ARCHITECTURAL DESIGN

July/August 2017
Profile No 248





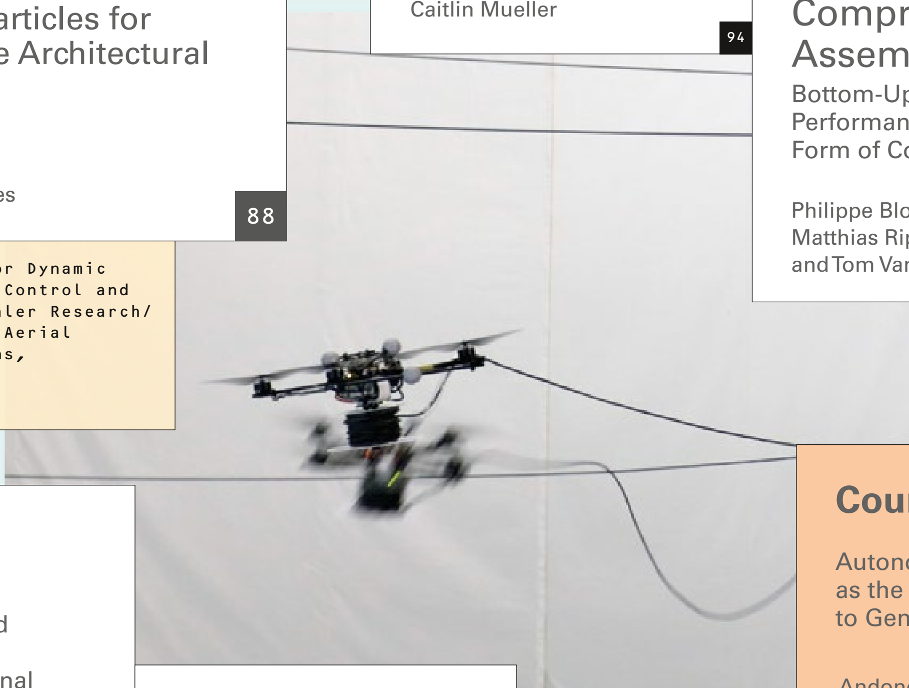
Self-Assembly Lab, Aerial Balloon Assembly, MIT, 2014

Termite mounds, Otjiwarongo, Namibia, 2011

ISSN 0003-8504
ISBN 978-1119-102359

Guest-Edited by **Skylar Tibbits**

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

Editorial Offices
John Wiley & Sons
9600 Garsington Road
Oxford
OX4 2DQ

T +44 (0)1865 776868

Consultant Editor
Helen Castle

Managing Editor
Caroline Ellerby
Caroline Ellerby Publishing

Freelance Contributing Editor
Abigail Grater

Publisher
Paul Sayer

Art Direction + Design
CHK Design:
Christian Küsters
Harrison Dew

Production Editor
Elizabeth Gongde

Prepress
Artmedia, London

Printed in Italy by Printer Trento Srl

ARCHITECTURAL DESIGN

July/August
2017

Profile No.
248

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

04/2017

Journal Customer Services
For ordering information, claims and any enquiry concerning your journal subscription please go to www.wileycustomerhelp.com/ask or contact your nearest office.

Americas
E: cs-journals@wiley.com
T: +1 781 388 8598 or +1 800 835 6770 (toll free in the USA & Canada)

Europe, Middle East and Africa
E: cs-journals@wiley.com
T: +44 (0)1865 778315

Asia Pacific
E: cs-journals@wiley.com
T: +65 6511 8000

Japan (for Japanese-speaking support)
E: cs-japan@wiley.com
T: +65 6511 8010 or 005 316 50 480 (toll-free)

Visit our Online Customer Help available in 7 languages at www.wileycustomerhelp.com/ask

Print ISSN: 0003-8504
Online ISSN: 1554-2769

Prices are for six issues and include postage and handling charges. Individual-rate subscriptions must be paid by personal cheque or credit card. Individual-rate subscriptions may not be resold or used as library copies.

All prices are subject to change without notice.

Identification Statement
Periodicals Postage paid at Rahway, NJ 07065. Air freight and mailing in the USA by Mercury Media Processing, 1850 Elizabeth Avenue, Suite C, Rahway, NJ 07065, USA.

USA Postmaster
Please send address changes to *Architectural Design,* John Wiley & Sons Inc., c/o The Sheridan Press, PO Box 465, Hanover, PA 17331, USA

Rights and Permissions
Requests to the Publisher should be addressed to:
Permissions Department
John Wiley & Sons Ltd
The Atrium
Southern Gate
Chichester
West Sussex PO19 8SQ
UK

F: +44 (0)1243 770 620
E: Permissions@wiley.com

Subscribe to AD
AD is published bimonthly and is available to purchase on both a subscription basis and as individual volumes at the following prices.

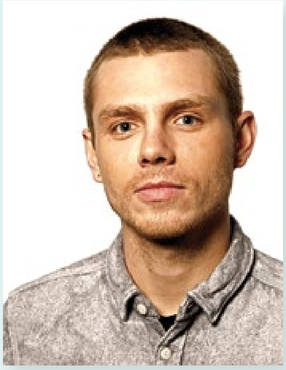
Prices
Individual copies: £24.99 / US$39.95
Individual issues on AD App for iPad: £9.99 / US$13.99
Mailing fees for print may apply

Annual Subscription Rates
Student: £84 / US$129 print only
Personal: £128 / US$201 print and iPad access
Institutional: £275 / US$516 print or online
Institutional: £330 / US$620 combined print and online
6-issue subscription on AD App for iPad: £44.99 / US$64.99

ABOUT THE

GUEST-EDITOR

SKYLAR TIBBITS

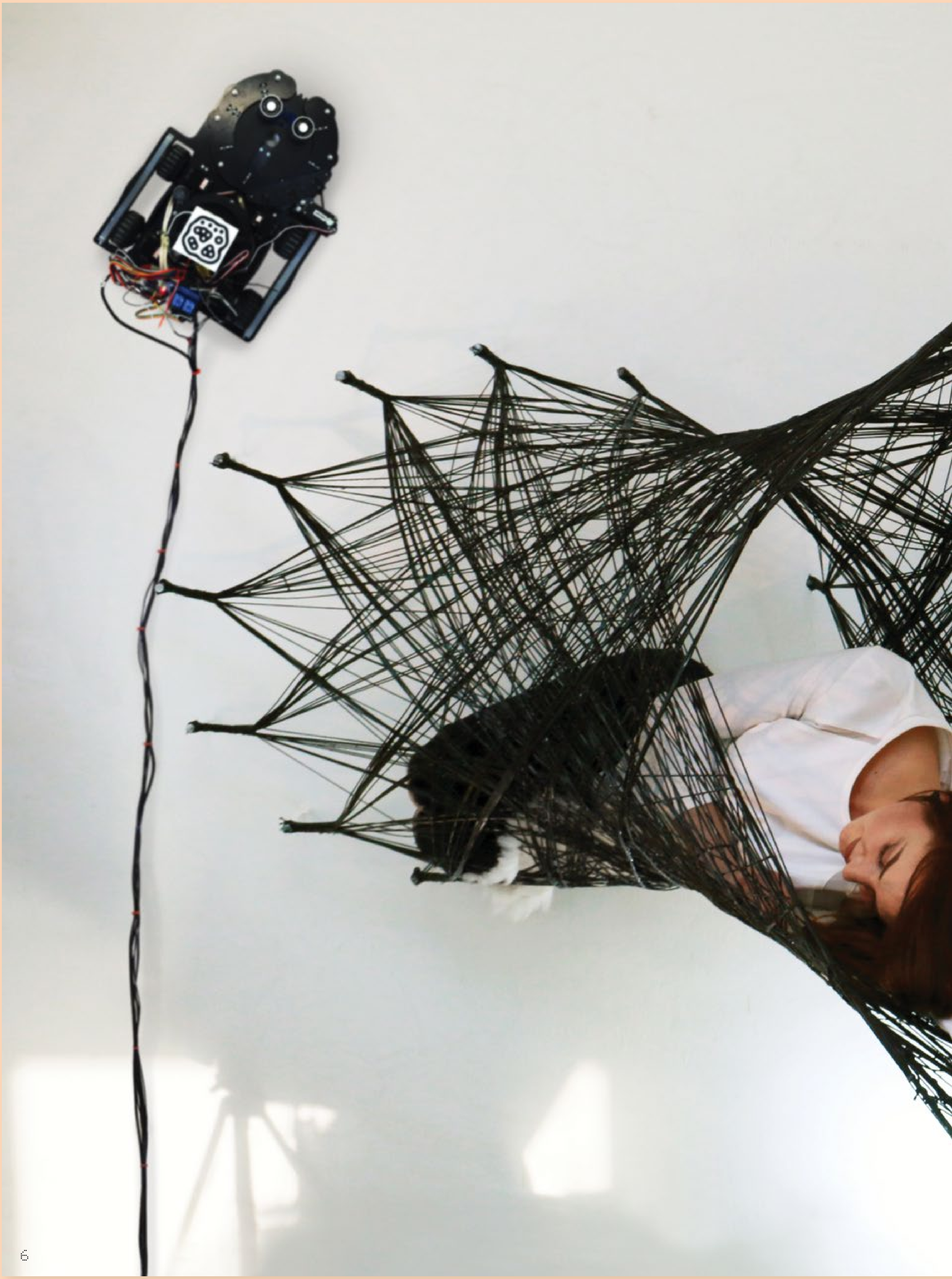


Skylar Tibbits is the founder and co-director (with Jared Laucks) of the Self-Assembly Lab at the Massachusetts Institute of Technology (MIT), and Assistant Professor of Design Research in the Department of Architecture. His invention of 4D printing has established a unique area of design research focused 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.



INTRODUCTION

SKYLAR TIBBITS

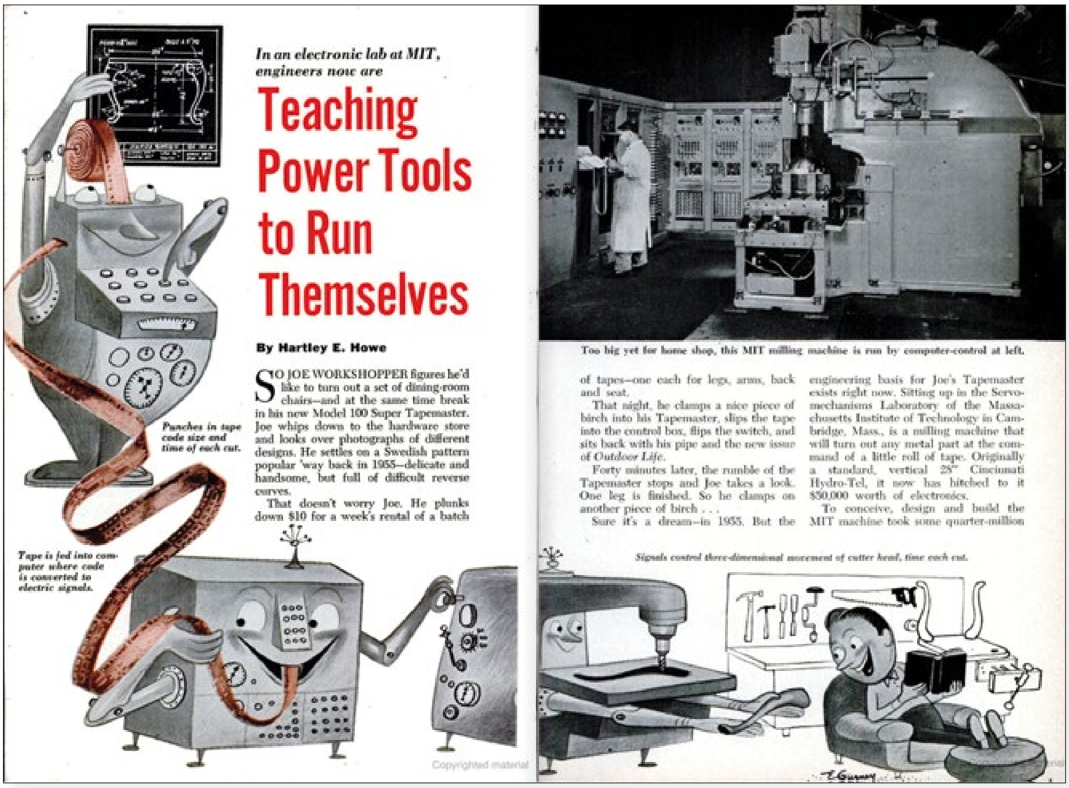
FROM AUTOMATED TO AUTONOMOUS ASSEMBLY

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 Servo-mechanisms 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.

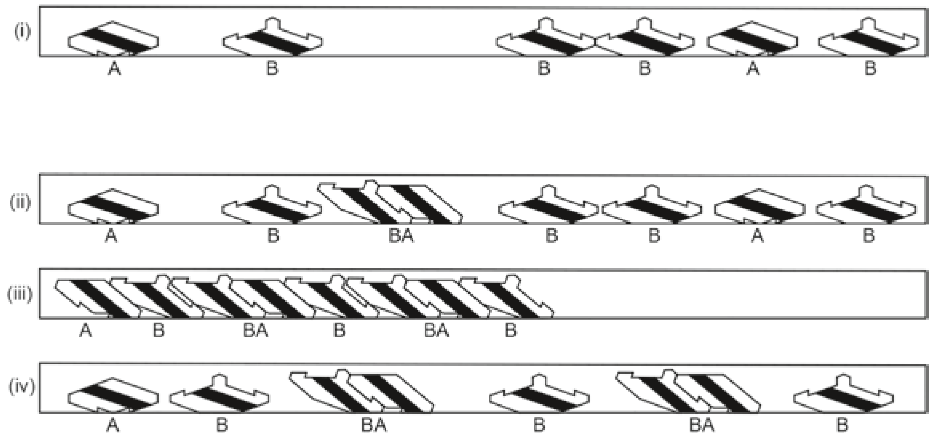
ROBOTICS AND CONSTRUCTION

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.

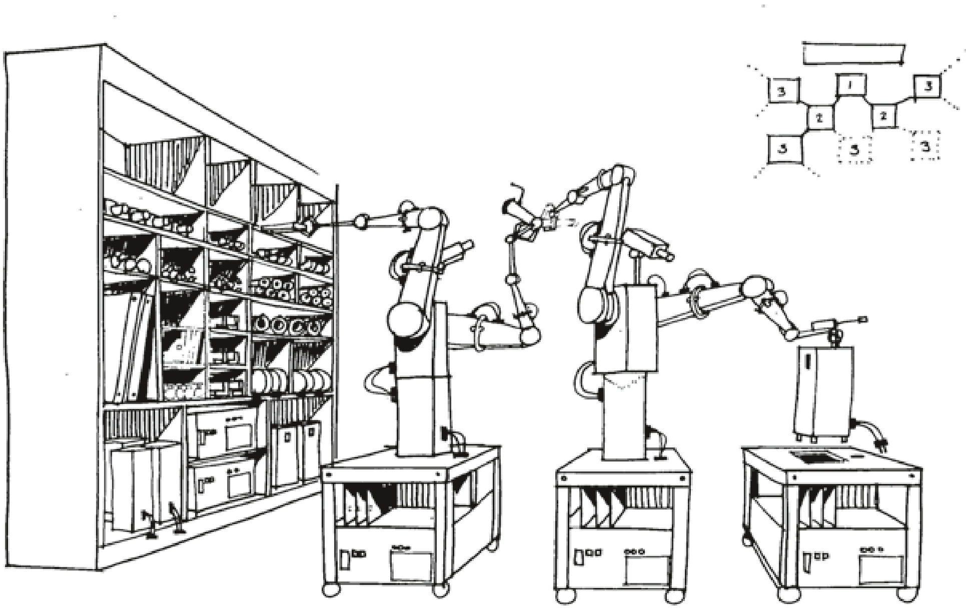
SELF-ASSEMBLY

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

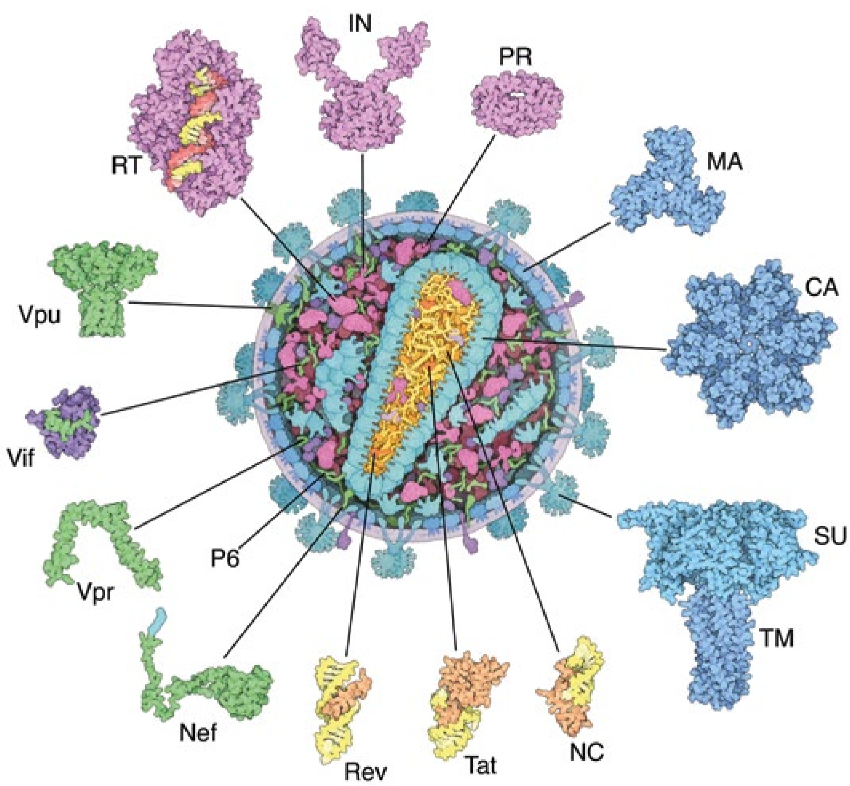
Starting with an initial pattern, when the blocks are agitated and bump into one another they pass information and promote the assembly of other pairings based on the original. Adapted by permission from Macmillan Publishers Ltd: *Nature*, Vol 179, 8 June 1957.



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

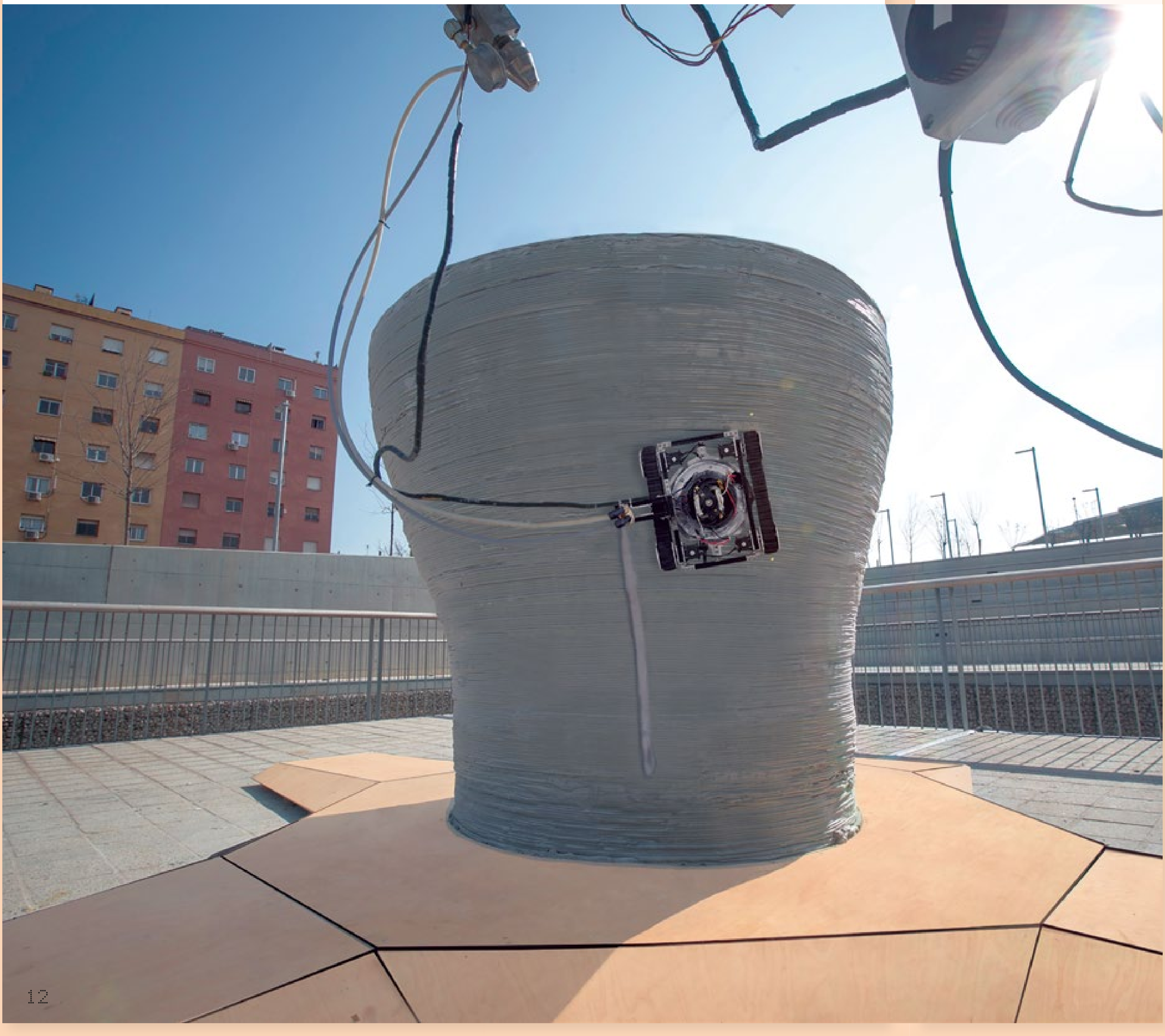
The process of assembling an Airbus A380 with building-scale robots, people and structures moving around the plane during construction.

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

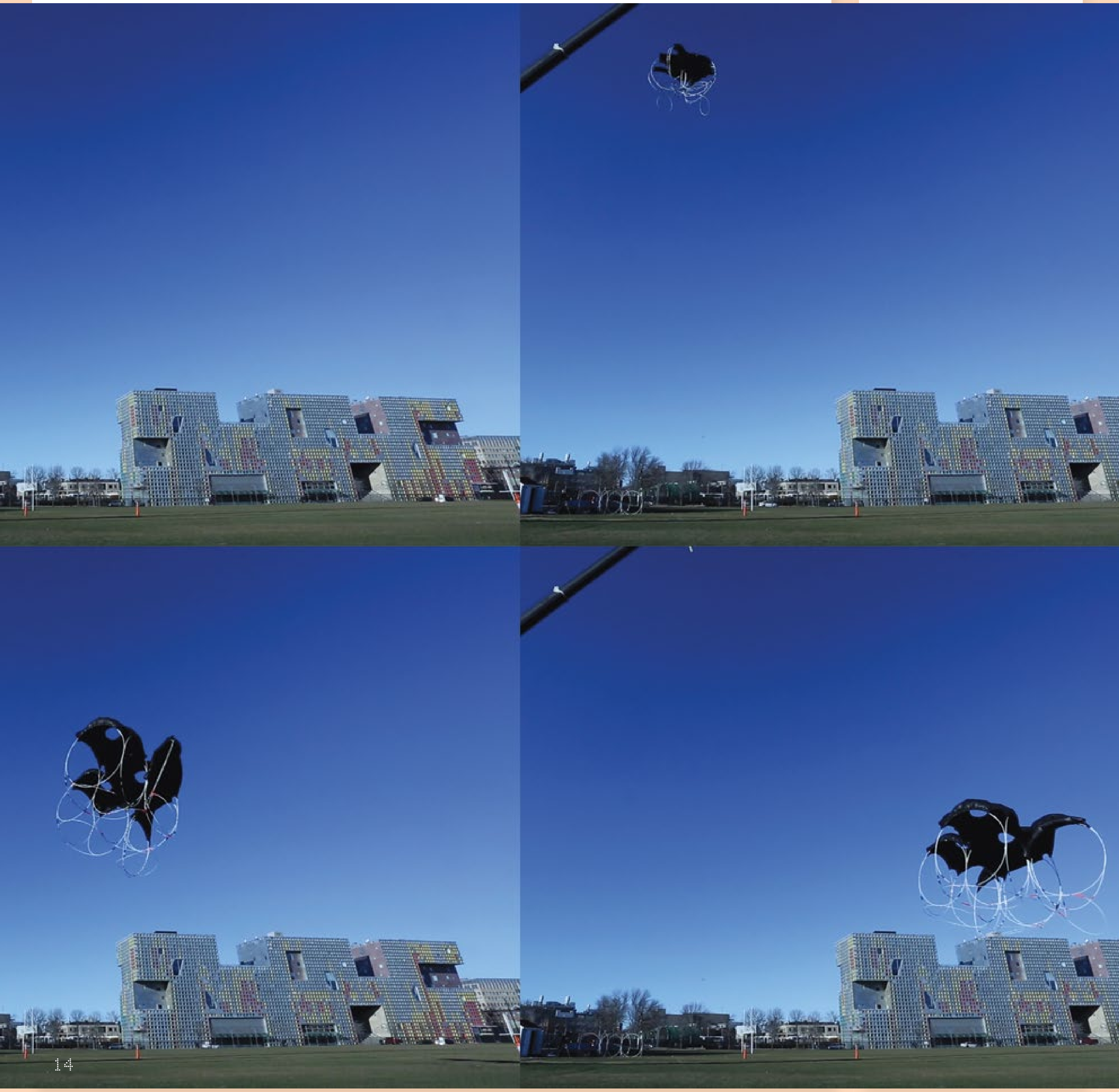
Top view of the pavilion as approximately 1,500 silkworms construct the fibrous composite. This insect-based construction method utilises self-organising principles to grow a structure without traditional human or robot assembly.

The principles of granular matter can be applied to large-scale systems, proposing new construction techniques and new bottom-up material logic. From amorphous material properties to granular structures, the issue includes the work of the JaegerLab at the University of Chicago (pp 74–81), the Institute for Computational Design at the University of Stuttgart (pp 88–93), Gramazio Kohler Research at ETH Zurich, and the Self-Assembly Lab's research on large-scale jammable structures (pp 82–7). Gramazio Kohler also highlight their work on 'disarmed strategies' (pp 110–19) – automated robotics, drones and other distributed construction techniques.

A series of bottom-up structural principles, where materials work collectively to span and form space rather than through traditional hierarchies of structure and construction, are featured in the contributions by Caitlin Mueller of the MIT Digital Structures research group (pp 94–103), and the Block Research Group at ETH Zurich (pp 104–9). Alvise Simondetti, Chris Luebkeman and Gereon Uerz of Arup Foresight + Research + Innovation paint a vision of the year 2060 that references recent Arup projects in collective construction (pp 120–27).

Danniely Staback Rodriguez, Zachary Angles, MyDung Nguyen, Zain Karsan and James Addison, Pop-up parachute structure, MIT Department of Architecture, Cambridge, Massachusetts, 2016

A series of photographs showing an MIT student project for a quickly deployable pop-up structure that can be dropped from high above the ground, self-assemble in the air, then parachute safely back to earth.



THE NEXT PHASE

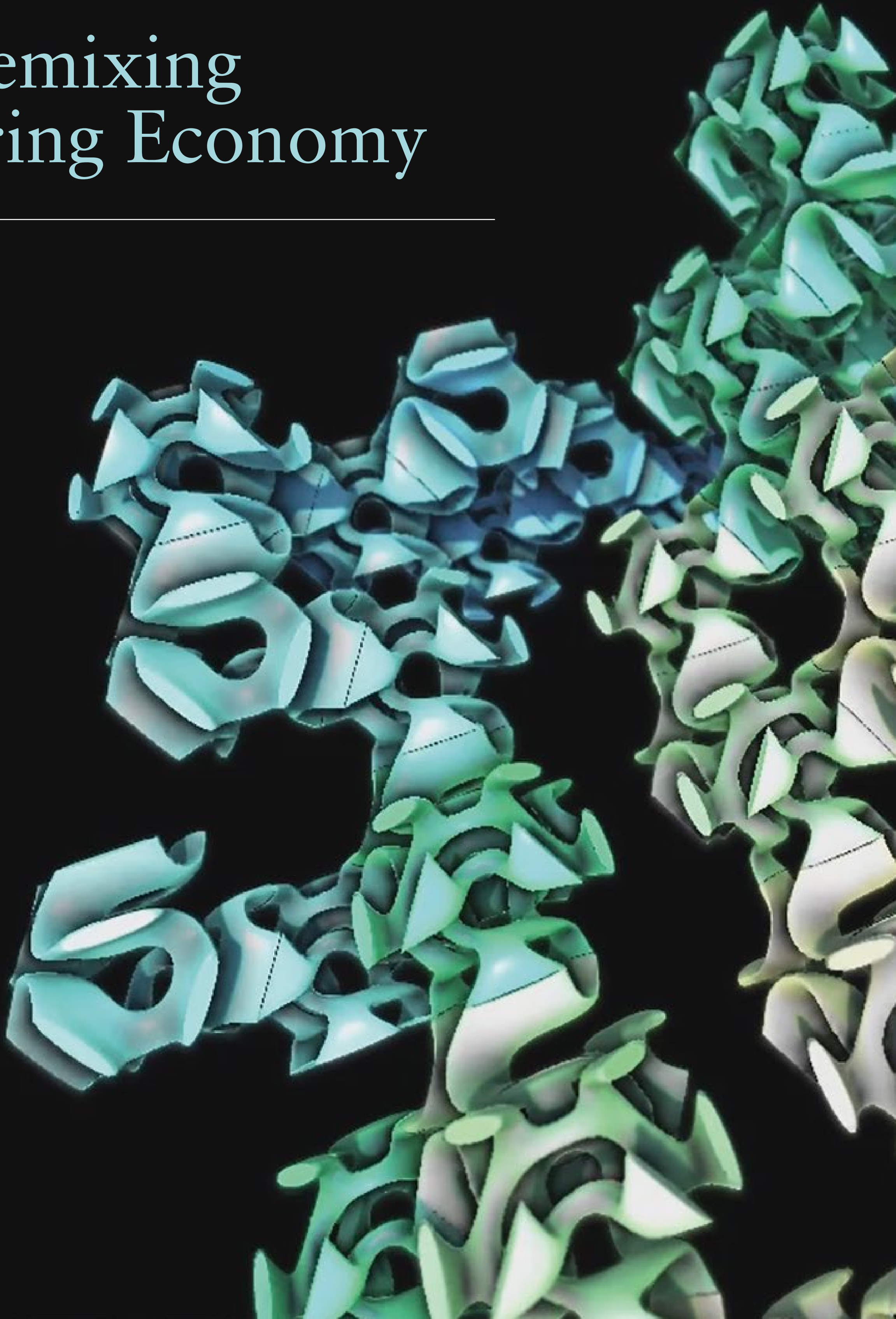
The issue spans the digital to the physical, the small scale to the large scale, from materials to construction and design to performance, offering a glimpse at the future role of autonomous assembly in architecture. It proposes a long-term vision whereby humans, robots and materials can collectively build structures through local interaction rather than top-down centralised control, with potentially more robust, adaptive, faster and more scalable construction. This emergent assembly process may lead to new design possibilities that are currently impossible to realise with manual assembly, such as physically evolving design solutions and continuously reconfiguring structures. Or remote construction capabilities where buildings can be assembled from a distance on hard-to-reach sites, where conditions are dangerous, or expensive and constrained, for example in urban locations. The next step for designers will be the development of smarter assemblies, with materials that come together spontaneously, adapt to the environment, transform themselves, and embed capabilities within our structures that enable them to get better with time. Autonomous assembly is thus set to change the future of construction, from the bottom up. AD

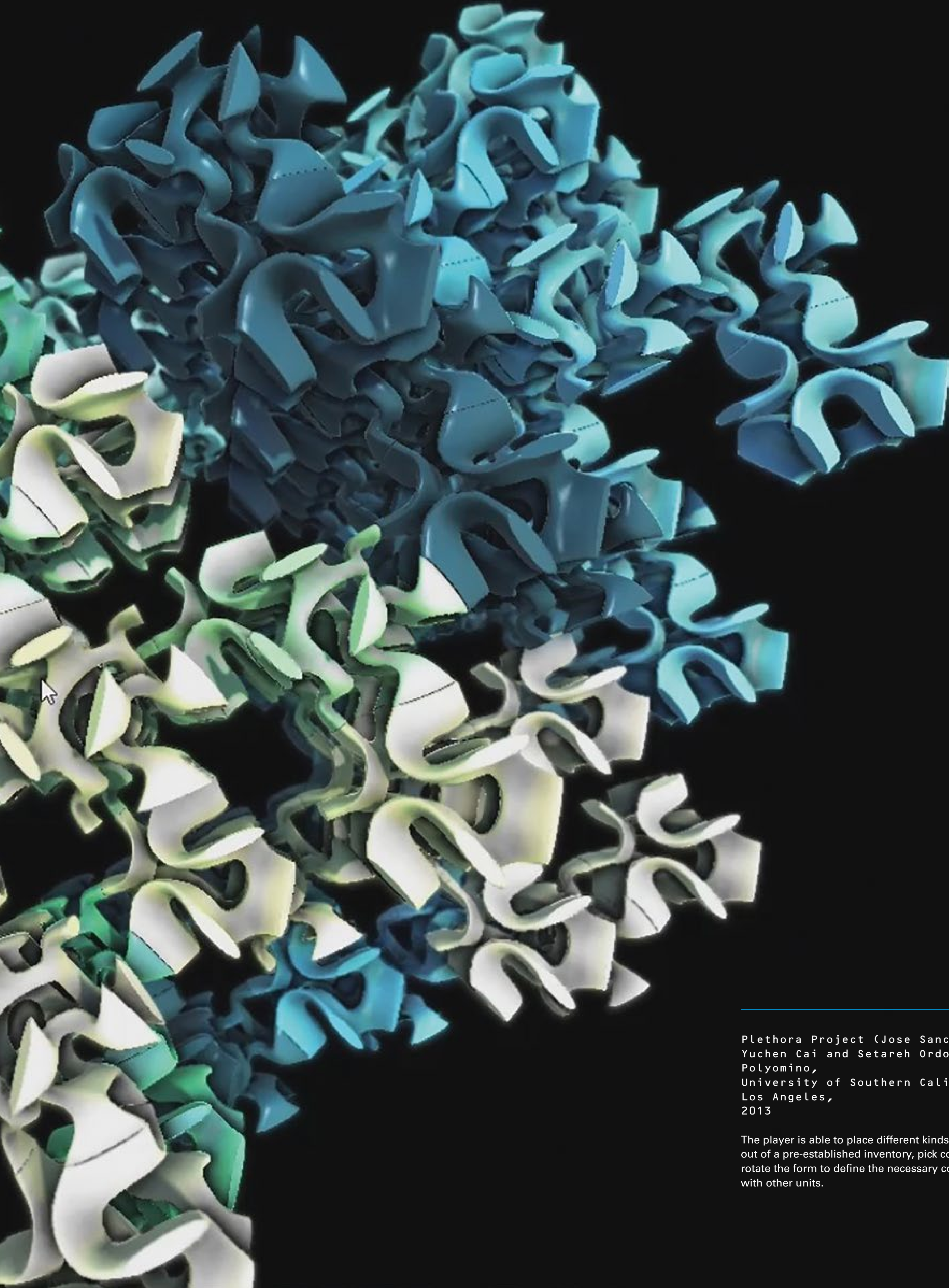
Notes

1. Branko Kolarevic, 'Designing and Manufacturing Architecture in the Digital Age', in *Architectural Information Management: 19th eCAADe Conference Proceedings*, Helsinki University of Technology, 2001, pp 117–23.
2. World Economic Forum, *Shaping the Future of Construction: A Breakthrough in Mindset and Technology*, 2016: www.weforum.org/reports/shaping-the-future-of-construction-a-breakthrough-in-mindset-and-technology.
3. 'Government Turns to Prefab Buildings to Save Resources', *China Daily*, 10 January 2016: www.chinadaily.com.cn/china/2016-10/01/content_26956827.htm.
4. Lionel Sharples Penrose and R Penrose, 'A Self-reproducing Analogue', *Nature* 179, 8 June 1957.
5. Victor Zykov *et al*, 'Robotics: Self-reproducing Machines', *Nature*, 435 (7039), 2005, pp 163–4.
6. John Frazer, *An Evolutionary Architecture*, Architectural Association (London), 1995, p 120.
7. George M Whitesides and Bartosz Grzybowski, 'Self-Assembly at All Scales', *Science*, 295 (5564), 2002, pp 2418–21.
8. Victoria Young, 'Can Computers Design Better Products Than Humans?', ASME, May 2015: www.asme.org/engineering-topics/articles/manufacturing-processing/am3d-can-computers-design-better-products-than.

Combinatorial Commons

Social Remixing in a Sharing Economy

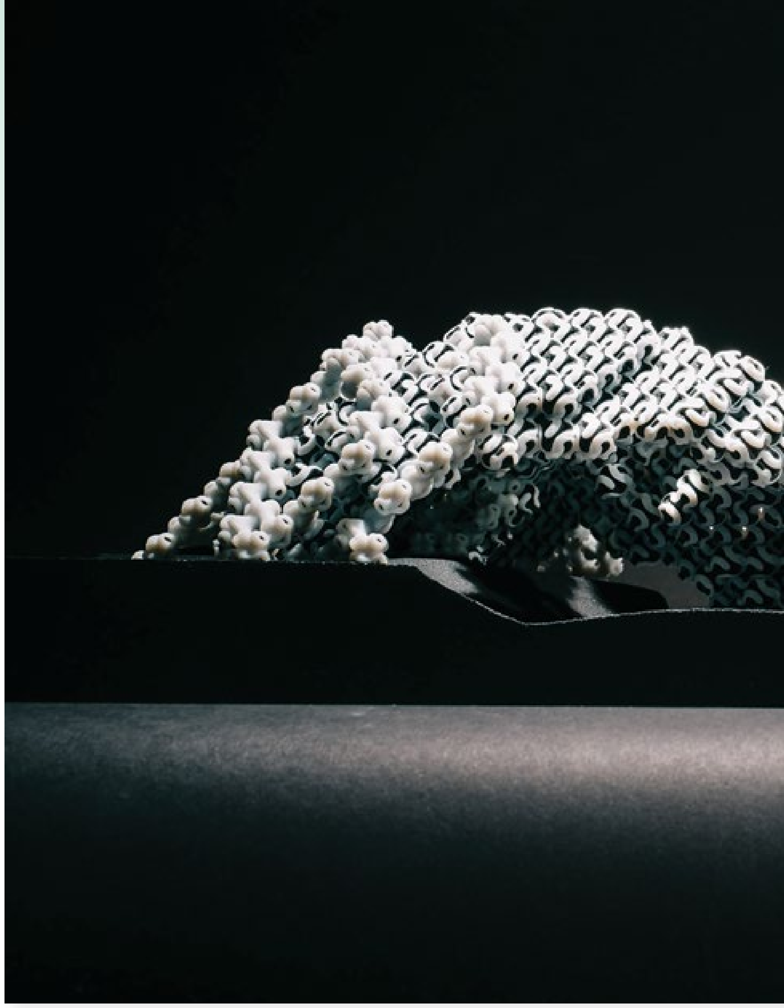


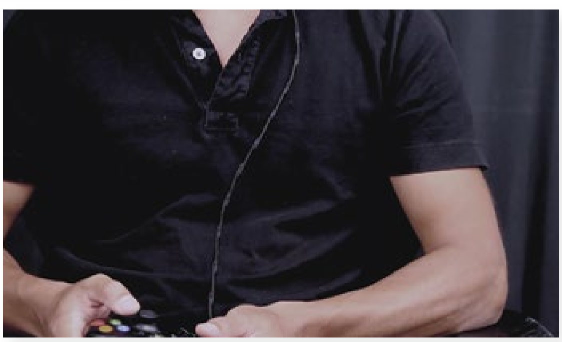


Plethora Project (Jose Sanchez,
Yuchen Cai and Setareh Ordoobadi),
Polyomino,
University of Southern California,
Los Angeles,
2013

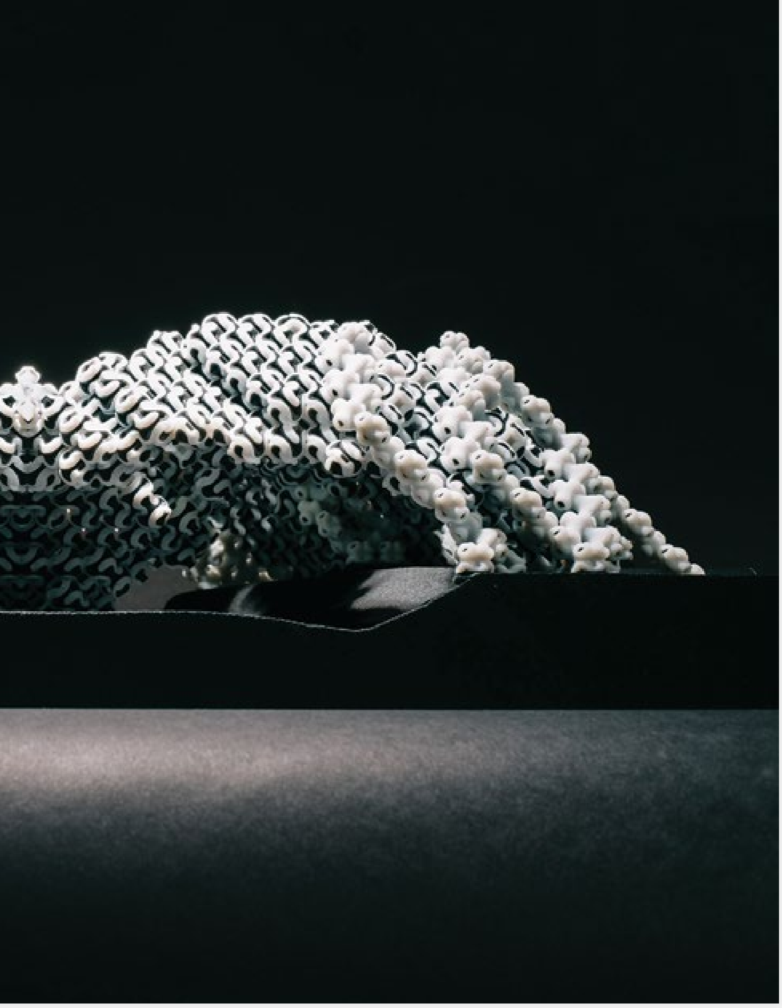
The player is able to place different kinds of units out of a pre-established inventory, pick colours and rotate the form to define the necessary connectivity with other units.

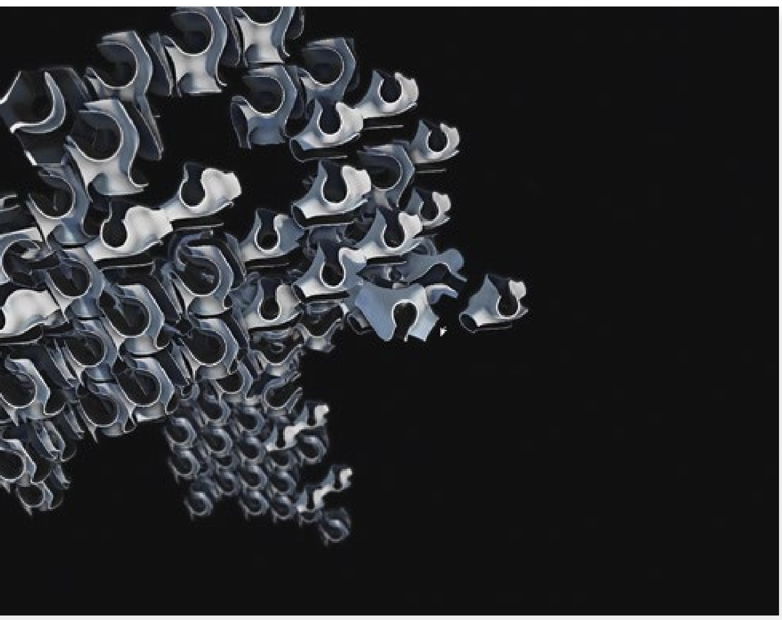
We have entered an era of prosumer culture, where consumers have become producers. This democratisation impacts on all scales of production, including that of architecture. The Polyomino research agenda at the University of Southern California, Los Angeles has been developed by architect, programmer and gaming designer **Jose Sanchez** to explore ethical forms of participation through growth of the commons, and to reconsider the role of parts in production. Here he explains the issues at stake, as illustrated by some of Polyomino's outcomes.





One of the students designing using the virtual reality platform.





Plethora Project (Jose Sanchez, Yuchen Cai and Setareh Ordoobadi), Polyomino, University of Southern California, Los Angeles, 2013

top: Virtual-reality gaming software. An aggregation of 3D-printed pattern is developed within the game simulation.

above: The player is able to place different kinds of units out of a pre-established inventory, pick colours and rotate the form to define the necessary connectivity with other units.

In 1959, American chemists Stanley Miller and Harold Urey, from the University of Chicago, developed an experiment to simulate the chemical interaction of different molecules in a mechanism that could emulate the conditions of a pre-biological Earth.[1] In the Miller–Urey experiment, the authors conceived apparatus that would simulate the water cycle, following a process of evaporation and condensation passing through an electric spark, which would simulate lightning. Like in pre-biological Earth, some gasses such as ammonia, methane and hydrogen were added, allowing the process to recombine the molecular structures of the elements present in the system. The device ran for two weeks, after which the water turned black, and further analysis demonstrated that complex molecules had formed, giving rise to amino acids – some of the building blocks of biological life. The results constituted the first step connecting ideas of chemistry with biological evolution. They gave rise to theories of chemical evolution that are still in development today. This was all possible, argues popular science author Steven Johnson, because of the combinatorial power of the carbon atom.[2]

Indeed, the carbon atom possesses a structure that allows it to connect to other elements and other carbon atoms. From this experiment, it was possible to start to extrapolate the ingredients for the spontaneous emergence of order, and to infer that 'design' was not required in the production of structures with a higher degree of complexity and order, which could perform functions.

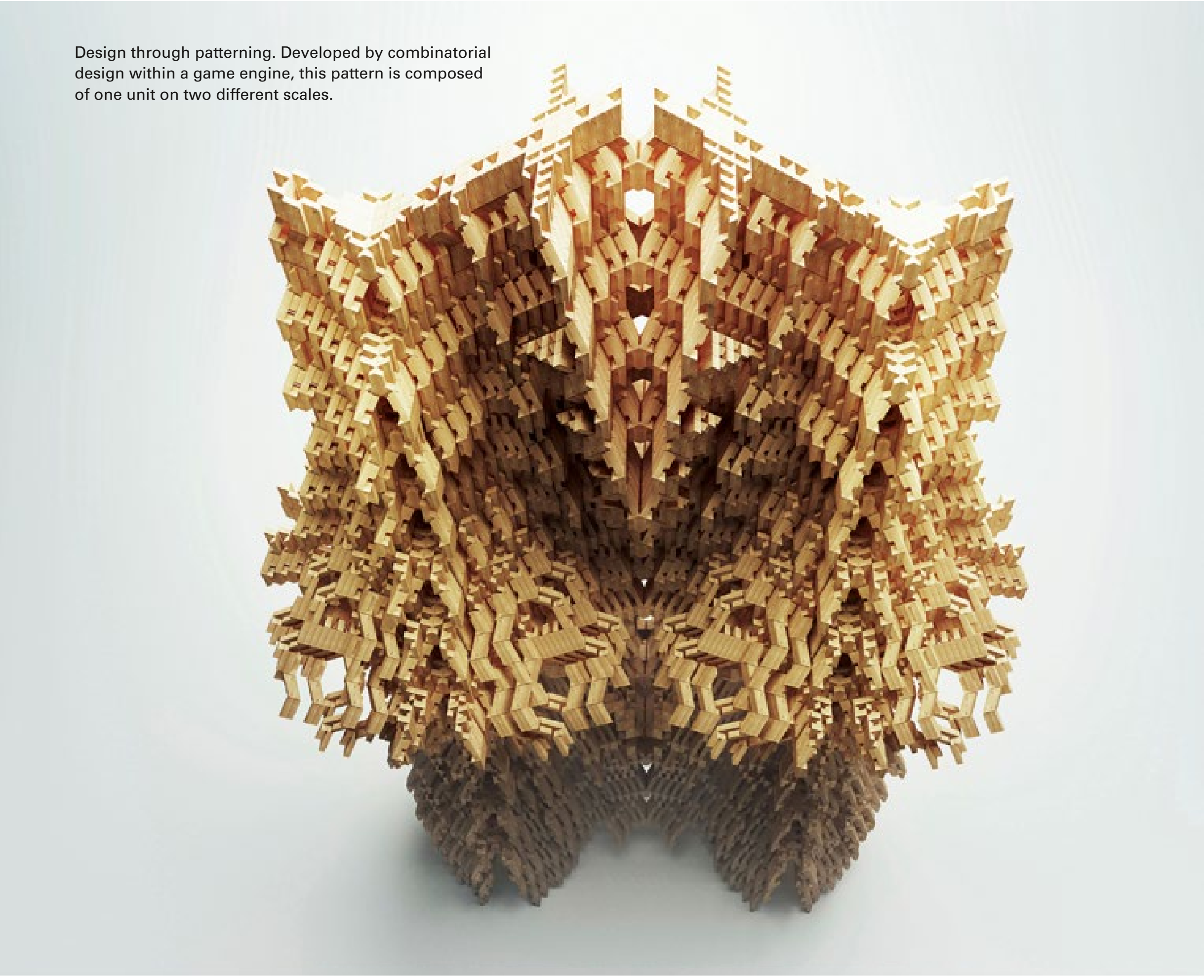
Four ingredients recognisably present in the experiment can be extrapolated to the current design ecosystem: parts; links; patterns; and commons. Parts are constituted by the atomic elements available to be recombined. These elements have a strict protocol of communication or bonding characteristics that can be denominated as 'links'. Patterns are defined by the structures that emerge from an elementary composition. Any combination of units can become the building block of another structure. Notice that designs here are defined through a combinatorial process giving rise to patterns, not by the definition of new unique parts. Finally, the commons is the recognition that for such processes to take place, there needs to be an abundant pool of easily and freely available elements that can be tried out and perhaps discarded.

This molecular perspective can prove to be productive when considering design strategies for the 21st century, providing a framework to pursue research in self-assembly robotic fabrication.[3] And perhaps this mentality can be extrapolated to a new form of social construction: one less mediated by architects.

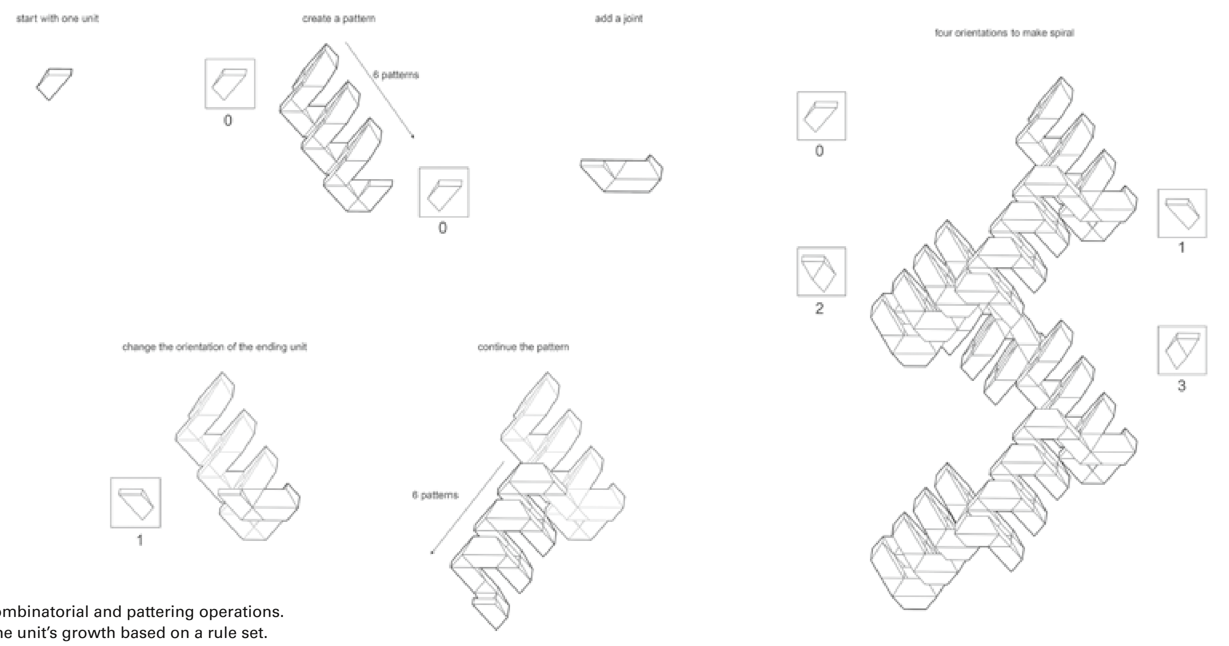
A new age of prosumer culture (consumers becoming producers[4]) is already upon us, generating new content in networks like YouTube, or building digital worlds in Minecraft. This active social sphere is the new force that is remixing the material world, from IKEA hacks to DIY housing initiatives.[5] For these phenomena to scale up and effectively democratise forms of production, it is imperative that the same molecular principles remain available: parts, links, patterns and commons.

Some of these principles are already being challenged by current technological and architectural development. The advent of 3D printing and other forms of material deposition, like robotic manufacturing, suggest a future without parts, one that leaves behind the legacy of a serialised form of production. Also, copyright laws are slowly adapting to incorporate architectural design. Both events can be considered 'market enclosures' that attempt to control who has access to design and modes of production. These

Plethora Project (Jose Sanchez,
Hanze Yu, Kaining Li and Siyu Cui),
Polyomino,
University of Southern California,
Los Angeles,
2015



Design through patterning. Developed by combinatorial design within a game engine, this pattern is composed of one unit on two different scales.

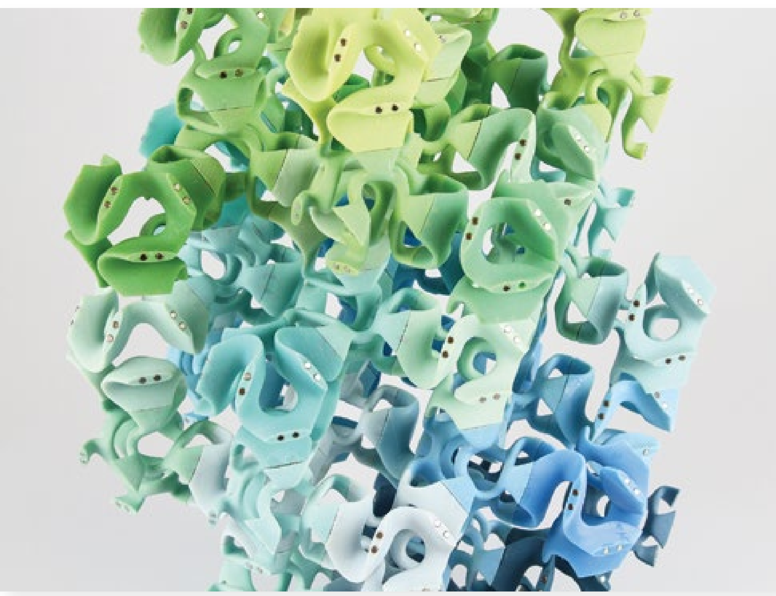


Combinatorial and pattering operations.
One unit’s growth based on a rule set.

Plethora Project (Jose Sanchez, Yuchen Cai and Setareh Ordoobadi), Polyomino, University of Southern California, Los Angeles, 2016

A 3D-printed piece developed out of the gaming platform. The units have been printed separately and magnets have been added to the face connections to allow the growth of the voxel structure.

Detail of a 3D-printed piece developed out of the gaming platform.



ideas stand opposed to a paradigm of participation and collective intelligence that could be enabled by network technology.

What might be called 'discrete architecture' is a new turn in design that understands the necessity of parts and patterns for the differentiation of form, and that rediscovers the need to protect the commons with technologies such as creative commons licences and open source.

This is the ethos driving the Polyomino research agenda at the University of Southern California, developed over the last three years by Jose Sanchez. Projects seek to reconsider the role of parts in production. By using units that can be serialised, the agenda places emphasis on design through patterning and combinatorial strategies.

Using principles of discreteness, units have unique positions and connections they can match with other units. A magnetic joint corrects connectivity and allows easy assembly and disassembly. This notion of reversibility is crucial where combinatorial patterns are concerned, as each assembly becomes a transient state, not a final product.

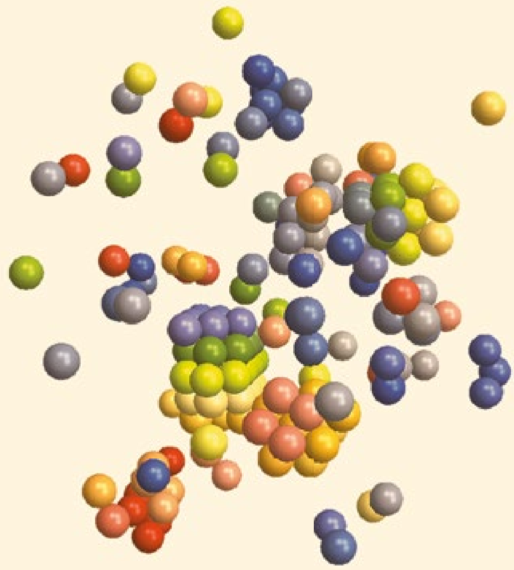
The impact of this needs to be understood in a broad context. As the field slowly adopts a post-capitalist paradigm, the organisation of matter through data will become increasingly relevant. The ability to rearrange existing parts will come together with the design of parts that can serve multiple combinatorial possibilities. Discrete architecture is a paradigm being developed for a sharing economy with a new role for social participation.

This research is framed through a larger interest in connecting gaming technologies with physical matter and the maker movement. Gaming is selected as a medium because of its capacity for social participation and to engage an extensive community of users. In this way, the design of building blocks is exposed to a large combinatorial engine that can create value and order for specific requirements. Central to the agenda is the desire to address an ethical form of participation: one in which, rather than users being harvested to provide value to a centralised authority or company, ways are envisioned for users to own their data and perform transactions over the network. The hope is to further develop the infrastructure that allows growth of the commons, enabling new units and patterns to define a new formal vocabulary for decentralised forms of production. ⅅ

Notes

1. Stanley L Miller and Harold C Urey, 'Organic Compound Synthesis on the Primitive Earth', *Science*, 130 (3370), 31 July 1959, pp 245–51. See also Stanley L Miller, S. 'A Production of Amino Acids under Possible Primitive Earth Conditions', *Science*, 117 (3046), 15 May 1953, pp 528–9.
2. Steven Johnson, *Where Good Ideas Come From: The Natural History of Innovation*. Riverhead Books (New York), 2011.
3. See Skylar Tibbits and Ana Falvello Tomas, 'Biomolecular, Chiral and Irregular Self-Assemblies', in *ACADIA 2013 Adaptive Architecture: Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture*, Riverside Architectural Press (Toronto), 2013, pp 261–8; and Gilles Retsin, 'Discrete Assembly and Digital Materials in Architecture', in Aulikki Herneoja, Toni Österlund and Piia Markkanen (eds), *Complexity and Simplicity: Proceedings of the 34th eCAADe Conference – Volume 1*, University of Oulu (Oulu, Finland), 22–26 August 2016, pp 143–51.
4. See Jeremy Rifkin, *The Zero Marginal Cost Society*, Palgrave Macmillan (London), 2014.
5. See http://www.ikeahackers.net/ and http://openbuildinginstitute.org/

How Specific Interactions Drive the Complex Organisation of Building Blocks



Can artificial materials be developed that rival nature's ability to self-assemble and self-replicate? **Zorana Zeravcic**, lecturer and researcher at the École Supérieure de Physique et de Chimie Industrielles Paris Sciences et Lettres Research University in Paris, outlines investigations on the subject being carried out by her department and by counterparts at Harvard University in the US. Drawing on methodologies and knowledge from across the sciences, their simulations have yielded previously unenvisioned complex functionalities that could transform the way we build.

The next generations of advanced materials are expected to have unprecedented functionalities. We want them to respond to environmental cues, transform at our whim, heal, self-replicate, adapt to changes, be capable of learning and so on. The development of such materials is a key challenge with an immense impact on society. This effort is in its infancy and requires innovative approaches to materials design and methods of construction.

Functionalities we expect from future advanced materials seem like those that already exist in biological systems. These biological materials are highly functional, and this comes from highly specific interactions on a microscopic level that are transferred to macroscopic behaviour through coupled reactions, feedback mechanisms and hierarchical information processing. A 'biology-inspired design' is a powerful paradigm for synthesising advanced materials and relies on the bottom-up design of building blocks with precisely programmed interactions. The building blocks assemble, without external actuation, into a functional material, and this takes place in solution, driven by thermal fluctuations, catalysts, or energy-donating solutes.

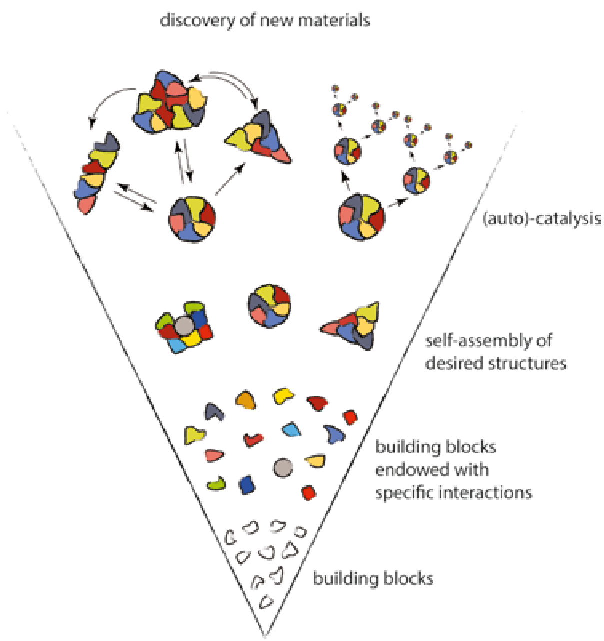
Techniques for bottom-up assembly of materials exist, yet despite decades of research there is still no general method for producing materials whose design and functionality rivals biological ones. Perhaps the most critical challenge is the enormity of the design space: every building block can interact with every other in a different way, which makes it prohibitively costly to test designs in experiments. Nature had eons to evolve biological materials!

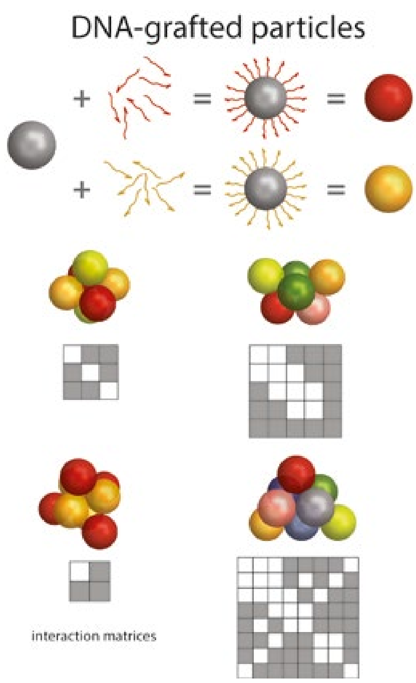
Building Blocks with Specific Interactions

The essential way forward is to systematically explore the design space with a combination of theory and numerical simulations. This is the motivation behind the approach to biology-inspired design of matter with advanced functionality being developed in recent years within the research group of Professors Brenner and Manoharan at Harvard University's School of Engineering and Applied Sciences in Cambridge, Massachusetts, and my own at the École Supérieure de Physique et de Chimie Industrielles of Paris Sciences et Lettres Research University in France. Combinatorial enumeration algorithms and computer simulations are used to analyse the space of possible designs of artificial matter composed of building blocks that interact through short-ranged specific interactions. The design of interactions determines how the building blocks organise into higher-order structures and what kinds of reactions occur at various organisational levels in the matter. In fact, using computer modelling and simulations to evolve functionalities in a given artificial matter allows the discovery of new functionalities that were not necessarily envisioned beforehand. In the 1940s John von Neumann, the father of artificial life, put forward abstract ideas about self-replicating systems.[1] Inspired by these, the research groups are actively seeking the minimal ingredients and necessary properties that matter should have to achieve certain functionality, but only matter that is a model of a physical system is considered.

Zorana Zeravcic, Biology-inspired design of materials with advanced functionalities, École Supérieure de Physique et de Chimie Industrielles (ESPCI), Paris Sciences et Lettres (PSL) Research University, Paris, France, 2016

Different building blocks are designed to interact in specific ways. The programming allows robust self-assembly of arbitrary structures, efficient self-replication and metabolism-like catalytic behaviour. Applying selection-amplification cycles to these systems could lead to the discovery of materials with greatly enhanced properties.





Zorana Zeravcic with Vinothan N Manoharan and Michael P Brenner, Towards living matter with colloidal particles, ESPCI PSL, Paris and Harvard University School of Engineering and Applied Sciences, Cambridge, Massachusetts, 2017

Micron-sized particles can be grafted with single strands of DNA. Interactions can be programmed between particles to achieve self-assembly of different desired structures. Four examples of small rigid clusters are shown here, together with the interaction rules between different particle types (interaction matrices).

Over the last decades there has been enormous experimental progress in making nano- and micro-scale building blocks (both synthetic and biological) that differ in shape and types of interactions, including peptides, polymers and colloids.[2] In fact, if the interactions between the building blocks are mediated by the experimentally available synthetic DNA strands, it is possible to have as many different types of short-range interactions as desired by precisely programming the DNA sequences.[3] A key advantage of the approach developed at Harvard University is that the designed interactions are implemented in computer simulations of a physical model of DNA-coated colloidal particles calibrated against experiments. The tested general principles however can be applied to materials built out of various types of building blocks with short-range interactions. Progress along this line of research has a tangible impact by providing guiding principles to experimental and engineering efforts in the design of advanced materials.

Self-Assembly of Desired Structures

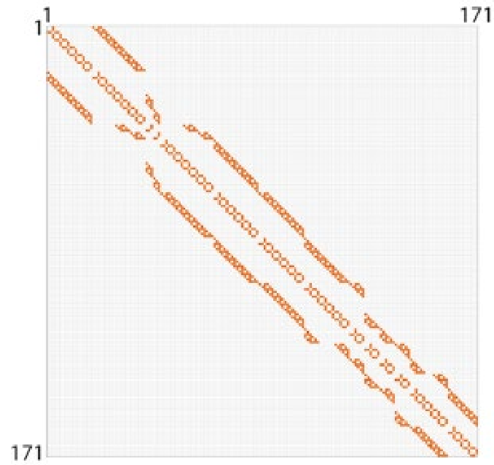
The work at Harvard University demonstrated how artificial matter can exhibit a fundamental property of biological materials: the ability to spontaneously assemble complex structures. The strategy for designing arbitrary complex structures is to impose specific interactions between building blocks such that the desired target structure is the energetic ground state. The surest way of doing this is by making every particle in the target structure different, with inter-particle interactions chosen to favour the desired local configuration. Interactions between different particles are coded into an interaction matrix, specifying the interaction energy between every pair of particles. The main tools for testing design ideas are combinatorial enumerations and dissipative particle dynamics (DPD) simulations in which the colloidal particles are subject to thermal fluctuations. It was found that structures comprising up to a thousand particles can be assembled with a high success rate. Extensive research led to insights about how the overall geometry of the structure (such as bulky versus planar) and increasing specificity (few versus many particle types) influence the success rate of the assembly.[4]

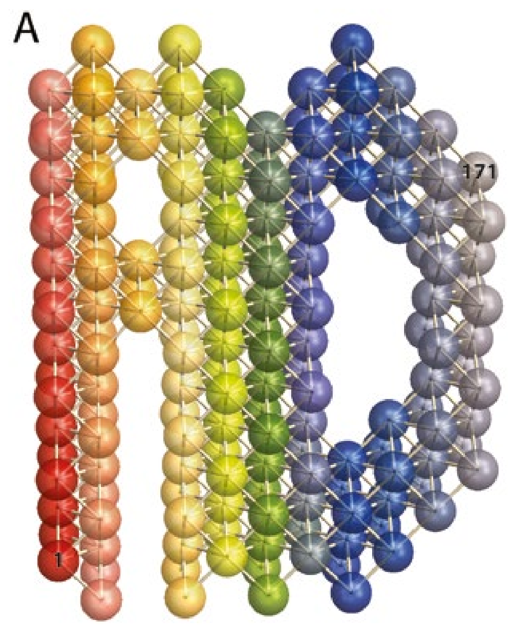
Extensive research led to insights about how the overall geometry of the structure and increasing specificity influence the success rate of the assembly

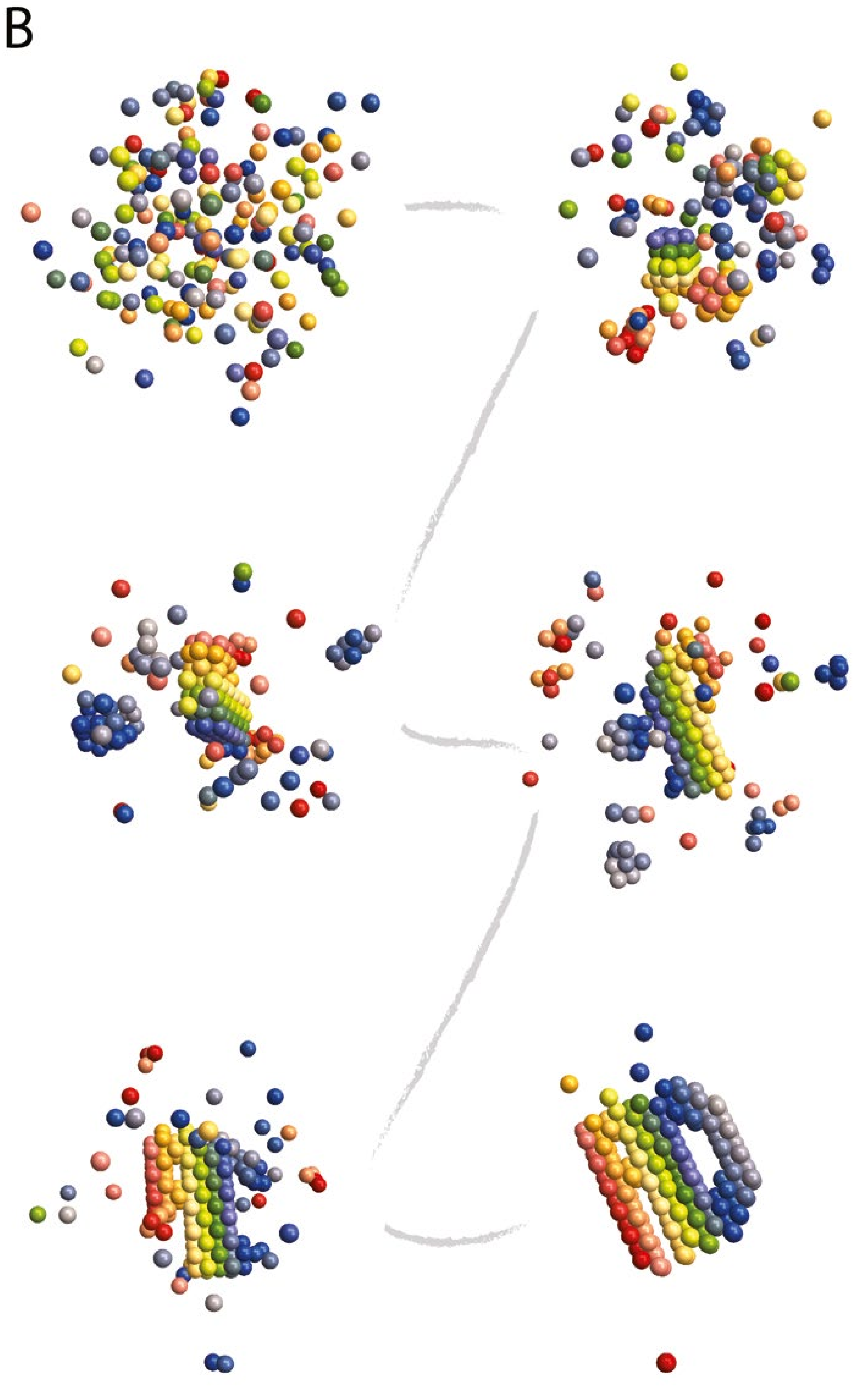
Zorana Zeravcic, Self-assembly of complex arbitrary structure, ESPCI PSL, Paris, 2016

below: The desired structure ('AD') and the interaction matrix specifying which particles interact favourably (orange entries) and which interact unfavourably (white entries). In total there are 171 different particle types comprising this structure.

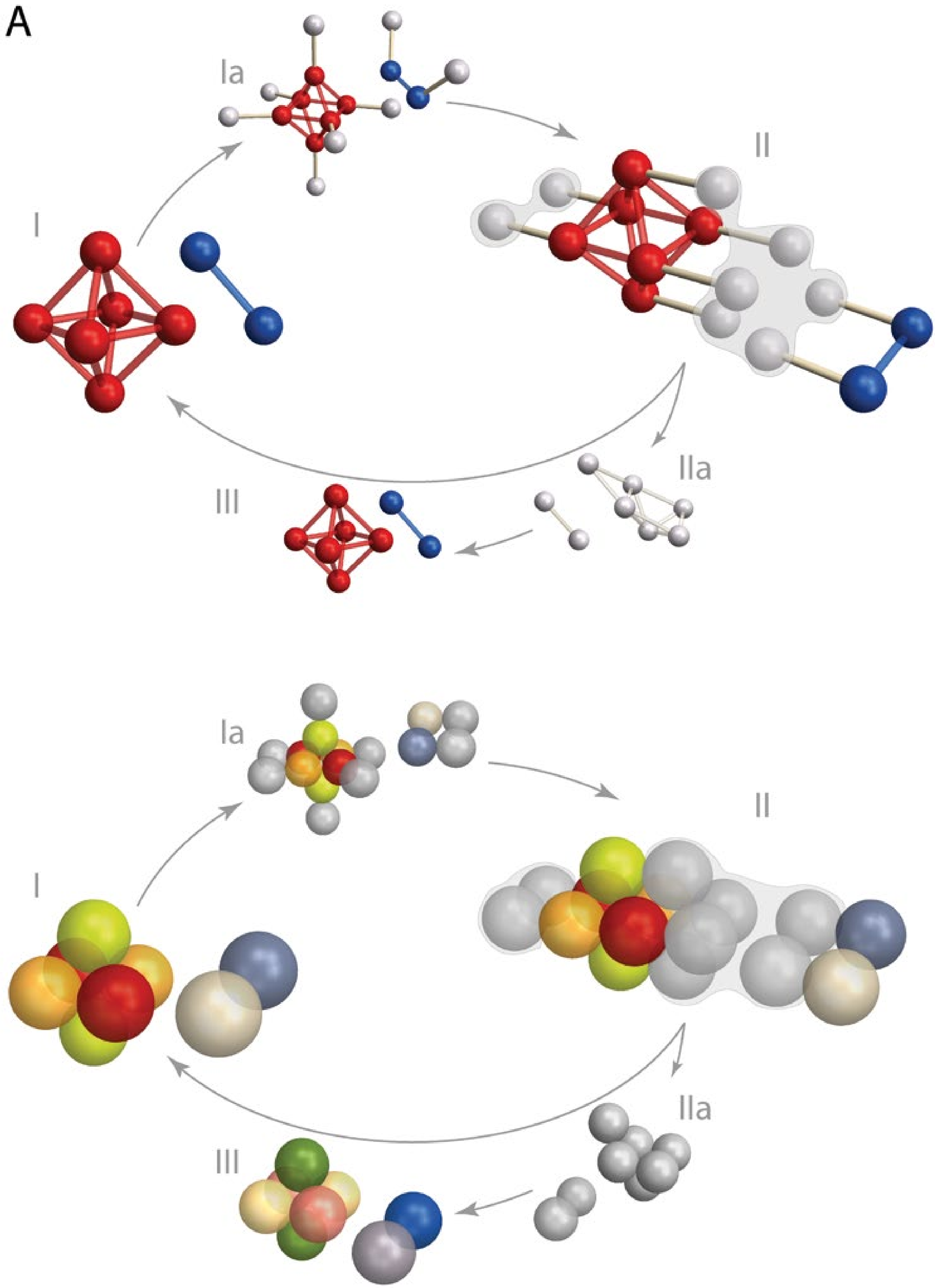
opposite: Snapshots in time of a dissipative particle dynamics (DPD) simulation of the AD structure.






B

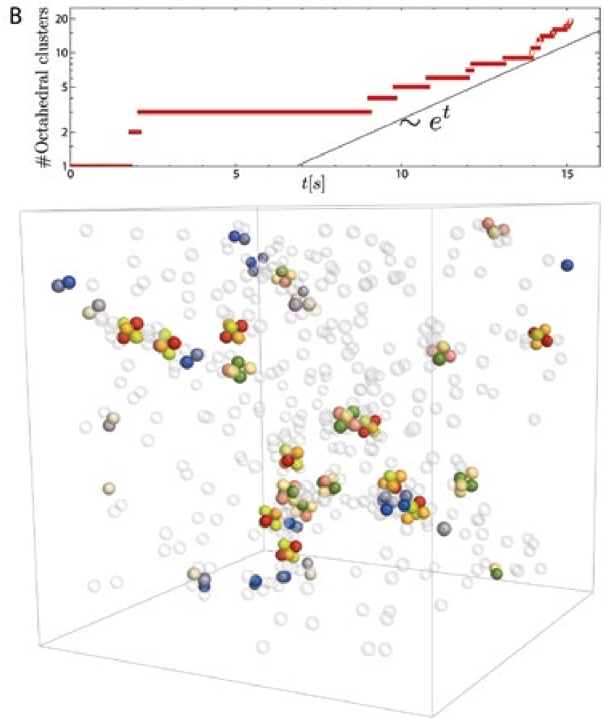
Zorana Zeravcic and Michael P Brenner,
Self-replicating colloidal clusters,
Harvard University School of Engineering
and Applied Sciences, Cambridge,
Massachusetts, 2014



Self-Sustained Self-Replication Reactions

A fascinating yet elusive property of biological materials is the ability to efficiently self-replicate. Templating reactions, in which particles form new structures by binding and unbinding to the surface of a given structure, were successfully introduced.[5] Such reactions required introducing particle interactions which have time-dependent bond strengths and which can limit particle valency.[6] Thereby a rare example of an exponentially fast rate of self-replication was realised in a computer simulation of physically realisable, geometrically complex structures, as opposed to symbolic reactions of chain-like matter inspired by DNA. To replicate structures that are geometrically more complex than a chain, it was found that a catalyst is necessary – that is, another structure whose geometry is suitably chosen to complement that of the one being replicated. Templating processes between geometrical structures opened the door to an incredibly rich landscape of behaviours. A given structure can template various structures, even ones with a larger number of particles, creating a population of geometrical structures over which there is some control through tuning time-dependent bond strengths. Ongoing research concerns managing the templating processes to make the system into a 'factory' of complex parts: desired objects will be created in chain reactions which are initiated by adding the appropriate seed structures.

The challenge of designing artificial materials with complex functionalities, as advanced as the ones in biological materials, lies at the interface of chemistry, physics, biology, materials science, architecture, engineering and computer science. It is important to use them all for inspiration and in methodology in building the world of future materials. ⌀



The total number of octahedron clusters as a function of time, as measured from dissipative particle dynamics simulations, together with a snapshot showing 19 replicas. Two of the replicas are error states. The attachment/detachment process for monomers requires time-dependent interactions and limited particle valency.

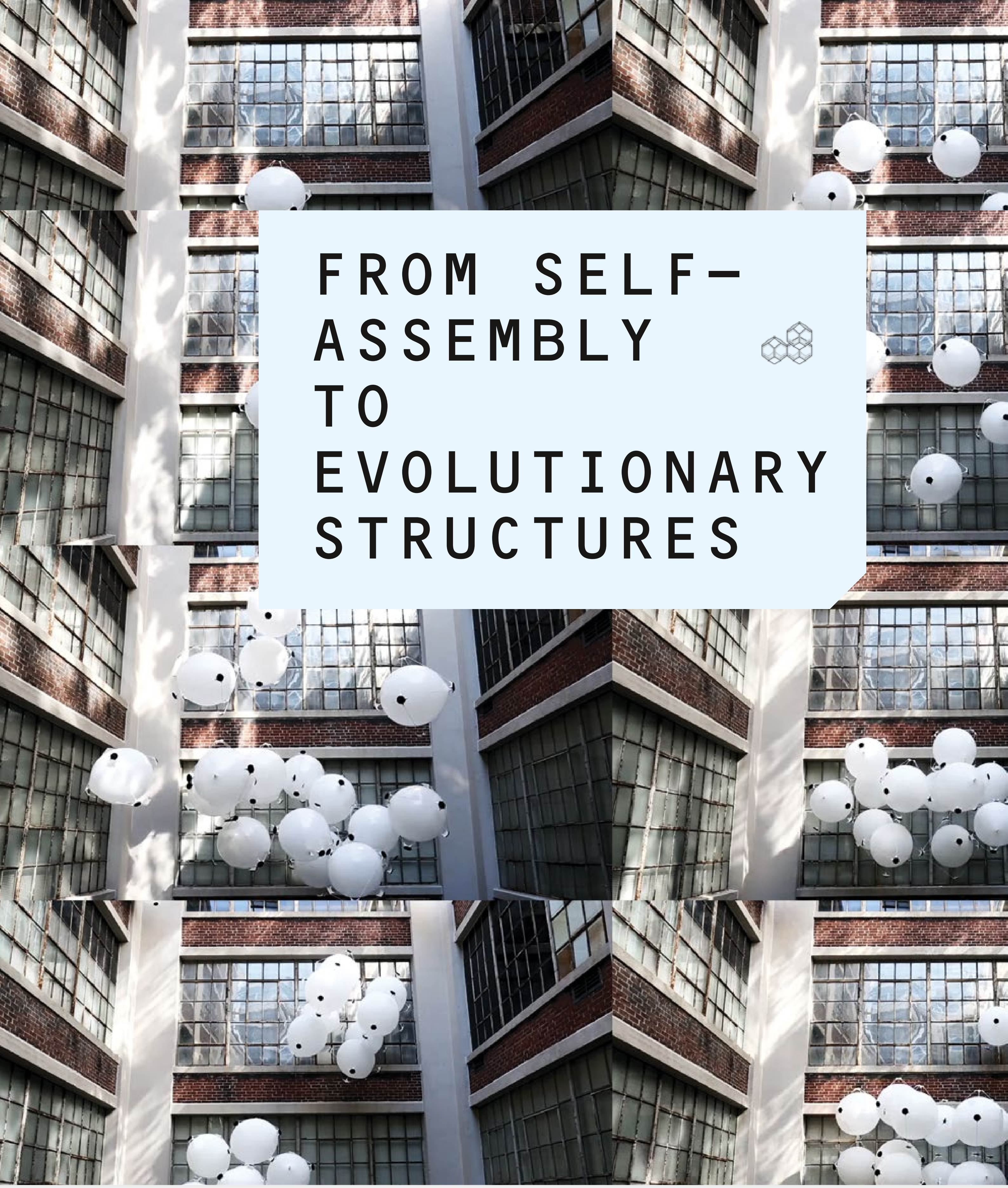
The challenge of designing artificial materials with complex functionalities lies at the interface of chemistry, physics, biology, materials science, architecture, engineering and computer science.

opposite: A minimal catalyst needed for the replication of the octahedron (red particles) is a dimer (blue). Only one appropriately coated particle (grey) can be attached to each of these particles (Ia). Attached particles can bond together, producing substructures (II) which then detach (IIa), becoming a new catalyst and a non-rigid cluster that folds into a new octahedron (III).

Notes

1. John von Neumann and Arthur W Burks, *Theory of Self-Reproducing Automata*, University of Illinois Press (Urbana and London), 1966.
2. See, for example, W Benjamin Rogers, William M Shih and Vinothan N Manoharan, 'Using DNA to Program the Self-Assembly of Colloidal Nanoparticles and Microparticles', *Nature Reviews Materials*, 1 (3), 2016, p 16008;
Ludovico Cademartiri and Kyle JM Bishop, 'Programmable Self-Assembly', *Nature Materials*, 14, 2015, pp 2–9; and Ana C Mendes, Erkan T Baran, Rui L Reis and Helena S Azevedo, 'Self-Assembly in Nature: Using the Principles of Nature to Create Complex Nano-Biomaterials', *Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology*, 5 (6), 2013, pp 582–612.
3. Rogers *et al* 2016, op cit.
4. Zorana Zeravcic, Vinothan N Manoharan and Michael P Brenner, 'Size Limits of Self-Assembled Colloidal Structures Made Using Specific Interactions', *Proceedings of the National Academy of Sciences*, 111 (45), 2014, pp 15918–23.
5. Zorana Zeravcic and Michael P Brenner, 'Self-Replicating Colloidal Clusters', *Proceedings of the National Academy of Sciences*, 111 (5), 2014, pp 1748–53; Hidenori Tanaka, Zorana Zeravcic and Michael P Brenner, 'Mutation at Expanding Front of Self-Replicating Colloidal Clusters', *Physical Review Letters*, 117, 2016, p 238004.
6. Rogers *et al* 2016, op cit; Zorana Zeravcic and Michael P Brenner, 'Spontaneous Emergence of Catalytic Cycles with Colloidal Spheres', under review.

FROM SELF-ASSEMBLY TO EVOLUTIONARY STRUCTURES



Self-Assembly Lab,
Aerial Balloon Assembly,
Massachusetts Institute of
Technology (MIT),
Cambridge, Massachusetts, 2014

The Aerial Balloon Assembly research investigated large-scale self-organisation of helium-filled units. The 90-centimetre (36-inch) weather balloons were set free in a four-storey building courtyard, floating around chaotically, propelled by fans on the ground. Various structures emerged, from cubes to beams and lattice structures.

The Self-Assembly Lab at Massachusetts Institute of Technology is at the forefront of the move towards evolutionary construction processes. Three of the Lab's members – doctoral researcher **Athina Papadopoulou**, co-director **Jared Laucks** and co-founder **Skylar Tibbits** – report on its recent experiments in macro-scale fabrication that relies on the reactions of specially designed material components, both among themselves and with their environment.

Over the past decade, the use of computational processes has slowly been shifting from digital design tools to physical material processes. Recent advances in robotics, synthetic biology and materials science have sparked a renewed interest in materials. Simultaneously, rapid advances in hardware technologies have made fabrication easily accessible to architects and non-specialised users. This growing interest in materials has led to new concepts and manifestations of generative processes in architecture. Natural phenomena such as growth, evolution and self-organisation are no longer only studied in design as mere metaphors or digital simulations. Rather, they can now be utilised in physical materials and fabricated systems.

The ongoing research of the Self-Assembly Lab at the Massachusetts Institute of Technology (MIT) demonstrates steps towards evolutionary structures by proposing design processes based on the dynamic interplay of materials and their environment. Such scenarios widen the spectrum of design as they allow creative processes to go from deterministic to partially planned or totally unpredictable with arbitrary complexity. This work also demonstrates a new perspective on construction as it envisions new possibilities for fully automated assembly.

John Frazer was one of the first to imagine self-generating and evolutionary architectural structures. In his seminal book *An Evolutionary Architecture* (1995), Frazer demonstrated generative CAD processes, and physical components that interacted with each other through the logic of cellular automata and responded to environmental conditions such as wind and sound. Contemplating an evolutionary future for architecture, he concluded that 'In the short term, the prospect of growing buildings seems unlikely, but self-assembly may be achievable.'[1]

The series of studies conducted at the Self-Assembly Lab illustrate that self-assembling structures are now possible with non-biological, macro-scale materials based on the interaction of material components and their environment. Contrary to Frazer's experimental structures, this work shows that information can be directly encoded in material components without the need for computer input or embedded electronics. The current state and future possible directions of this work demonstrate that we are now much closer to the prospect of evolutionary structures than ever before.

INGREDIENTS FOR SELF-ASSEMBLY

Self-assembly can be defined as the process by which disordered parts build an ordered structure without humans or machines. Self-assembly has a vital role in many natural phenomena such as cellular replication, crystal formation, the swarming behaviour of animals or insects, and even at the planetary scale, in the formation of weather patterns.[2] The self-assembly studies conducted extend the study of self-assembly into design and macro-scale fabrication through the use of three main ingredients: (1) components, (2) the environment within which the components interact with one another, and (3) the interactions between the components and their environment.

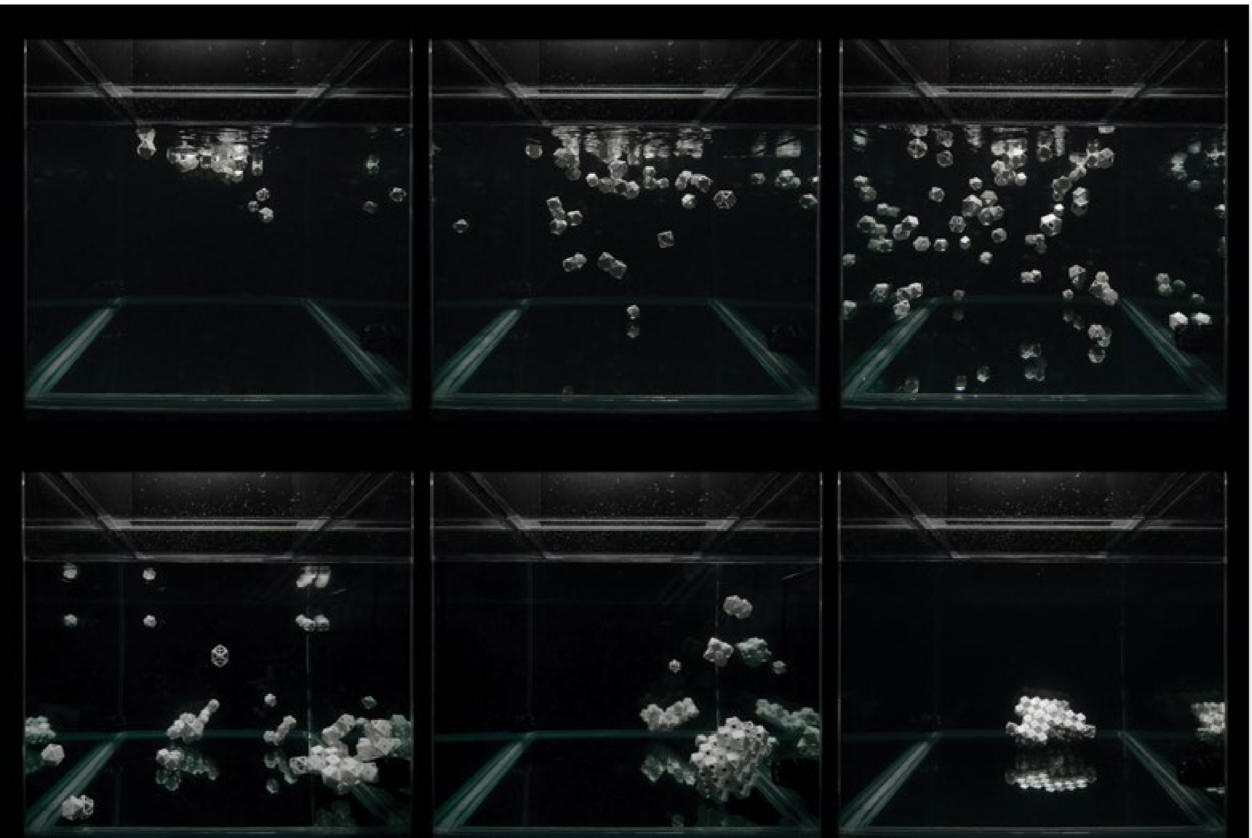
Most of the information regarding the self-assembly process can be directly encoded in the components though the design of their physical parameters, such as geometry, texture, size, mass, weight and polarity. The geometry of the component, for example, will dictate the types of local and global structures that emerge. A cube geometry may allow for a cubic lattice to emerge with continuous, and potentially arbitrary, growth patterns. A pentamer geometry, on the other hand, may lead to a precise and closed dodecahedron. Similarly, the mass or density of a component may change the type of structure, whereby neutrally buoyant objects may assemble into three-dimensional structures, while objects that float on the surface of water may promote two-dimensional assembly.

Different physical environments, such as fluids or air, can be used for self-assembly; and different types of activation energy, such as turbulence or agitation, can be used to trigger motion in the system. To self-assemble, the system requires just the right amount of energy: not too much or the parts will break; not too little or they will not be able to move and find one another. There are two main types of self-assembly: static self-assembly, whereby the process results in a fixed structure; and dynamic self-assembly, which results in a continuously changing structure, always dissipating energy.

The interaction between the components and the environment promotes ordered structures through equilibration and error-correction. Equilibration is the ability of the components to alternate between aggregated and non-aggregated states, whereas error-correction is the ability of the components to adjust their position relatively to one another and weed out errors during the construction process.[3] Equilibration and error-correction allow self-assembly to be self-adaptive, responsive to the environment, and a reversible process. An important design feature of the component is the moment of connection. As the components get close to one another, a part of the component – whether a magnet, interlocking geometry or sticky surface – will temporarily connect the components together, resulting in a bond. Over time, stronger global structures will emerge from locally weak bonds, promoting accurate structures with mechanical loops.

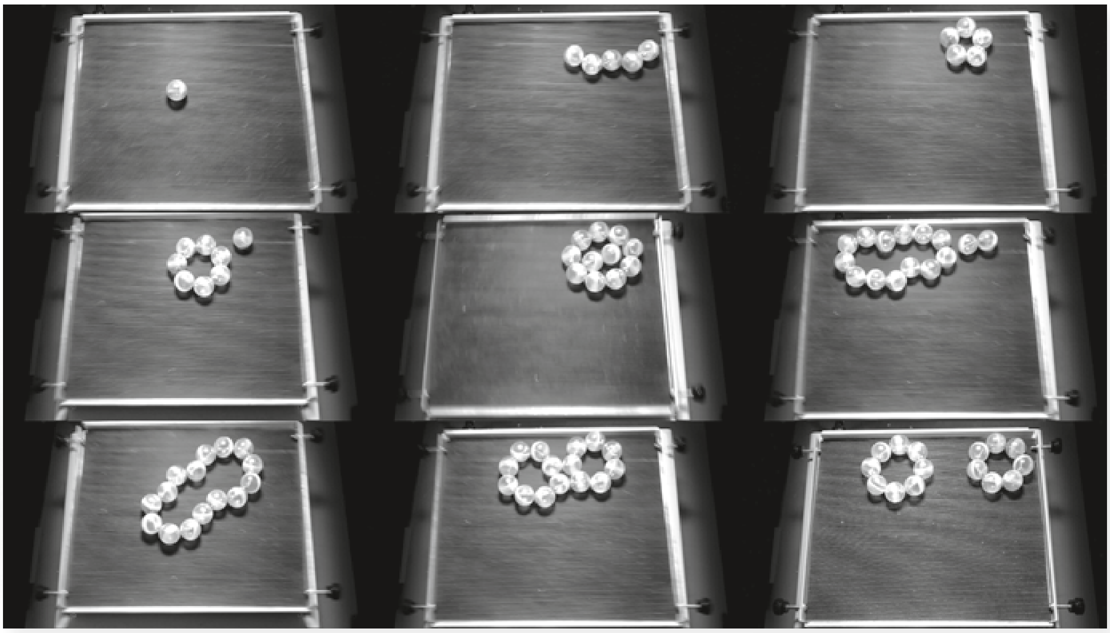
EXPLORATIONS IN SELF-ASSEMBLY

The Self-Assembly Lab's first study on self-assembly was BioMolecular Self-Assembly (2012).[4] Developed in collaboration with Arthur J Olson, Director of the Molecular Graphics Laboratory at the Scripps Research Institute, California, the project demonstrated macro-scale biomolecular self-assembly using fabricated components and agitation as the activation energy. Since then, the research has been to



Self-Assembly Lab, Fluid Lattices, MIT, Cambridge, Massachusetts, 2014

The Fluid Lattices research consisted of a series of truncated cubic units that self-organised within a 1,900-litre (500-gallon) tank of water, forming crystalline lattice structures. Neutrally buoyant, the units moved freely in all directions, forming three-dimensional aggregations that nearly never repeated the same structure twice.



expand the palette of material components, environments and complex interactions made possible through self-assembly.

One of the important benefits for design offered by self-assembly systems is an expanded exploration through bottom-up, emergent solutions. Fluid Lattices (2014) was a study of emergent lattice formations, similar to the processes of crystal growth, in a fluidic environment. For this study, a number of identical units were individually released inside a 1,900-litre (500-gallon) tank of water while pumps were positioned around the tank to create turbulent flow. Each individual unit was made of a thin plastic sheet folded into a truncated cube and had a single weak magnet embedded in each of the six main sides to allow for bonding and error-correction. After being released in the water, the units gradually formed clusters and eventually aggregated into a single cubic-lattice structure.

The topology of the final lattice was based on the complex variables in the environment, including the interactions of the units and the fluid flow. For example, if the pumps were positioned on the sides of the tank, three-dimensional formations emerged, whereas if the pumps were positioned on the bottom surface pointing upwards, two-dimensional configurations of lattices emerged on the water's surface. The number and complexity of the variables, as well as the cubic geometry which promoted continual aggregation, ensured that there was low probability that any two of the same configurations would assemble twice. By continuously promoting the emergence of different lattice configurations, the fluid lattice experiment can be seen as a physical design generator.

Self-Assembly Lab,
Self-Replicating
Spheres,
MIT,
Cambridge,
Massachusetts,
2015

above: The Self-Replicating Spheres research explored macro-scale cellular mitosis, or cellular growth and division, with non-biological material and non-robotic components. The spherical units were placed on an agitating table to promote their movement, growth and division.

above left: The Self-Replicating Sphere units were a hollow plastic spherical shell with internal magnetic and metal spheres that formed the core. The core had just the right amount of magnetic attraction and flexibility to allow the unit to connect to and disconnect from neighbouring units and promote the growth and division of the system.

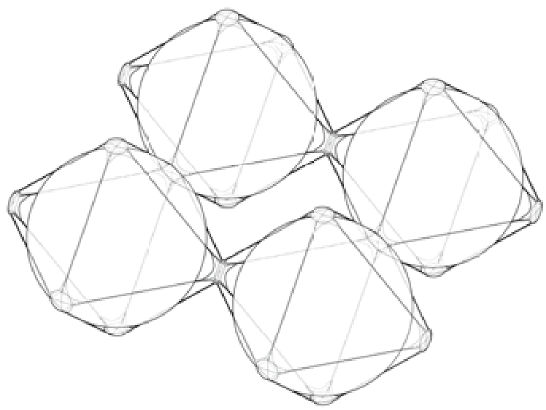
The Self-Assembly Chair (2014) was another study in fluidic environments, but instead of emergent crystal-like growth, it explored the possibility of automated assembly of arbitrarily complex, yet predetermined, structures. For this study, the chair was selected due to its irregular shape, without symmetry in all axes, and unique components. Successful assembly can also be clearly demonstrated with the precise and final assembly of a recognisable chair. The chair consisted of six individual components, made of folded light plastic sheets and 3D-printed connectors with male and female nodes and embedded magnets. Contrary to the fluid lattice, where all components are of the same type, the components of the chair were individually unique such that they could only assemble in the desired configuration. The component and node geometries as well as the pattern of magnetic polarity in each node were all unique, thus encoding the correct male and female bonding partners.

To start the assembly process, all the components were released in random order and position inside a 38-litre (10-gallon) tank of water. In that configuration, the self-assembly process culminated successfully after approximately seven hours. The Self-Assembly Chair experiment demonstrated an alternative scenario for the repetitive manufacturing of precise components through deterministic self-assembly rather than human or machine labour.

To investigate possibilities of structural assemblies in larger scales, that could potentially lead to automated building solutions, the Self-Assembly Lab expanded into aerial environments. Aerial Balloon Assembly (2014) investigated the possibility of large-scale self-assembly in aerial environments using lightweight structures filled with helium. For this study, 36 identical units were made from fibreglass rods, in the shape of truncated octahedrons. At each connecting point of the rods, nodes were placed containing Velcro with a specific pattern to create male/female faces. These nodes simultaneously acted as the error-correction and bonding mechanism. Each unit contained a 90-centimetre (36-inch) helium-filled weather balloon. The particular design of the geometry and selection of the materials created neutral buoyancy of the unit.

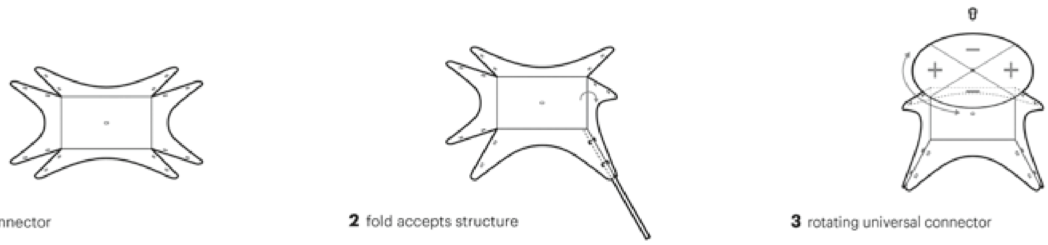
The assembly process took place in an open-air courtyard with boundary walls on all four sides. The assembled structures, which varied from irregular lattices to regular shapes such as cube, beams and lattices, were the result of the dynamic interaction between the turbulent air created by two fans located on the ground, the helium contained within the balloons, the other environmental forces and the pattern of attraction at the

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

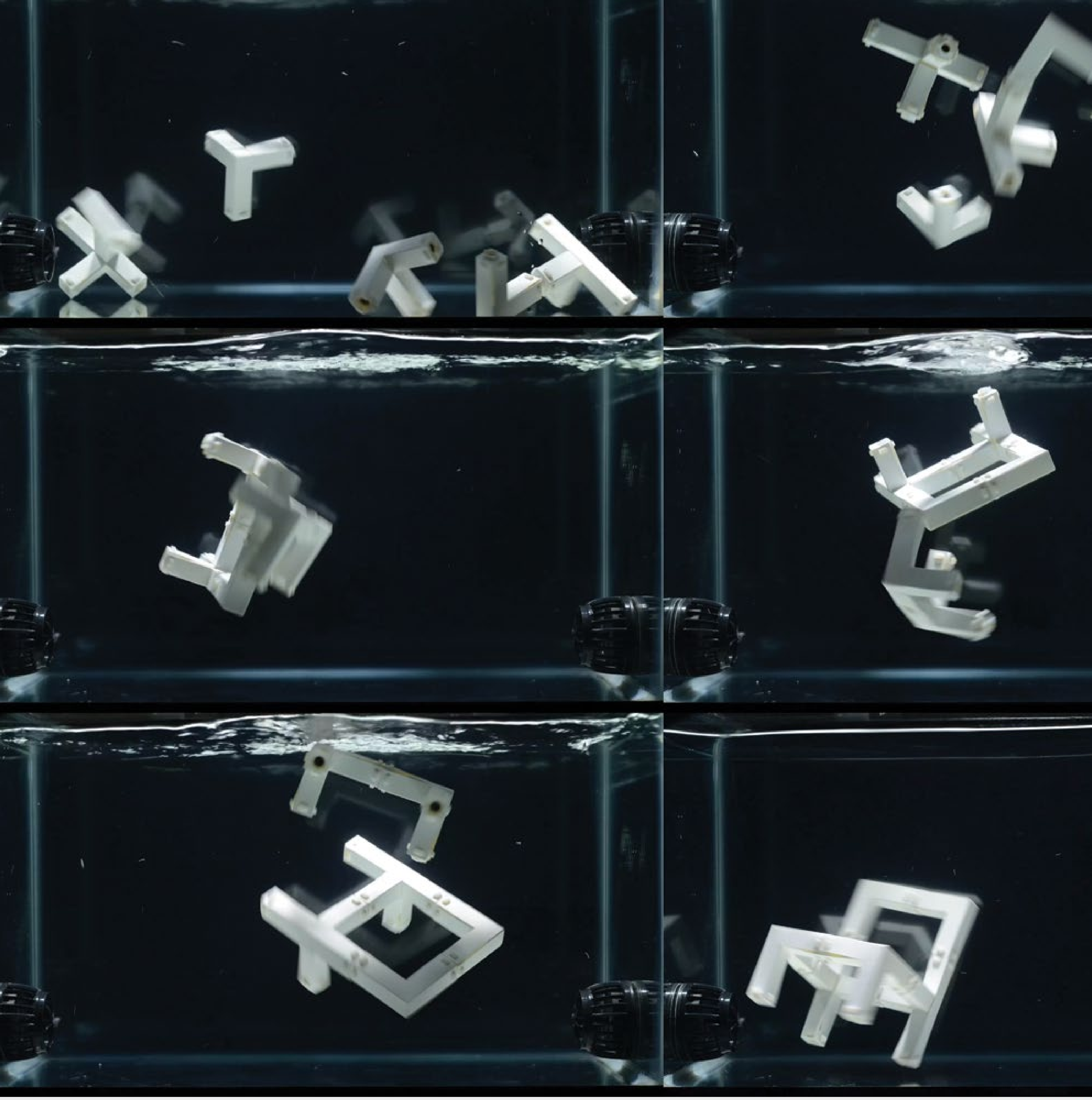


below: The Aerial Balloons were made from 90-centimetre (36-inch) weather balloons surrounded by a fibreglass frame in the shape of a truncated octahedron. At each of the nodes, a male/female pattern of Velcro was placed to allow for connection and error-correction to form precise lattices.

bottom: The experiment formed a cubic space frame lattice measuring 3 metres (10 feet) on each side filled with helium balloons, light enough to lift with a finger. When the helium balloons were removed, the completed space frame stood on the ground.



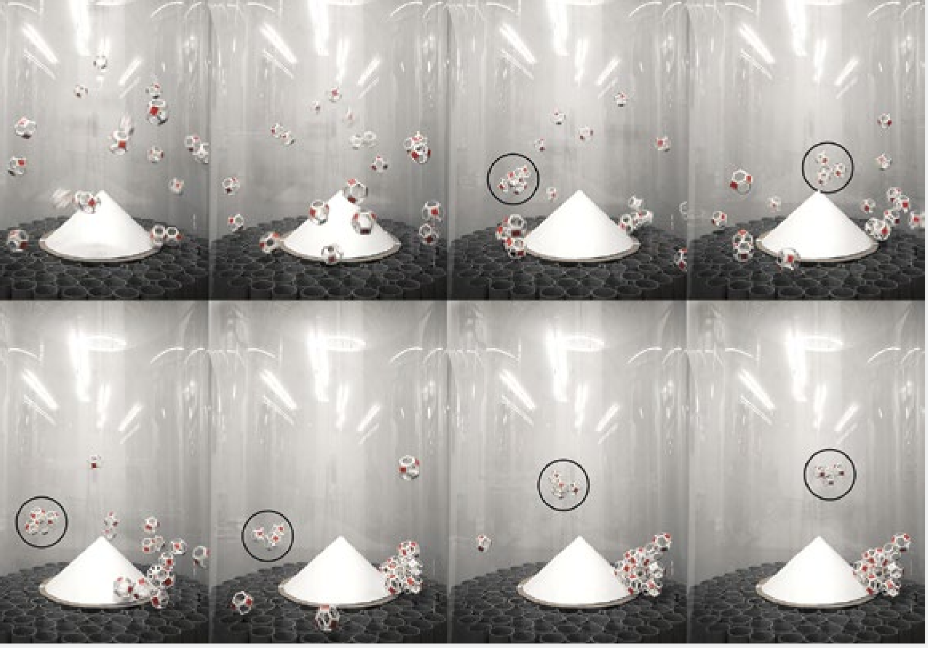
1 flat cut connector **2** fold accepts structure **3** rotating universal connector



The process of growth and subdivision continued indefinitely, demonstrating dynamic self-assembly, rather than static self-assembly, and a simplified version of cellular mitosis or growth and division of non-biological components.

Self-Assembly Lab,
Self-Assembly Chair,
MIT, Cambridge,
Massachusetts, 2014

The Self-Assembly Chair research demonstrated the precise self-construction of an arbitrary design, in the form of a small chair, consisting of six unique components. The geometry of the unit and connection surfaces, as well as the polarity of the magnets on each surface, allowed for error-correction and ensured the accurate assembly of the structure.



Self-Assembly Lab, Aerial Fan Assembly, MIT, Cambridge, Massachusetts, 2016

For the Aerial Fan Assembly project, octahedron units were placed in a chamber with a fan, causing them to float around chaotically, assembling and disassembling with other units. Ultimately, they formed configurations with the capacity to fly while also growing in size and complexity. One of the most successful configurations was a four-unit cluster (circled).

nodes. After the helium faded, the units landed on the ground leaving a self-assembled cubic lightweight self-supporting space frame, 3 metres (10 feet) on each side, demonstrating large-scale self-assembly.

Apart from crystal-like growth and deterministic assembly of complex structures, the Self-Assembly Lab has also explored biological processes such as cellular replication in physical, non-biological, components. For example, Self-Replicating Spheres (2015) explored the processes of growth and division though the agitation of simple spherical units. For this study, a number of spherical units were made, consisting of a hollow shell containing an identical configuration of metal spheres and magnets. The configuration of the metal spheres and magnets, which provided the force of attraction for the units, was chosen as the best connecting solution for their growth and division, after a series of studies. The strength of the magnets and the flexibility of the internal shape were just strong enough to permit bonding, but weak enough to allow them to continually separate when stretched to a certain angle.

The individual units were placed randomly on an oscillating table, allowing them to shuffle dynamically and continuously assemble, grow and divide. The interplay of agitation and attraction forces resulted in the connection of the spherical units into aggregations in the form of rings. When more units were added into the system, the rings would grow, become unstable and eventually divide into smaller, more stable rings. The process of growth and subdivision continued indefinitely, demonstrating dynamic self-assembly, rather than static self-assembly, and a simplified version of cellular mitosis or growth and division of non-biological components.

Finally, in the most recent study of Aerial Fan Assembly (2016), the Self-Assembly Lab explored the possibility of evolutionary assembly with environmental fitness criteria in aerial environments. The units were made of lightweight plastic sheets in the form of truncated octahedrons, with weak magnets embedded on each side. The system utilised the force of air pushing upwards from a fan positioned below. The units, which were released into the clear cylindrical container, were initially flying chaotically around as individual entities and then gradually started to form larger assemblies.

A large screen at the bottom of the chamber created roughly laminar flow on the edges of the cylindrical chamber but had a dead zone in the middle. This made the units fly upwards around the edges, often causing them to assemble with one another, and then crash down towards the middle of the chamber, frequently breaking the assemblies apart. A cone was placed in the middle of the chamber to push the units back outwards into the path of airflow. The clustered units would continue to fly, crash into the centre, break apart, then fly again until more stable configurations emerged.

The process of growth started from disorganised individual units and evolved into organised bigger clusters. In order to evaluate the evolving form, fitness criteria were used based on the capacity to fly and the size of growth. For example, although individual units demonstrated a strong ability to fly, they did not demonstrate growth. On the contrary, large assemblies demonstrated growth and complexity but could not fly. The most 'successful' were the moderate-sized assemblies of units of some arbitrary design, as these exhibited both the capacity to fly and substantial growth.

This type of 'successful' design exhibited properties of adaptation where the fitness criteria promoted the functional design and self-assembly of optimal flying structures to evolve. In one of the studies, a single structure in the form of a tripod shape, resembling a tricopter, emerged that lasted for nearly half the life cycle of the system and flew in a stable position to the mid-height of the chamber. This proved to be the most evolved functional configuration for flight, assembly size and duration of life.

A FUTURE OF EVOLUTIONARY STRUCTURES

The various case studies conducted by the Self-Assembly Lab provide evidence of the range of possibilities for self-assembly in architecture by demonstrating bottom-up, generative processes that can be emergent, self-adaptive and responsive but also precisely controlled, leading to both design and fabrication of structures. Each exploration has been undertaken as a step towards autonomous and evolutionary assembly. The conducted studies include the exploration of crystalline growth and continuous aggregation of lattice structures, the self-assembly of arbitrarily complex predetermined shapes like furniture, the growth and division of cellular mitosis with non-biological simple physical components, large-scale assembly in open-air environments, and small steps towards evolutionary growth of structures in aerial environments.

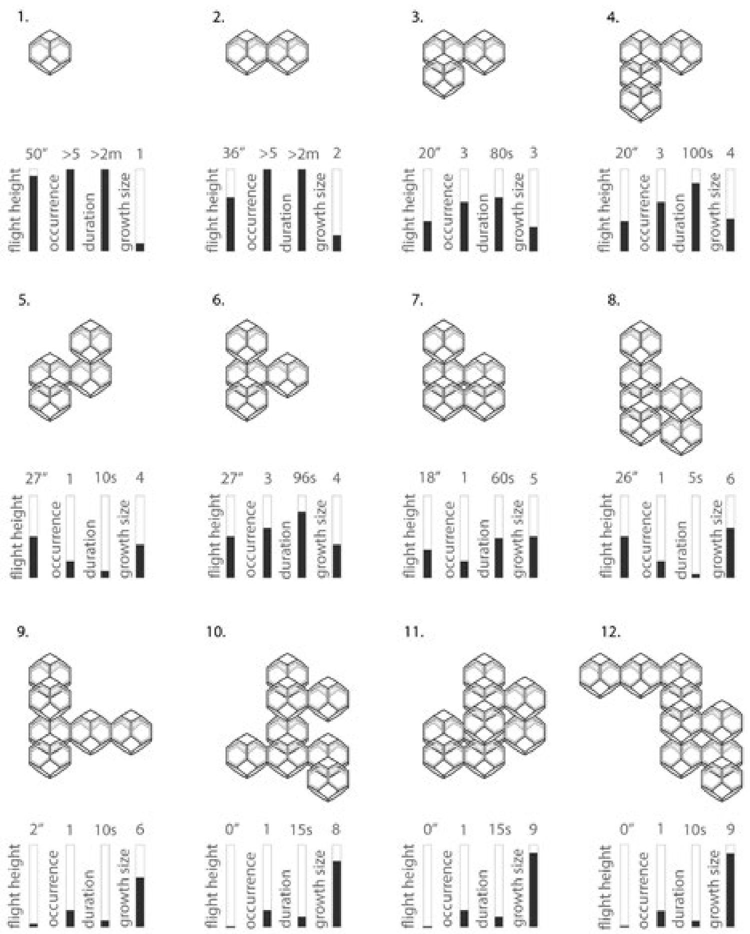
The theoretical biologist Stuart Kauffman, who has described the role of self-organisation in evolution, argues that 'To some great extent evolution is a complex combinatorial optimisation process in each of the coevolving species in a linked ecosystem, where the environment of each actor deforms as the other actors move.'[5] The Aerial Fan Assembly study, by defining simple formal and environmental constraints and imposing the basic fitness criteria of flight and size of growth, points towards the possibility of material functionality and design emerging through self-assembly.

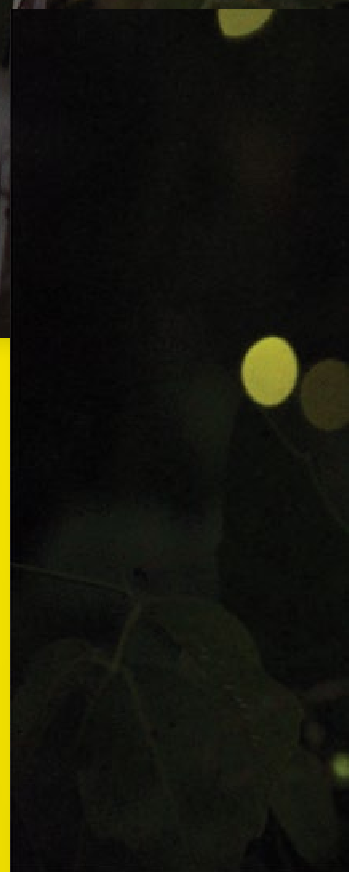
In the early twentieth century, D'Arcy Wentworth Thompson, a pioneer in mathematical biology, described form as the result of the action of forces. According to him, the form of any portion of matter and the changes of form during its growth can be described as the result of the actions of forces that have been impressed upon it, its own motion, and the interaction or balance of forces that retain its equilibrium.[6] The results of the Self-Assembly Lab's case studies demonstrate that through the dynamic interplay between components, environments and the forces of their interaction, design, functionality and self-construction can emerge. The presented explorations bring us closer to a future of evolutionary structures by proposing a model for design where fabrication is considered the design generator, rather than a purely post-design production process, pointing towards autonomous physical construction and design.[7] ᗡ

Notes

1. John Frazer, *An Evolutionary Architecture*, Architectural Association (London), 1995, p 102.
2. See George M Whitesides and Bartosz Grzybowski, 'Self-Assembly at All Scales', *Science*, 295 (5564), 29 March 2002, pp 2418–21.
3. Skylar Tibbits, 'Design to Self-Assembly', in Achim Menges (ed), ᗡ *Material Computation: Higher Integration in Morphogenetic Design*, March/April (no 2), 2012, pp 68–73.
4. Skylar Tibbits, Arthur Olson and Autodesk Inc., 'BioMolecular Self-Assembly', http://www.selfassemblylab.net/BioMolecularSelfAssembly.php.
5. Stuart A Kauffman, *The Origins of Order: Self-Organization and Selection in Evolution*, Oxford University Press (New York), 1993, p 644.
6. D'Arcy Wentworth Thompson, *On Growth and Form: The Complete Revised Edition* (first published 1917; second edition 1942), Dover Publications (New York), 1992, p 16.
7. The authors would like to thank MIT Department of Architecture, MIT International Design Center (IDC), Autodesk Inc., Arthur Olson and the researchers at MIT's Self-Assembly Lab that have contributed in the presented projects: Dimitrios Mairopoulos, Carrie McKnelly, Baily Zuniga, Chris Martin, Hannarae Annie Nam, Christophe Guberan, Kate Weishaar, Cosima du Pasquier, Björn Sparrman and Schendy Kernizan. The authors would also like to thank the Institute for Computational Design (ICD), Stuttgart, for their contributions to the initial aerial fan concepts.

'Flight height' is the maximum height of the unit in the chamber; 'occurrence' is the number of times the same configuration appeared; 'duration' is the time that the units remained connected; and 'growth size' is the size of the cluster. Configurations 4 and 5 were the most 'successful', displaying both the capacity to fly and substantial growth.





Synchronicity is a series of artworks that explore the self-organisation of collective organisms by manipulating the flashing of fireflies and the chirping of crickets. One of its co-creators, artist and composer **Robin Meier,** together with philosopher **Bastien Gallet,** explain how it relates to personal and societal emergence, through constantly evolving networks of interactions. They go on to describe the different manifestations of the series in detail.

Robin Meier and Bastien Gallet

The Vanishing Actor

Robin Meier and Andre Gwerder, *Synchronicity (Thailand)*, video still, Samut Prakan, Thailand, 2015

opposite: Live fireflies are made to synchronise their flashes with computer-controlled LEDs. By imitating the insects' bioluminescent signals, the artists could influence the rhythm of thousands of fireflies.

left: By engaging in a dialogue with the insects, the artists explored how organisation can arise from the inside out without a single force driving this collective behaviour.

How to Let Things Happen: The Art of Order Without Orders

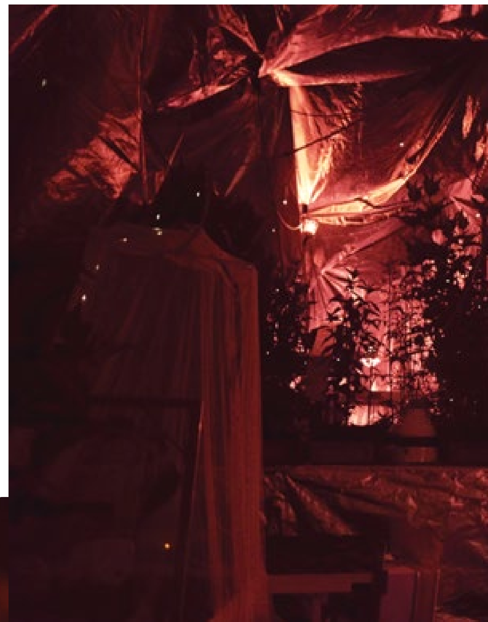
Organisation can arise from the bottom up, emerging from local interactions without help from an outside planner or guide. This kind of self-organisation is a distinctive feature of life itself: a cell, maybe the minimum form of life, maintains its boundaries with its environment by taking energy from the same environment to literally make itself (autopoiesis).[1] In this sense, organisation – and particularly self-organisation – is a fundamental property of life, a biological concept reflected in the word 'organism'. It is at the heart of the conceptual puzzle connecting physical matter to life.

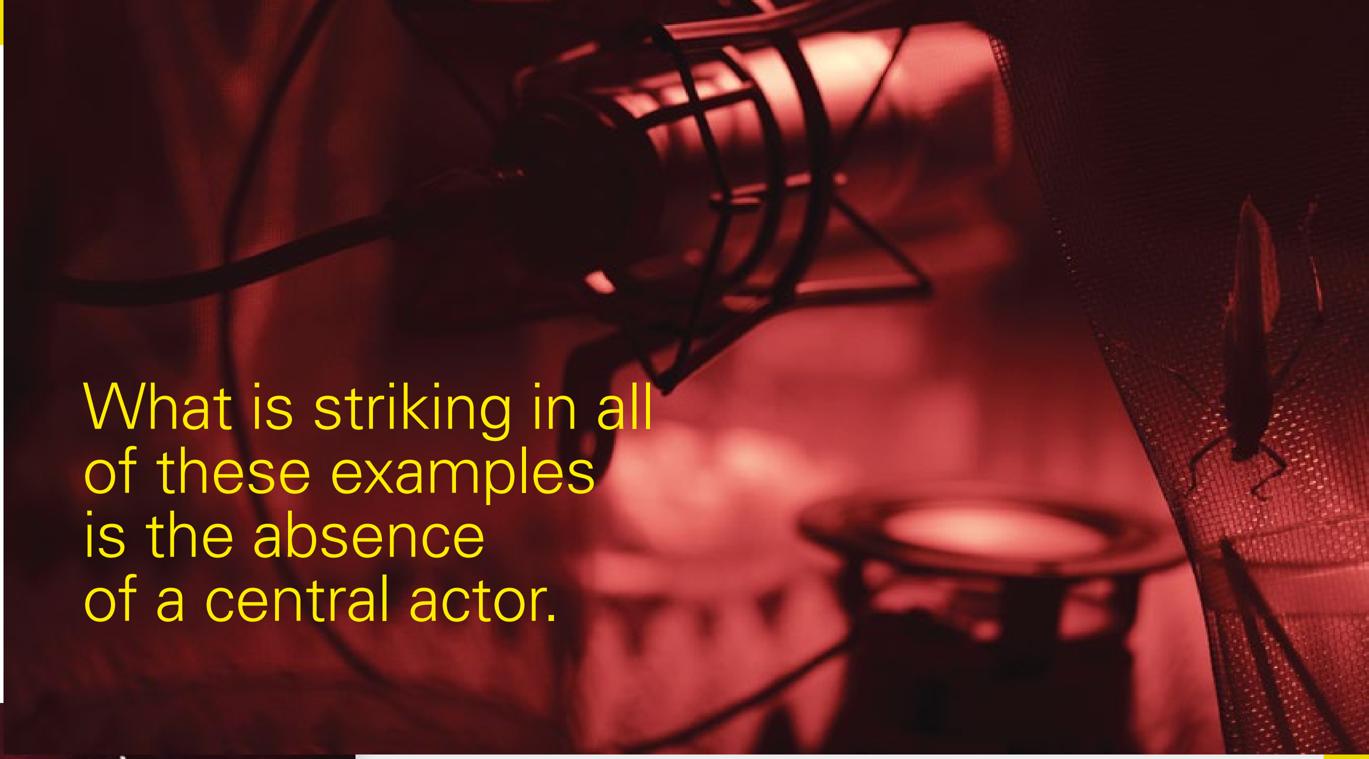
Studies of self-organisation are abundant: from synchronising fireflies, mating mosquitoes and bird swarms to human interactions such as posture and speech coordination when having a conversation. But self-organisation is also used to explore the relationship of mind and matter in theories of perception and even consciousness. How does a physical arrangement of atoms give rise to an individual experience of the self? For example, what creates that 'sensory feel' we get when we see the colour red as opposed to just imagining it?

Many would suggest this is caused by the activity of neurons in the brain. But what is it about neural activity that creates the distinct feel of this sensory consciousness? One explanation is that this kind of consciousness is a skill rather than a mechanism: a process rather than a state.[2] It is an ongoing interaction with the environment around us – an autopoietic loop of sorts between what we perceive and what we do. It is something that happens to us as we are embedded in our environment, just like the meaning of a word is not caused by the shapes of its letters, but in the way it is used and embedded.

Robin Meier and Andre Gwerder, *Synchronicity*, Volkshaus Basel, 2015

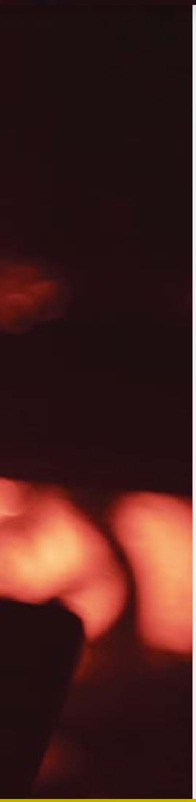
In sync with the pendulums, dozens of LEDs imitated the fireflies' regular flashing. Confusing these LEDs with other males, the fireflies living inside the installation readily adjusted their own rhythm to match that of the light sources, and synchronised to the beat of the pendulums.





What is striking in all of these examples is the absence of a central actor.

Lodged inside acoustically isolated chambers, small groups of *Mecopoda elongata* crickets were subjected to regular bursts of noise emitted by an analogue synthesiser. Sure enough, they joined the synchronised choir of pendulums, fireflies and various other machinery inside this strange rhythmic organisation.



For the installation version of *Synchronicity*, a simple toy-like mechanism beat the central pulse of a self-organising orchestra of machines, crickets and fireflies: two electromagnetic pendulums were placed close enough for their magnets to slightly influence each other's field. Steadily synchronising, they settle on a common beat that pervades the entire installation.

Removing the 'Self' from Organisation

What is striking in all of these examples is the absence of a central actor. Agency is not simply distributed among many actors, because the resulting behaviour is more than the sum of individual actions. Perhaps the proper way to consider it is to imagine organisation (in the broad sense, including organisms, societies and even cognition) as something inherently passive. It is self-organisation without the self. It is the intelligence of a river flowing through a landscape finding the optimal path through its constant interaction with the environment.

The artistic practice described here is concerned with how we emerge as persons, minds and societies in continuous exchange with the world around us. Art is used as a tool to represent and think about how we organise and how we are organised by our environments physically, biologically and culturally.[3] In this sense it is a tool similar to writing. Writing allows us to represent and explore language by externalising it and making it amenable to physical manipulation. In the same way, art can be seen as a tool for exploring behaviour and phenomena that are beyond our control because they emerge autonomously through our engagement with the world around us. Much like philosophy and science, this artistic practice, in its own way, strives to make sense of the world.

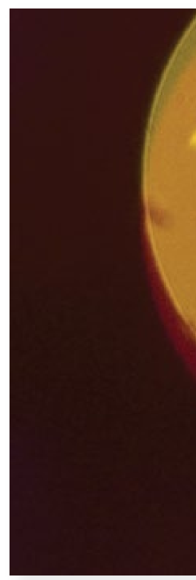
Oscilloscopes, electroencephalograms, synthesisers and other objects were synchronised to the regular rhythm of the synchronising pendulums.

The Order of the Fireflies

Every night, shortly after sunset, thousands of tiny insects gather in the bushes of the Thai mangrove forests for a fascinating mating ritual. *Pteroptyx spp*, a male Southeast Asian firefly, starts blinking in a regular rhythm, isolated at first, but slowly coordinating the timing of its flashes to synchronise with other fireflies around it. Patterns soon start to emerge – waves of light like on a ferris wheel at times, a single synchronised flash at others – as the thousands of fireflies coordinate to illuminate entire streams, trees and fields in a hypnotic light show, highly organised but constantly evolving.

Who creates this stunning coordination between thousands of tiny insects? There is no central conductor or agent that controls them. There is no outside signal that allows them to sync. Rather, the synchrony emerges from the bottom up through simple interactions between individual fireflies: each reacts to the flashing of a neighbouring firefly, slowly adjusting its own timing to match that of its neighbours. Through this simple exchange, based on a low-level neural circuit, the insects achieve a degree of organisation that surpasses that of the individual. A meta-organism seems to have arisen. Although facilitating the fireflies' mating process, it remains completely out of the control of its constituent individuals.

There is no ghost in the machine to lead the insects. Mathematical models and computer simulations confirm the absence of a leading actor.[4] With a few lines of code, millions of virtual fireflies can be simulated and their virtual flashing patterns observed and measured: the same waves, spirals and synchronies emerge autonomously out of a chaotic flickering of what resembles static noise on an old TV.



Synchronicity was produced by the Audemars Piguet Art Commission and shown during Art Basel 2015.

Synchronicity

Synchronicity is a series of artworks including a filmed experiment with synchronising fireflies in Thailand and a large-scale installation where live fireflies, crickets and various objects are synchronised with each other. Achieved by emitting specific light patterns for the fireflies and sounds for the crickets, the work asks the question: Can the common rules of self-organisation be used to compose environments where various organisms and objects self-assemble into one collective organism?

Synchronicity can be read on various levels: poetic, scientific, visual, but as a composition it is a musical form emerging on its own from the natural interactions between individuals and their environment. The organisms and objects here are not piece materials, but actors of their own individuation made audible as an ever-evolving composition brought forth by this self-creating process.

Strictly speaking, the composition resides not in the music, but in the conditions of this perpetual process of synchronisation. The music emanates from this very process, not just during static moments of synchrony, but rather as the consequence of the constantly evolving dynamics in a complex network of interactions. A multiplicity of differentiated synchronisations relate to one another, as if every evolving group is interpreting the common pulse in its own way, creating idiosyncratic rhythms of lights, movements and sounds. These rhythms appear and dissipate only to reappear a moment later, slightly different, elsewhere in the installation.

A massive tent designed by architect Ivan Mata recreated the necessary climatic conditions for the synchronisation of fireflies, crickets and machines inside the Volkshaus concert hall.

The visual and acoustic musical forms that emerge from this process are not predictable, for they are the result of a living and evolving relationship. But they are nonetheless produced. The process that *Synchronicity* reveals is neither natural nor artificial, but what French philosopher Gilbert Simondon, known for his theory of individuation, would call 'transindividualistic'.[5] This relationship surpasses and transforms the beings it relates to one another. It enables them to act in new and unpredictable ways and to collectively become something else. In such a system, relations precede the individuals they associate: there are in fact no more individuals, only processes of individuation.

Synchronicity is music without authors. Or rather, the authors are the insects, but they are not present through stylised reproductions of their songs and tunes; they are present – and creative – because they seek to adjust to the piece's central pulse. They do not sing, they evolve. And the voices we hear and see are theirs.

Notes

1. Francisco Varela, Humberto Maturana and Ricardo Uribe, 'Autopoiesis: the Organization of Living Systems, its Characterization and a Model', *Currents in Modern Biology*, 5 (4), 1974, pp 187–96.
2. Kevin O'Regan, Erik Myin and Alva Noë, 'Sensory Consciousness Explained (Better) in Terms of "Corporality" and "Alerting Capacity"', *Phenomenology and the Cognitive Sciences*, 4, 2005, pp 369–87.
3. Alva Noë, *Strange Tools*, Simon & Schuster (New York), 2015.
4. Renato Mirollo and Steven Strogatz, 'Synchronization of Pulse-coupled Biological Oscillators', *SIAM Journal on Applied Mathematics*, 50 (6), 1990, pp 1,645–62.
5. Gilbert Simondon, *L'individu et sa genèse physico-biologique*, PUF (Paris), 1964.

Kirstin Petersen
and
Radhika Nagpal

COMPLEX DESIGN BY SIMPLE ROBOTS

A COLLECTIVE EMBODIED INTELLIGENCE APPROACH TO CONSTRUCTION

Kirstin Petersen,
Justin Werfel
and Radhika Nagpal,
Termes,
Harvard School
of Engineering
and Applied Sciences,
Cambridge,
Massachusetts,
2014

Collective construction of user-specified structures by Termes robots in real life and in simulation.

Nature's builders – from termites to beavers – offer a model of collective intelligence that can inspire robotic construction. **Kirstin Petersen**, Assistant Professor in Electrical and Computer Engineering at Cornell University, Ithaca, New York, and **Radhika Nagpal**, Professor in Computer Science at the Harvard School of Engineering and Applied Sciences, Cambridge, Massachusetts, describe several recent projects in this field that they have been involved in, both separately and collaboratively.

Collective construction in nature is diverse and plentiful: from families of beavers damming up water using twigs and mud, to hundreds of sociable weaver birds precariously knitting stiff grass to form large nests in trees. On a smaller scale, hundreds to millions of insects work together to build huge living quarters using wax, mud, cellulose and faeces. These wondrous examples have a surprising unifying feature: complete lack of centralised control. Individuals coordinate by leveraging embodiment in a shared physical world. Not only can they store and pass information through the environment; they also continuously modify it to suit their own capabilities, however limited. This strategy is inherently decentralised, scales with colony size, and allows many to work efficiently on the same structure at once. Correspondingly, these natural builders have inspired the design of autonomous robot collectives that, despite being made up of simple and inexpensive individuals, can reliably create a wide range of novel structures in unprecedented settings.

COLLECTIVE EMBODIED INTELLIGENCE AND DISTRIBUTED CONTROL STRATEGIES

Collective intelligence occurs when complex behavioural patterns emerge from local interactions between many simple individuals. Not only does this methodology work across large scales in terms of both size and population; since behaviours average out, individual accuracy becomes less critical as numbers increase. These features were demonstrated at the Harvard School of Engineering and Applied Sciences in the Kilobots project (2014), a 1,024-robot swarm able to aggregate into user-specified shapes in two dimensions. Besides being very efficient, nature has proven such collectives to be relatively robust and able to quickly adapt to changing circumstances such as structural damage or loss of workforce. Furthermore, construction is an inherently embodied task. Robots both modify and sense their shared environment, leaving local cues and reacting to those left by others. They actively create the environment within which they navigate. This offers unique design advantages whereby structure, material and robots can be co-designed, minimising the complexity of each. An equivalent example in nature are mound-building termites who communicate their building intentions for later termites using local pheromone depositions. Their mounds can reach up to 10 metres (33 feet) tall. Yet these centimetre-scale termites are individually vulnerable and heavily dependent on the structures they create; they never leave their mound and build tunnels to forage.

Mike Rubenstein, Alejandro Cornejo and Radhika Nagpal, Kilobots, Harvard School of Engineering and Applied Sciences, Cambridge, Massachusetts, 2014

A swarm of 1,024 robots autonomously forming a starfish pattern in 2D. Instead of manipulating material, these centimetre-scale robots can vibrate over flat surfaces, communicate with neighbours, and exploit algorithms inspired by natural swarms to assemble user-specified patterns out of their own bodies.

Termite mounds, Otjiwarongo, Namibia, 2011

Millions of centimetre-scale African termites can construct metre-tall mounds without blueprints or centralised control.

Inspired by collectives in nature, robots may be guided by decentralised algorithms, independent of key individuals and single points of failure. Such systems rely on simple robots that may realistically and reliably perform the tasks they are given: devoid of global awareness that requires expensive sensors; of global communication that may result in bandwidth issues with increasing populations; and of complicated mechanical manoeuvres that are likely to have low success rates. Biologically inspired control methods dependent on locally propagated gradients, positive and negative feedback mechanisms, stochasticity, stigmergy and environmental templates may be employed. Evaluation criteria include power and time efficiency, convergence guarantees, scalability, and robustness to individual failures. The projects outlined below focus on two types of systems: the first leads to deterministic structures, the second to approximate structures according to environmental templates or functional goals. Although the methodology of collective embodied intelligence relies on simple individuals, it can result in robust and complex behaviours.

SUCH SYSTEMS RELY ON SIMPLE ROBOTS THAT MAY REALISTICALLY AND RELIABLY PERFORM THE TASKS THEY ARE GIVEN: DEVOID OF GLOBAL AWARENESS THAT REQUIRES EXPENSIVE SENSORS; OF GLOBAL COMMUNICATION THAT MAY RESULT IN BANDWIDTH ISSUES IN INCREASING POPULATIONS; AND OF COMPLICATED MECHANICAL MANOEUVRES THAT ARE LIKELY TO HAVE LOW SUCCESS RATES.

COLLECTIVE CONSTRUCTION IN RESEARCH

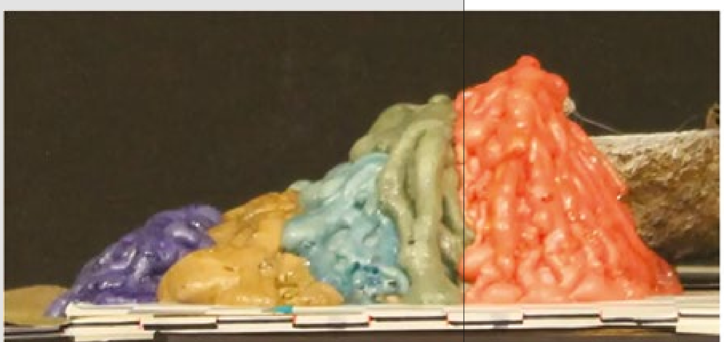
The Termes project,[1] started in 2009 at the Harvard School of Engineering and Applied Sciences, is a robot collective capable of assembling square bricks in three dimensions. Every robot has the final blueprint stored in its memory, as well as instructions on how it may be navigated, and a ruleset dependent on its mechanical capabilities. Together these guide the movement of the robots, ensuring that the local information available is enough to guarantee completion of the target structure. The robots work independently of each other; coordination is mediated without communication, only through the growing structure. If there are several pathways, the final goal may be reached in many ways.

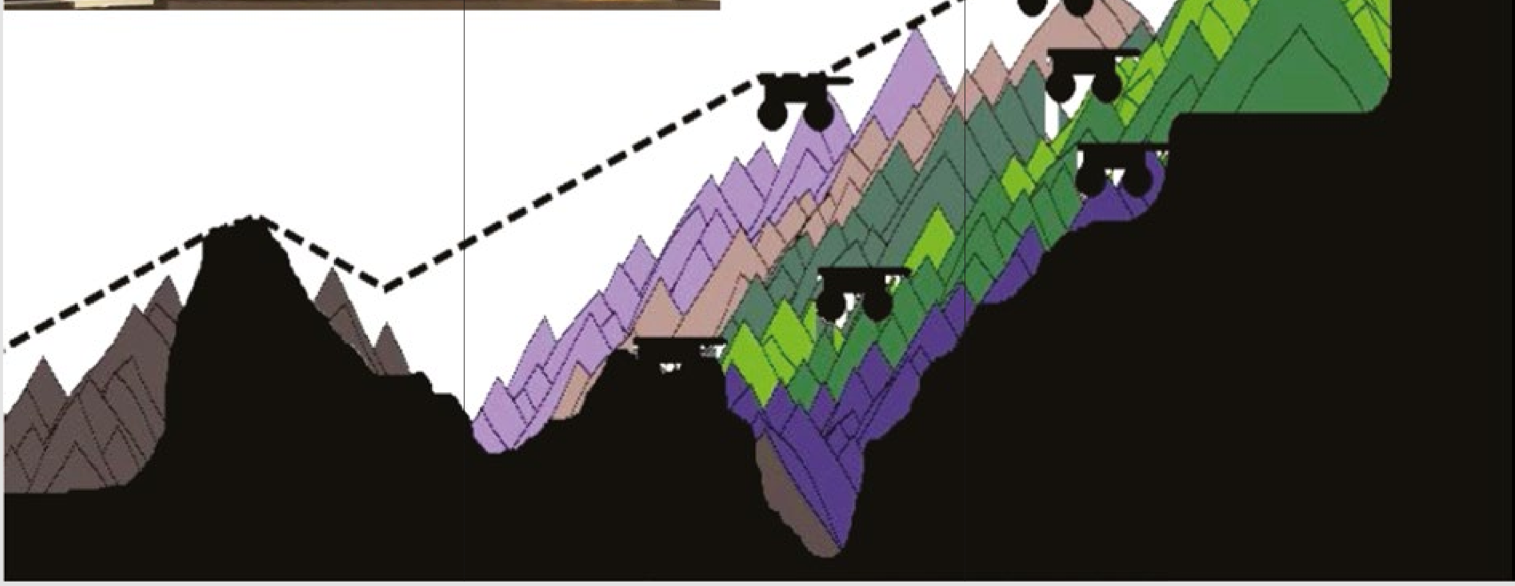
Termes is a great example of embodied intelligence. To eliminate the need for complicated sensors and control, all components are co-designed and optimised in terms of how they relate to and work with the others. The bricks have visual patterns that help guide robot navigation, notches to aid alignment and climbing, and an indented bowl to help concise on-brick turning. Magnets and interlocking features allow easy stacking. When the robots come to the end of the structure, they follow the perimeter back to the entry brick, which is also where the brick cache is located. Each has only three actuators and four types of simple sensors, yet they are capable of assembling structures more than 18 times their own volume.

In contrast to the deterministic structures in the Termes project, those defined with respect to a desired functionality may be easier to achieve. For example, in the school's Amorphous Ramp Construction project (2014), a mathematical framework was proposed where robots use local reactive behaviour to lay out material that allows them to move over unstructured terrain. Here, the robots can locally sense and drive over limited inclines while extruding foam to create ramps;[2] robots that fail or run out of material are encased within the structure. Amorphous depositions not only allow construction of continuous

Nils Napp and Radhika Nagpal, Amorphous Ramp Construction, Harvard School of Engineering and Applied Sciences, Cambridge, Massachusetts, 2014

Robot constructing with amorphous foam depositions in real life and in simulation.





structures, they also conform easily to accommodate uncertainty in the environment. Dedicated bricks are well suited for traditional shape-specific architecture and thin walls, and may aid robot navigation; expanding foam depositions are low cost and omit the need for alignment and attachment mechanisms, and allow lower-volume payloads.

In an extreme case of collective embodied intelligence, large swarms of physically programmed robots may skip traditional software control altogether. Swarmbot Assemblages,[3] a cross-institutional effort shown at the Smart Geometry Workshop in Gothenburg in 2016, involves simple vibrating robots covered in different geometrical shapes capable of assembling two-dimensional structures with user-specified properties such as temporal stability, porosity or cluster eccentricity. These systems are highly dedicated to only one or perhaps a few structural outcomes; however, they may have the potential to produce these reliably despite large internal and external perturbations. Although these systems

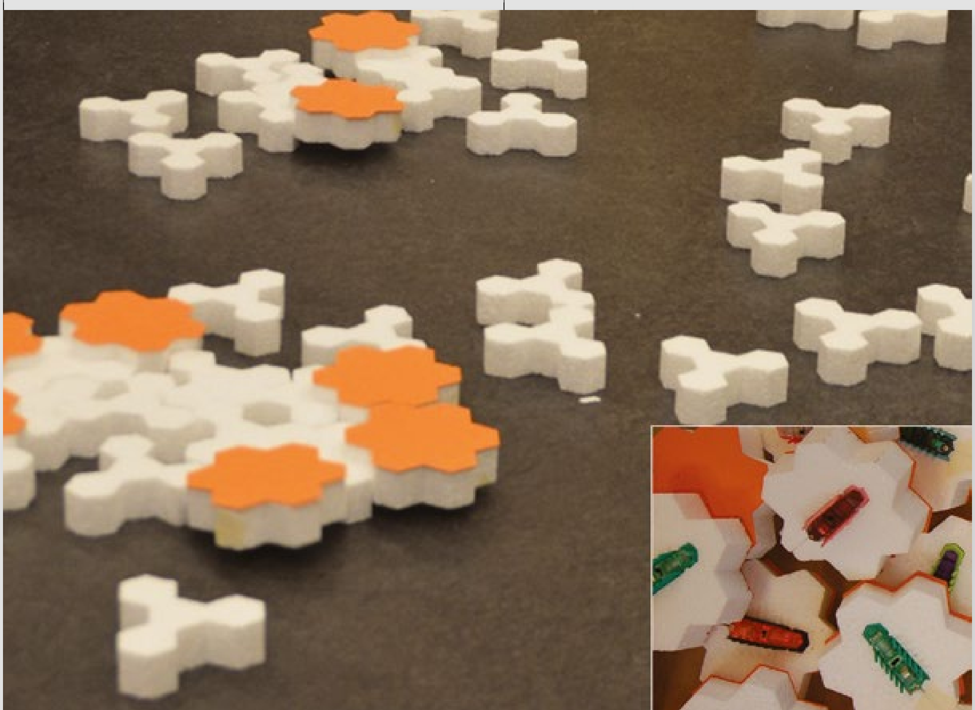
David Andreén, Petra Jennings, Nils Napp and Kirstin Petersen, Swarmbot Assemblages, Smart Geometry Workshop, Gothenburg, 2016

left and below: Two-dimensional structures with user-specified properties emerge from local interactions between large swarms of extremely simple, physically programmed robots.

are simple, thorough studies may reveal a general scientific approach on how to achieve robust collective behaviour that future systems may build on to achieve more complex objectives.

CHALLENGES IN REAL-WORLD CONSTRUCTION

The field of automated construction is gaining attention and now includes demonstrations of robot collectives, brick-laying robot arms and 3D-printed houses. Every strategy has advantages and weaknesses; it is likely that hybrid solutions will pave the way for truly automated construction. Many challenges remain, however, before these systems can be translated to the real world; most notably long-term autonomy in dynamic environments. For robot collectives, this implies both local and global error tolerance. In the TERMES system, the focus is not on error-free behaviour but rather on robots that can perceive and recover from local errors before they become a global problem. When, inevitably, a robot fails, the algorithmic framework for the collective must provide a solution. Such challenges in robot-enabled construction may continue to be addressed using biologically inspired principles for robustness and scalability. ⌂

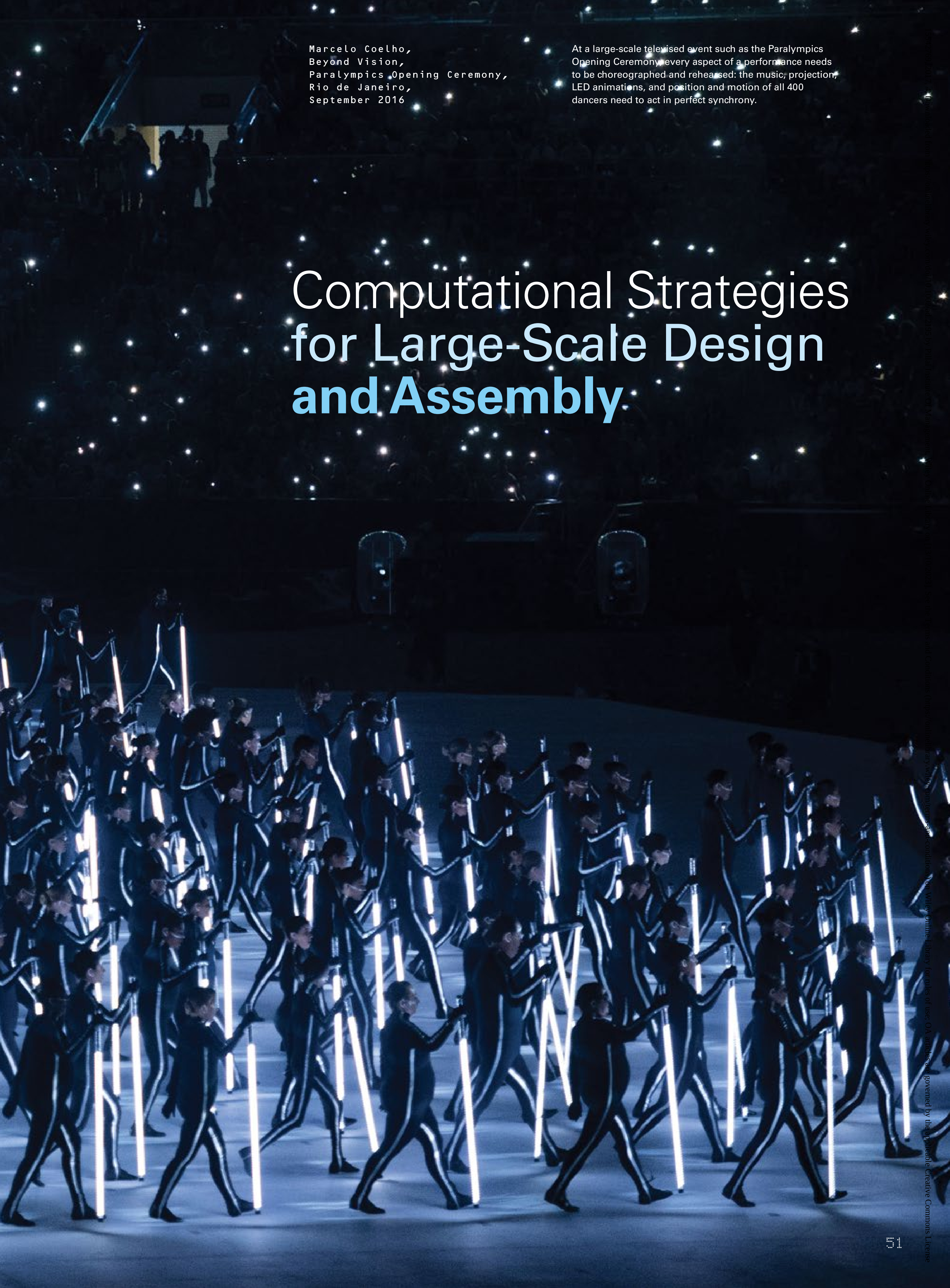


Notes

1. Justin Werfel, Kirstin Petersen and Radhika Nagpal, 'Designing Collective Behavior in a Termite-inspired Robot Construction Team', *Science*, 343 (6172), 2014, pp 754–8.
2. Nils Napp and Radhika Nagpal, 'Distributed Amorphous Ramp Construction in Unstructured Environments', *Robotica*, 32 (2), 2014, pp 279–90.
3. David Andréen, Petra Jenning, Nils Napp and Kirstin Petersen, 'Emergent Structures Assembled by Large Swarms of Simple Robots', *Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, Ann Arbor, Michigan, 27–29 October 2016, pp 54–62.

Marcelo Coelho
and
Tovi Grossman

Crowd-Driven Pattern Formation

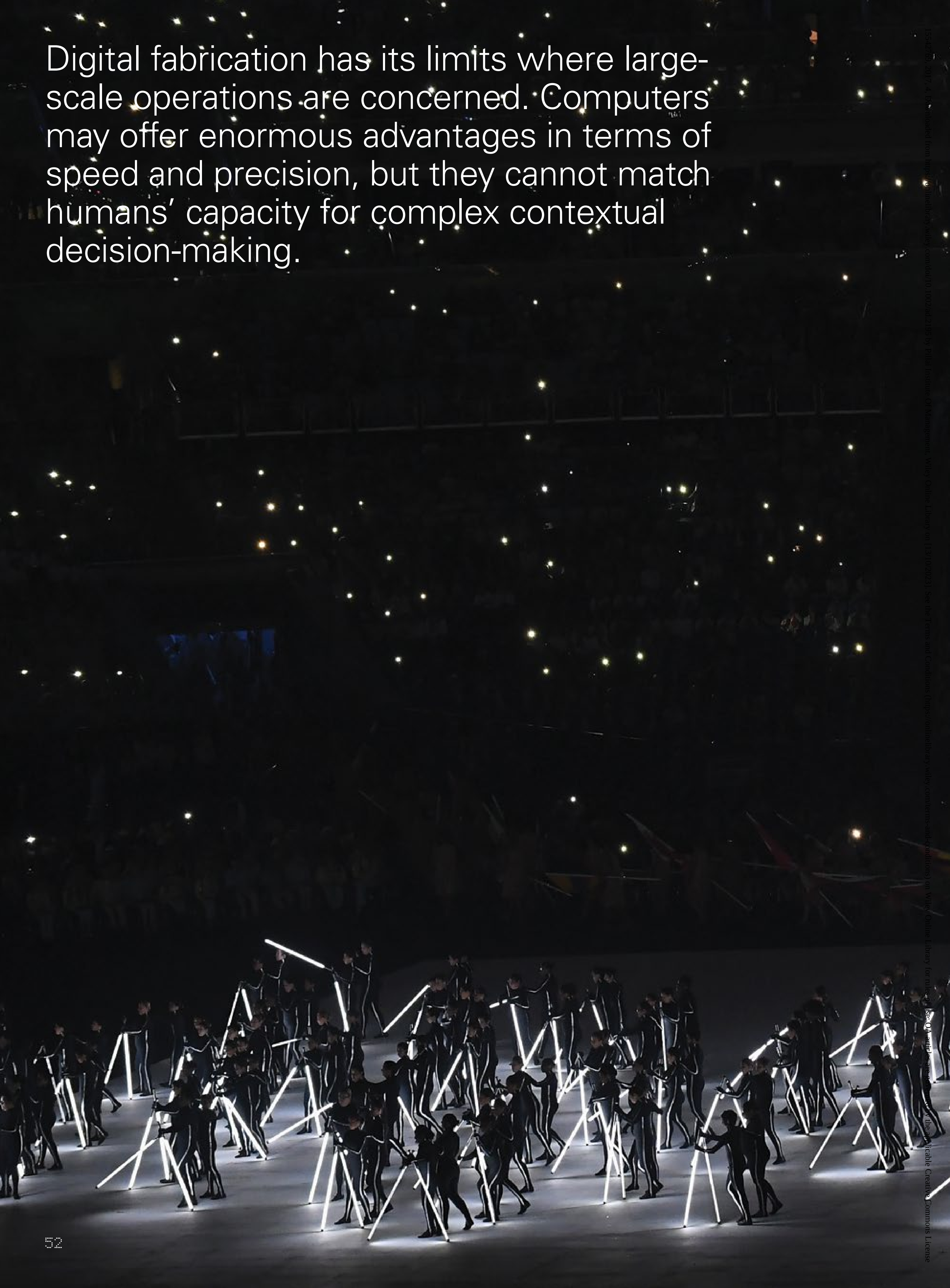


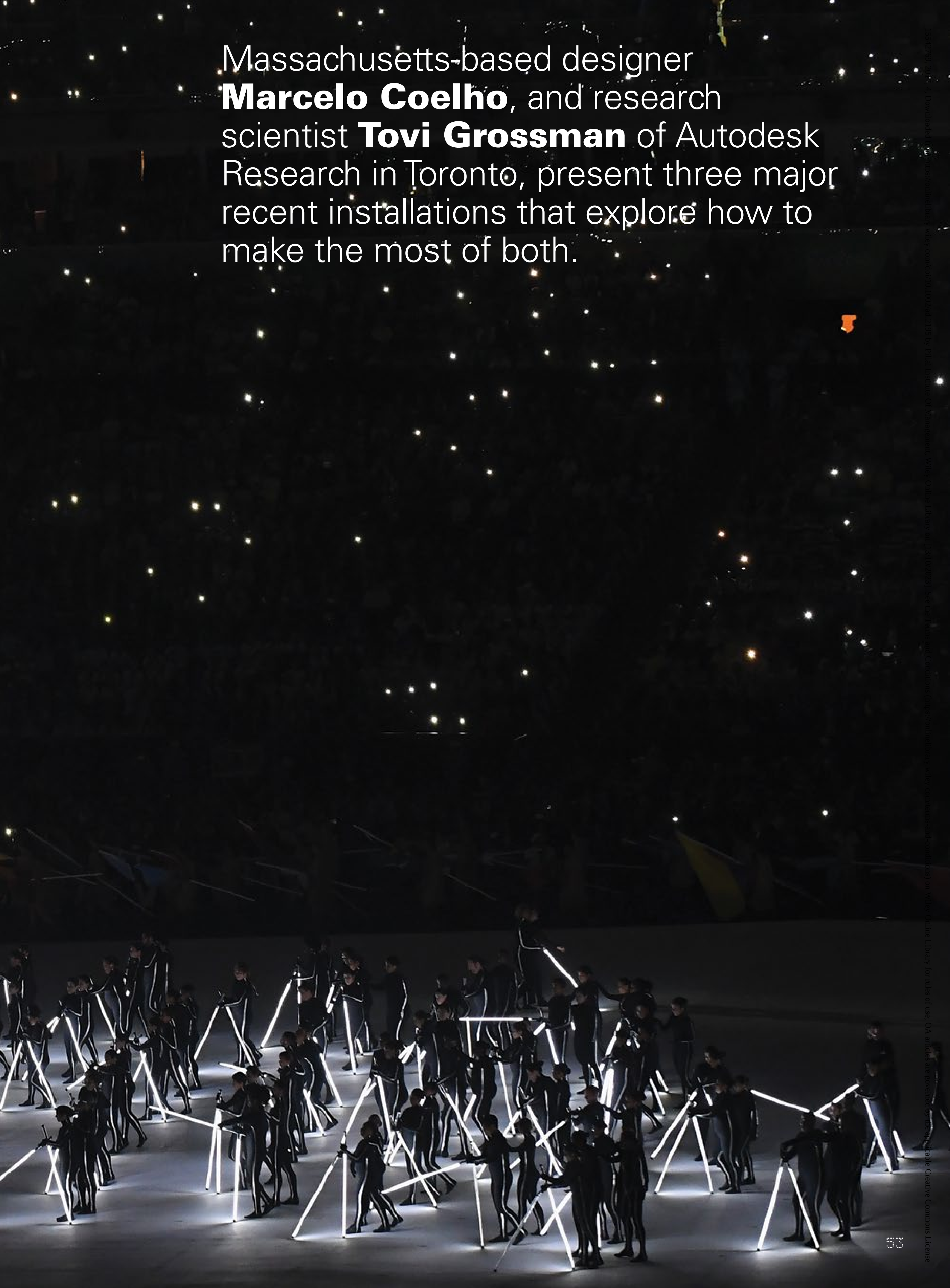
Marcelo Coelho,
Beyond Vision,
Paralympics Opening Ceremony,
Rio de Janeiro,
September 2016

At a large-scale televised event such as the Paralympics Opening Ceremony, every aspect of a performance needs to be choreographed and rehearsed: the music, projection, LED animations, and position and motion of all 400 dancers need to act in perfect synchrony.

Computational Strategies for Large-Scale Design and Assembly

Digital fabrication has its limits where large-scale operations are concerned. Computers may offer enormous advantages in terms of speed and precision, but they cannot match humans' capacity for complex contextual decision-making.





Massachusetts-based designer **Marcelo Coelho**, and research scientist **Tovi Grossman** of Autodesk Research in Toronto, present three major recent installations that explore how to make the most of both.

Every year the Arirang Mass Games held in Pyongyang, North Korea, organises an impressive spectacle of perfectly choreographed dancing and gymnastics in what might be the most incredible example of human coordination in the world. Every 20 seconds, for a period of two hours, a human mosaic composed of thousands of people switches the panels of coloured flip books to create pixellated images honouring the country's cultural heritage and political regime. In the words of photojournalist Jeremy Hunter, a crowd-driven display of this magnitude 'could only be achieved in a place where you have an unlimited resource of humans who do whatever they are directed to do. Every breath of these people is coordinated.'[1] Despite its tyrannical undertone, such a display encapsulates a stunning example of coordinated human workers collaborating to assemble an emergent large-scale form.

Marcelo Coelho, *Beyond Vision*, Paralympics Opening Ceremony, Rio de Janeiro, September 2016

previous spread: As dancers move to predetermined locations on stage, their exact position is resolved through subtle, real-time and local low-level interactions among them. In contrast, the animations displayed by the LED sticks are determined a priori, controlled by an external radio system, and are perfectly synchronised to both music and projection.

An Assembly Problem

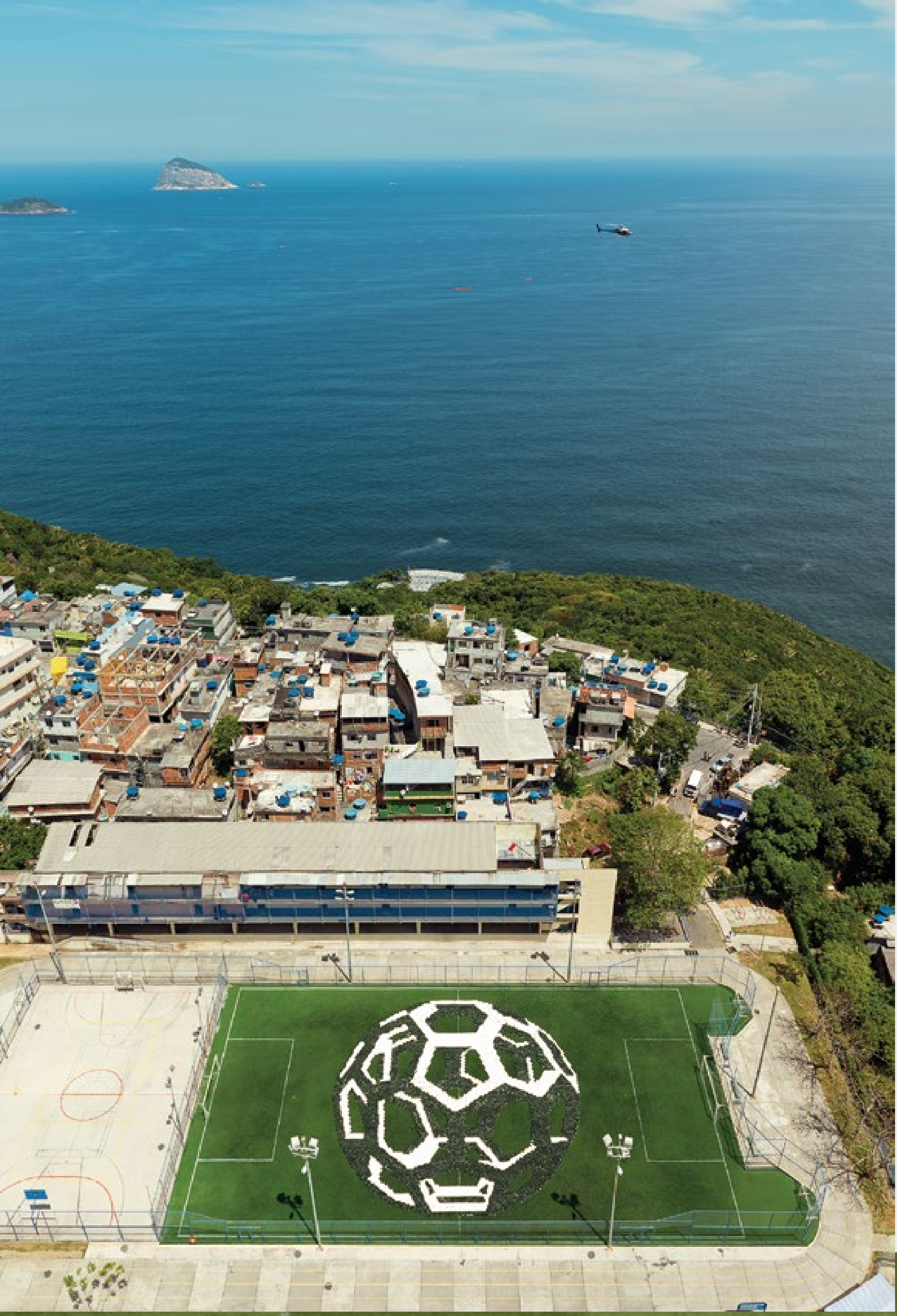
Though design software and digital fabrication tools have had a transformative effect on how we make things, their utility is still severely limited when it comes to the assembly of large-scale forms. Traditionally, information and logic flow unidirectionally and without human intervention from computers to tethered fabrication devices through programmatic instruction sequences such as G-code. For large-scale fabrication and assembly, this introduces a whole host of problems: for example, the size of machines inherently limits the size of the parts they can make; small variations in part geometry or placement can introduce compounding errors during assembly; and machines are incapable of improvising to address changing environmental conditions.

One solution is to introduce human workers back into the fabrication equation, where their observation and cognitive abilities complement the strengths of digital tools for performing repetitive and precision tasks.[2] Automaker Toyota has for years employed people alongside robots to retain human insight in its manufacturing processes,[3] a concept that can be extended to crowd-driven pattern formations in which coordinated human workers collaborate to assemble large-scale, high-level designs through small-scale, low-level and distributed interactions. This novel design space provides a number of unique challenges and opportunities. In all of the large-scale installations described below, which are collectively assembled by humans and computers working in close collaboration, there is a clear distinction between parts (the multistate physical voxels that are arranged in the space), pattern (the image or target design the system seeks to achieve) and instructions (the guidance system that provides assembly information to the human workers).

A custom software tool developed by Marcelo Coelho was used to determine the scale, place and arrangement of the balls in order to create the desired visual effect. Black and white areas are pre-registered with the help of strings and high-powered video projectors. Each soccer ball acts as a multi-state pixel that can be individually rotated to display a different black-and-white gradient.

This is Not a Ball

Created in anticipation of the 2014 FIFA World Cup, *This is Not a Ball* is a documentary directed by Brazilian artist Vik Muniz and Juan Rendón that follows the design and fabrication process of a stadium-scale drawing.[4] The film culminates with a formation of 10,000 soccer balls, recreating Leonardo da Vinci's illustration of a truncated icosahedron for Luca Pacioli's 1509 book *The Divine Proportion*.



Vik Muniz,
This is Not a Ball,
Rio de Janeiro,
April 2014

A re-creation from 10,000 soccer balls of Leonardo da Vinci's drawing of a truncated icosahedron for Luca Pacioli's 1509 book The Divine Proportion. Only when seen from the same angle from which Da Vinci drew the original image does Muniz's work appear to be three-dimensional.

The film culminates with a formation of 10,000 soccer balls, recreating Leonardo da Vinci's illustration of a truncated icosahedron

The distribution and pattern of all 400 dancers at any point in time was charted on a Cartesian grid and given to each dancer as a series of coordinates to be memorised.

Unique to the work is a custom-designed soccer ball, printed with a black-and-white gradient that acts as a multi-state pixel. A custom software tool transcoded Da Vinci's drawing into a grid of hexagonal black-and-white spheres, taking into account fundamental constraints such as field and ball size, and number of available balls. Since no industrial robots are as big as a soccer stadium, a team of volunteers acted as a large-scale human printer, rotating and placing the balls within areas delineated by a video projector.

Humans are not deterministic fabrication machines, but are good at improvising, making complex contextual decisions and real-time error correction. Prior to receiving detailed assembly instructions, the volunteers tried to parallelise their work by breaking away from the grid and following the projection outline. This deviation in the raster sequence broke the hexagonal relationship between parts and made proper tiling impossible. On the other hand, however, these low-level human decisions made it possible to easily accommodate variations in ball size and pressure changes throughout the day that would otherwise have made the task completely unachievable.

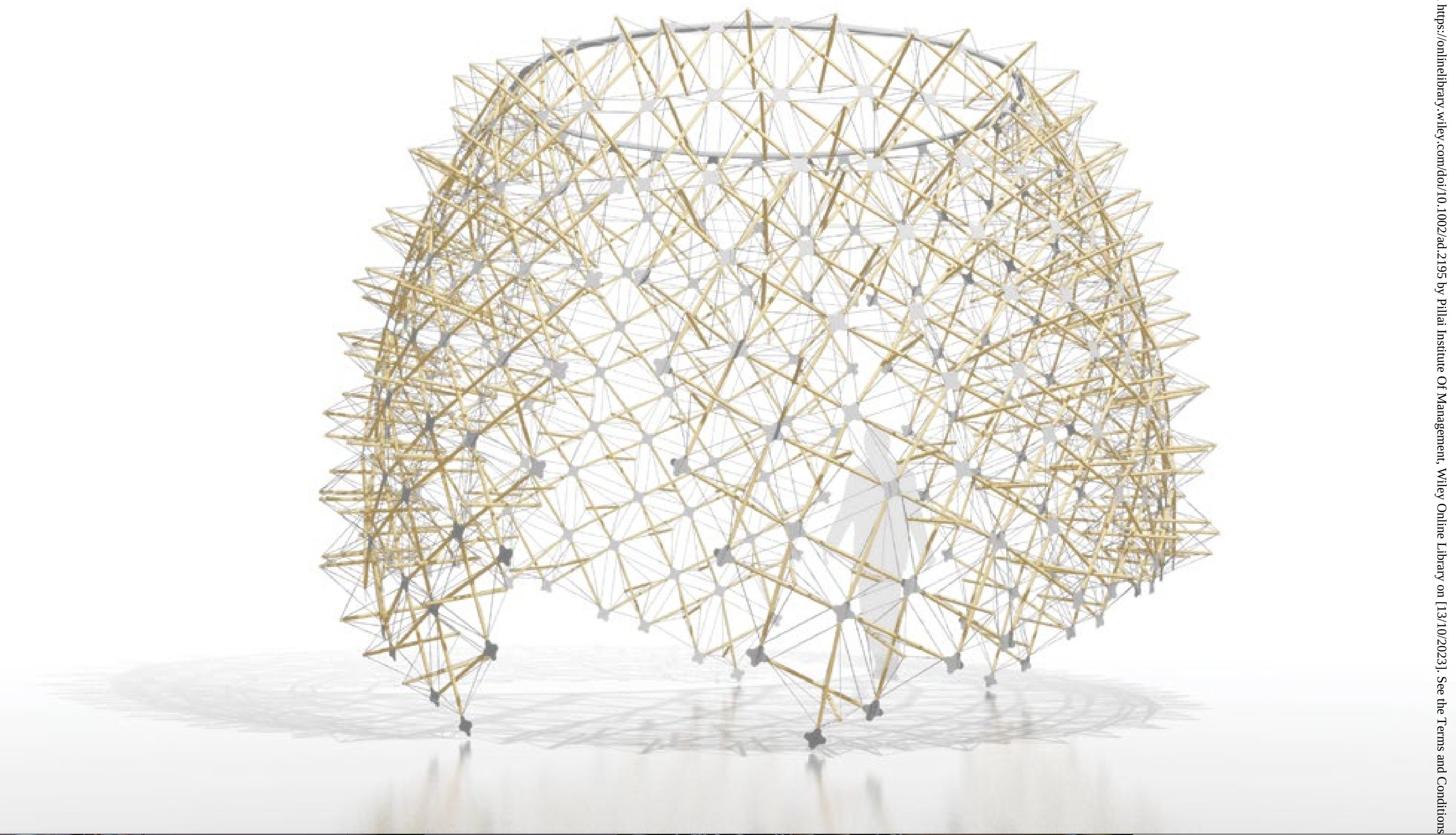
Beyond Vision

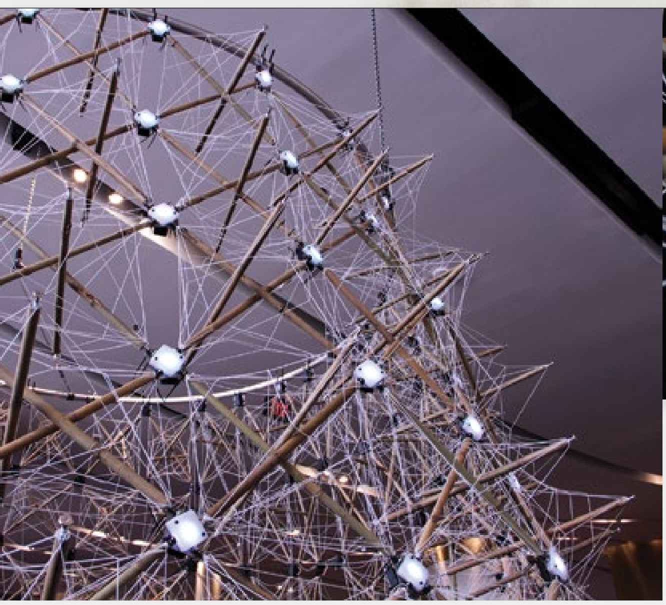
Crowd-scale pattern formation can also be used to create dynamic digital forms. In the *Beyond Vision* audiovisual performance created for the Rio 2016 Paralympics Opening Ceremony, 400 dancers were equipped with illuminated walking sticks to form a large-scale 2.5-dimensional display. As a poetic representation of the sense of sight, each stick was outfitted with a row of 128 programmable, high-intensity LEDs, which were triggered by a radio transmitter to play a series of pre-programmed animations. The distribution and pattern of all 400 dancers at any point in time was charted on a Cartesian grid and given to each dancer as a series of coordinates to be memorised.

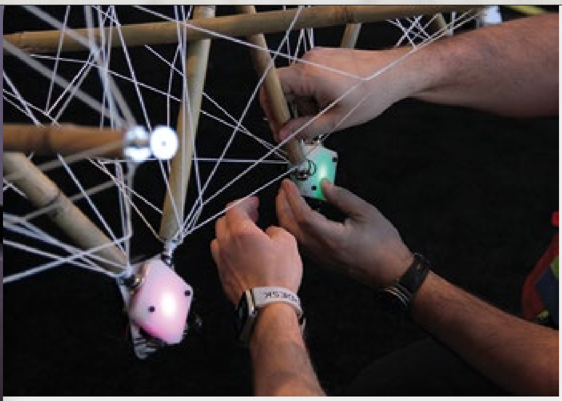
In a live televised event such as this, every aspect of a performance needs to be choreographed and rehearsed. However, even with rehearsal, it was crucial to balance the properties of a high-level animation control system with the ability of the dancers to resolve their exact location in real time through local low-level interactions. Once at a new location, dancers needed to adjust their exact position through their relative distance to others nearby. Balancing the high fidelity and precision of radio control with the improvisational skills of situated humans allowed an incredibly complex performance to be achieved in record time and to great effect.

Marcelo Coelho,
Beyond Vision,
Paralympics Opening Ceremony,
Rio de Janeiro,
September 2016

Formation of 400 dancers collectively acting as a 2.5D crowd display. While humans determine the Cartesian location of a pixel, the LED sticks animate to create large-scale visual effects.







Hive is an architectural-scale pavilion made from 224 tensegrity parts built by humans and robots working in close collaboration.

Autodesk,
Hive,
Autodesk University,
Las Vegas,
November 2015

opposite top: Illustration of the final pavilion structure, where tensegrity units are assembled together by humans and robots in close collaboration. Each layer provides both structural and informational guidance for the following layer of assembly.

opposite bottom left: As each layer of the pavilion is assembled, the structure is hoisted to make space for another layer. Once completed, large-scale animations can be played on the pavilion surface through its array of embedded LED nodes.

opposite bottom right: Two workers collaborate to attach a tensegrity unit to the larger pavilion structure. Radio-controlled LED lights and wearable devices provide guidance on where and how parts should be attached.

Hive

Extending these prior examples into the realm of 3D construction, *Hive* is an architectural-scale pavilion made from 224 tensegrity parts built by humans and robots working in close collaboration. Assembled at Autodesk University in Las Vegas over the course of three days in 2015, unskilled volunteer workers were guided through a sequence of construction steps while directly collaborating with a group of UR-10 robotic arms.[5] Instructions were generated by a central software engine and distributed in real time to the workers using a custom smart-watch application.

The unique global design of the pavilion required that each of the pavilion's parts had a unique pre-defined geometry and that they be added to the structure in a particular location and orientation. To accommodate these complex variations, each tensegrity unit was composed of three bamboo rods held together with a string wound by a robotic arm so that part geometry could be computationally specified and remain oblivious to human workers. Once a part was ready for placement, LEDs embedded in connector nodes pulsed to direct the workers to the exact location it should be attached. As every layer of the structure was assembled, an animation was played across the pavilion surface so that they could verify the accuracy of their work and correct any errors.

This division of labour affords a variety of new opportunities: digitally fabricated structures can be infinitely large; higher-level design patterns can be adapted in real time to accommodate for errors; and human dexterity can address some of the challenges of special-case assembly.

What is Next?

As the boundaries between materials and computers become blurred, new avenues will surface for digital fabrication and pattern formation to be become an interactive, distributed and highly collaborative activity in which humans play a significant role. The question still remains, however, as to where information and logic should reside and how it should flow through a dynamic system of computational materials, robots and humans. The human workers in the examples above had varying degrees of prior skills and training, ranging from rehearsed professionals to unskilled volunteers. Ultimately, by recognising and taking advantage of the skills perfected and evolved in humans for thousands of years, we can unleash completely new paradigms for design and production. ⅅ

Notes

1. 'North Korea's Amazingly Choreographed Human Mosaics', 30 April 2013: www.odditycentral.com/events/north-koreas-amazingly-choreographed-human-mosaics.html.
2. Austin Weber, 'ASSEMBLY Planbook: Man vs Machine', *ASSEMBLY*, 28 February 2008: www.assemblymag.com/articles/85269-assembly-planbook-man-vs-machine.
3. 'The Human vs Machine Race in Manufacturing', 23 April 2014: www.sikich.com/blog/post/The-Human-vs-Machine-Race-in-Manufacturing#.WCCyveErJE5.
4. *This Is Not a Ball*, directed by Vik Muniz and Juan Rendón, Netflix, 2014.
5. Benjamin Lafreniere et al, 'Crowdsourced Fabrication', in *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*, ACM (New York), 2016, pp 15–28.

The Immersive

Stagecraft to Urbanism

Alongside their architectural practice in Cambridge, Massachusetts, **Simon Kim** and **Mariana Ibañez** also run a multidisciplinary research lab. The ideology driving its work is 'The Immersive' – a notion of reconfigurable, encompassing environments created through a synthesis of science, arts and humanities. They explain their motivations and outline three manifesto projects, ranging in scale from the body to the urban.

Ibañez Kim is a design practice with a parallel research lab, Immersive Kinematics, that has been conducting several studies into an architecture and urbanism under a concept of The Immersive. Addressing the separation of scientific research from the humanities and the arts, the goal of The Immersive is to synthesise them into active and reconfigurable environments that are seamless and encompassing. The methods in which these immersive environments are produced may be highly technical and engineered, but are bent towards a refinement of affect and culture that places the importance in the social realm of theatre and spectacle.

The confluence of micro-electromechanical systems, synthetic biologies, and infrastructures governed by artificial intelligence, is bringing rapid potential to the discipline of architecture and urbanism. Architecture as a building industry, however, has been slow in responding to these recent new technologies, unlike the rapid implementation of new typologies brought about by the introduction of glass, steel and ferroconcrete in the industrial age.

The Immersive is an ideology that tethers these oncoming fields of programmable matter, multi-agent systems, and self-governance or nonhuman agency, to a humanities-based study. This Immersive recognises that human culture will exist on the same plane alongside the cultures of other species or compound beings. How the artistic production of one culture is shared with another is the subject of speculation here, with plausibility that drama, performance and music will be fundamentally different and shared within native domains. New domains of artistry, community and culture are to emerge from a shared ecology, and negate the preceding anthropocentric model.

This necessitates the superseding of a prior worldview of human at the centre and all nature and matter in subservience. Given the rise of intelligence in machines and programmable cellular assemblies, the cross-product sentience of compound beings of human–nonhuman will bring about a synthetic nature where the wild or exterior conditions are collected within a continuous immersive environment. The three projects put forward in this synthesis range from the scale of the body to the module to the urban.

Cybernetic Theatre

Architects are not strangers to theatre design. A lineage of stagecraft projects of architects may be traced from London's Architectural Association to the German Bauhaus: *Metapolis II* (2007) and the 2014 set for *Così Fan Tutte* from Zaha Hadid Architects, *The World Upside Down* (1991) by Tod Williams and Billie Tsien, and *Moving Target* (1996) by Diller + Scofidio are a few examples. What work is done in such a setting finds parallels to the production of duration and time in their building work to make it a unique form of self-critical riposte. Furthermore, if Le Corbusier can transpose the power of new industry to an architecture of machines in which to live,[1] then the new media of this current age should require that the machinery be lively and communicate a vitality at the highest expression. The venue of theatre is an ideal scenario in which to play out the forms of performance and life on nonhuman agents.

For the 2012 production *Science per Forms*, Ibañez Kim collaborated with Meredith Rainey, a former solo dancer of the Pennsylvania Ballet with his own Carbon Dance Theatre, and primatologist-turned-choreographer Marcel Williams Foster. Working on an idea of cyborgs and compound beings as raised by science and technology scholar Donna Haraway, human and nonhuman performers were entrusted with the cooperative agenda of dance. Haraway's 1984 essay 'A Cyborg Manifesto' allowed for the construction of autonomous agents and identities outside of the normative via electronic and trans-organic frameworks.[2] Completely new cultures as well as their fictions or social orders were open for occupancy. The nonhuman agents were to be as supple, gestural and emotive as their human partners on stage. Working with modular CKBots[3] (a name derived from 'connector kinetic robot') as developed by Mark Yim from Immersive Kinematics and the Modular Robotics Laboratory (ModLab) at the University of Pennsylvania, the length of limbs, number of joints and – more importantly – degrees of freedom and variations of speed were catalogued and assigned artistic values or expression. Still other modes of representation of dance were wearable devices that would trace the movements of the human dancers to a live feed that controlled digital objects, such that human dance was mirrored by a digital twin.

Given that the audience was human, the emotive elements of each turn, of each posture were communicated in intent and manners that best provoked audience response. What performance a nonhuman audience would appreciate is a question being studied in zoosemiology and in what Haraway would characterise as machine and organism hybrids with no origin story, no parts nor whole.

Ibañez Kim,
Science per Forms,
Christ Church Theatre,
Philadelphia,
2012

previous spread: The authors collaborated with choreographers and roboticists to produce an interactive and programmable ballet among human and nonhuman performers.

left: In a theatre setting, the technical aspects of the nonhuman agents' motors and joints were secondary to their grace and elegance in motion.

Ibañez Kim,
PolyHouse,
University of Pennsylvania,
Philadelphia,
2014

below left: The 'wave-gait' exhibited in modular robotics is equally productive in building-scale locomotion, more so in conditions of changing and uneven terrain.

bottom right: Outcomes of this new urban model include the exchange or sharing of resources, and a wholly different mode of ownership and occupancy.

Modular Communities

The next scale of the modular robotic unit was in community building, or in the active negotiations that drive a reconfigurable set of homes. Unlike houses of static and unyielding brick and mortar, modular robotics systems may self-assemble and organise into deployable aggregations appropriate to dynamic conditions. One advantage of this modularity over mechanisms of specialised and fixed formats is that units and modules may change in function and position as needed. What a bipedal or wheeled robot may not traverse due to overgrown terrain may be accomplished by reconfiguring into a snake-like assembly, for example.

The strength of multi-variant outcomes in goal-oriented tasks and a combinatory logic has a direct applicable transfer to architecture. Urban conditions may change in terms of number or demographics of residents, and ecologies may undergo transformation where tectonic plate movements or expanding deserts may require a human community to move. Buildings that are readily mobile, and that can reconfigure, contain certain properties that address urban life no longer based on ownership of ground, or in service to an outdated idea of value in permanence. An ideology of shared or transient groups, unencumbered with fixity in geographic location as well as tribal identity based on this urban morphology, may find new endeavours suited to adaptive situations.

The PolyHouse project (2014) developed by Ibañez Kim allows for a range of suitable urban typologies such as courtyard, coil, linear and others. The dynamic gaits and means of mobility add another dimension to this community of modular buildings that may shift, connect and refold into as-needed scenarios as their constituent occupant families change. Furthermore, as single strands, these modular buildings may move along different terrain to other settings. The enclosure of *kirigami* folds allows for openings and passages for modules to connect and seal into closed membranes when the modules detach. In another configuration study, end effectors may be attached to the modules to allow for other modes of movement.

Ibañez Kim, RolyPolygon, Harvard University, Cambridge, Massachusetts, 2016

above: Designing for human occupancy became a primary consideration over technical procedure, allowing for inclusion of soft surfaces and interactive systems.

below: Layering and directional winding of carbon fibre tow produced optical effects and patterns that could be real-time adjusted and accentuated as artistry dictated, superseding machine-conscripted point-to-point programming.

Indeterminate Environments

The RolyPolygon Confessional series (2016) was an enquiry into lightweight monocoque shells for deployable shelters. Working with the Tyler School of Art at Temple University in Philadelphia, carbon fibre reinforced polymer (CFRP) was wound about a temporary frame in a pattern that produced rigid self-support after being baked in a large-format kiln at the school. The resultant RolyPolygon Confessional is a human-sized pod that is lighter than a concrete masonry unit, made within a day, and can be tumbled into various positions for different human occupancies. Each shell is based on a sphenoid hendecahedron, a family of polygon that is able to aggregate efficiently into larger assembly so that a pod could be single or joined into a group as desired.

A higher end goal was to not only demonstrate the technical merits of CFRP winding, but to find ways to create optical effect such as moiré or interference patterns. Such differences in surface articulation could produce individual interest in mass-customising porous enclosures with varying percentages of opening. Layered with this human-fabrication interaction was a tensile fabric that lined the shell. Easily hooked into the loops of the carbon fibre, the soft surface provided a counterpoint to the rigid shell, and was also customisable with stencilled or printed graphics. Embedded into the soft surface were sensors that respond to human touch and voice. Individual systems could be developed to address the lighting or ambient sounds desired by its passenger.

The three projects converge upon the nonhuman agent and autonomous entity in a shared cooperation with human societies as put forth in The Immersive. The scalar shifts present not only the technical and tectonic aspects of the individual manifesto projects, but test the unknown domains of compound sentience for new production of shape and form that is governed in duration and time. These new social realms will have cultural and ethical differences, all present and equal, that will fundamentally change the directions of architecture as a container of form and social order, dependent on the new and expanded sentience of its occupants.

A higher end goal was to find ways to create optical effect such as moiré or interference patterns.

Notes

1. Le Corbusier, *Towards a New Architecture*, The Architectural Press (London), 1923, p 10.
2. Donna Haraway, 'A Cyborg Manifesto', *Simians, Cyborgs and Women*, Routledge (London), 1990, p 293.
3. Mark Yim, 'Dynamic Rolling for a Modular Loop Robot', *International Journal of Robotics Research*, 8 (6), 2009, pp 758–73.

Aranda\Lasch and Terrol Dew Johnson,
'Meeting the Clouds Halfway',
Museum of Contemporary Art (MOCA),
Tucson,
Arizona,
2016

Coil table prototype made from steel mesh and a half-inch bent solid-steel rod.

Baskets & Architecture

Ritualistic Making & Collective Design

You follow the rules and just relax, let those pieces of fibre in that basket just dance in your hands

— Julia Parker, weaver[1]

Is algorithmic design and fabrication really a new thing? Not according to **Benjamin Aranda** and **Chris Lasch**, co-founders of New York and Tucson-based design studio Aranda\Lasch. Through over a decade of collaborations with a Native American basket weaver, they have observed clear parallels between age-old craft forms and contemporary architectural processes. Here they give their account of the outcomes of these collaborations to date, including an ongoing project for sophisticated collective construction to serve indigenous communities.

Aranda\Lasch and Terrol Dew Johnson,
'Meeting the Clouds Halfway',
Museum of Contemporary Art (MOCA),
Tucson,
Arizona,
2016

The exhibition explored the blending of contemporary design and traditional Native American craft. This piece, made from laser-cut aluminium and creosote branches, is exemplary of this approach.

Terrol Dew Johnson,
Gourd Basket,
2008

Native American artist Johnson is known for his contemporary take on traditional basketry, as evidenced in this mixing together of a carved gourd with traditional coiling in bear grass.

For the past decade, our design practice Aranda\Lasch has been experimenting with the making of baskets as a way to blend traditional Native American craft with procedural design. What has resulted has both deepened our engagement with rule-based techniques and also informed our understanding of how to locate them within a larger cultural context. The explorations began with the observation that weaving is at its core an algorithmic process; one that builds form through action, developing material in discrete steps to eventually create a complex cultural artefact. The parallels with contemporary architectural design are unmistakable. In 2006 we collaborated with Native American weaver Terrol Dew Johnson to explore this unexpected shared foundation between our two practices and made a series of baskets for an exhibition at the Artists Space gallery in New York called 'Baskets: Rules of Exchange'. This collaboration continued piecemeal until 2016 when we redoubled our efforts in our 'Meeting the Clouds Halfway' show at the Museum of Contemporary Art (MOCA) in Tucson, Arizona.

In those 10 in-between years we realised that our explorations were not a simple juxtaposition of craft and computation. Terrol talked about his intention as an artist 'to walk in two worlds', to participate in traditional native culture while answering to the diversity of contemporary life, and be an active participant in the evolution of both. Bringing computation into the art of basketry was only one side of the exchange; the other was equally challenging and epitomised an important struggle for us as designers, namely how to understand issues such as history, tradition and ritual alongside notions of procedural, generative and collective design. Or to put it more broadly, what happens when architecture learns from baskets and the conventional divisions between craft and technology or historical and contemporary techniques begin to erode.

Building Relationships

The first watershed moment came when we asked Terrol what defines a basket in the first place. Many of his vessels contain open weaves with a lot of transparency, and throughout our exchange we were trading objects that could not necessarily hold anything in particular, like water or grain. Some of them could not hold anything at all. Terrol answered that a basket is something that holds a conversation; the practice of creating baskets is inherently social, an activity that produces opportunities for dialogue among the people making them, and with the ancestors whose practice each basket extends. But also that some baskets are in conversation with others because they share attributes and materials – a crosstalk between the objects involved in their formation. To Terrol, the baskets are about the relationships around the object, more than the object itself. Since we were mining baskets to disclose insight into architecture at large, his definition helped us open up our ideas of what architecture could be and particularly the application of rule-based systems in the making of it. Architecture also converses – between themes of universal significance, geometry and systems, and the actual experience through which these become manifest. Architecture also walks in two worlds: one entirely abstract and coded, the other very real and alive.

Ritual

The idea of making as a conversation resonates through our collaborations with Terrol in other ways as well. Ritual is a conversation between the past and present, and weaving is a material practice performed through ritual. For Terrol's tribe, the Tohono O'odham of southern Arizona and northwestern Mexico, ritual material culture and everyday utilitarian material culture are inseparable. Weaving's rituals encode knowledge through action; they contain instructions for making something while simultaneously communicating the foundational values of the society. In this way, ritual and material action are always intertwined. Through the ceremonial foraging and preparation of materials and their transformation into a basket, the weaver is guided to understand that the community and its place in the natural world – its traditions, myths and memories – exist in an extended process of materialisation.

Essentially, ritual is an encoding of rules, a way to pass knowledge from one weaver to the next, from one generation to the next. Each weaver interprets those rules through the lens he or she is given by their particular time and place. In this way, material culture progresses collectively through a feedback loop that extends to cosmic proportions, with each new generation revitalising the practice of their ancestors and evolving the practice over time. Architecture as a material practice is similarly intertwined, embedded with larger collective structures that are rebuilt and revitalised over and over again.

Coiling

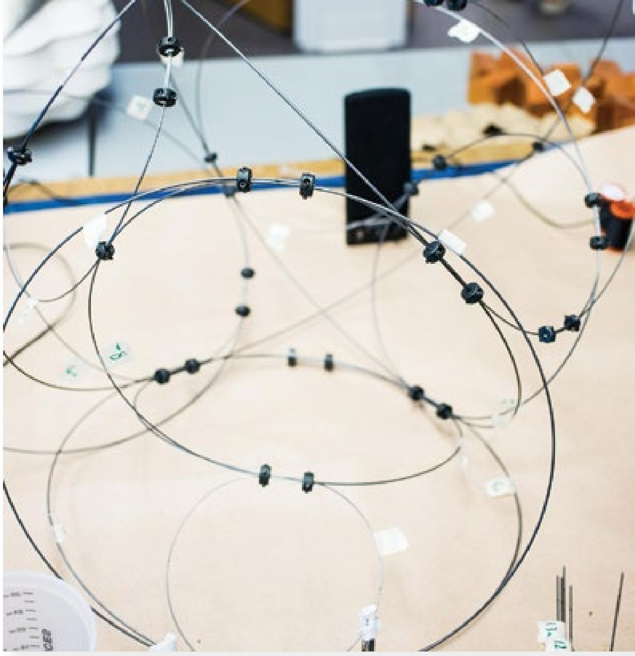
For the Tohono O'odham, ritualistic making is embodied by the coil. The act of coiling starts with one central point around which a material is wound, spiralling outwards in concentric circles to create a structural surface. Coiling generates form through pattern, building on a set of principles that can be manipulated to generate shape. As the bundles of fibre are wound around one another, the outer layer extends to create a plate-like surface, or further to create a bowl, vase or more elaborate form.

For our MOCA collaboration, we decided early on to coil three-dimensionally so that rather than ending up with surfaces we would make more open structures that would move through space and capture it. At Aranda\Lasch we have long been obsessed with the three-dimensional lattice as a way to measure and structure space, and the lattice formed the basis of this project's coiling framework as well. If traditional coiling begins and ends as a single spiral, our lattice of nested, fractal circles encourages coiling through space around multiple centres. What develops is a single line that comes back to itself to form a continuous loop, but not a complete shape. Here, the coil does not display the qualities it is most known for, but rather explores what it could be. It does not simply expand, but also grows into itself. The coil struggles to become dense, yet remain endless.

For all its complexity and limitlessness, the coil grows from a finite set of modular arcs. The lattice encodes information in the arcs through its inherent modularity and symmetry so that fabrication of a coil amounts to a sequential set of instructions made up of only the radius of each arc in the chain accompanied by rotation around its incoming and outgoing tangent vectors. In this

A number of coiled copper baskets were created using a polyhedral MDF jig.

As we bounced back and forth between digital and material experiments, each approach iteratively informed the other.



Aranda\Lasch and Terrol Dew Johnson, 'Meeting the Clouds Halfway', Museum of Contemporary Art (MOCA), Tucson, Arizona, 2016

Designs for the wire pieces were first tested in simulation software before being realised in spring steel. Ultimately, the final designs were formulated through an iterative, cyclical process of digital simulation and physical material testing.

way, a standard set of localised instructions, along with a simple custom jig, affords a practically infinite number of designs to be produced simply in a variety of materials that are suitable for plastic deformation – those that keep their shape after having been deformed by work or heat, like copper tubing or steel rod. It is a localised assembly method, like weaving; one does not need to understand the overall design, as long as one follows the simple rules that bind part to part, or action to action together in sequence. The jig is simply a single cell in the lattice. Within it is contained all of the information needed to decode the sequential instructions. Like making a basket, 'You follow the rules, and just relax ...',[2] and the pattern plays out over time, with many individual decisions conspiring to create a continuous coil.

Another approach explored elastic deformation for the construction of bending-active structures made up of thin materials with a high-elastic modulus-like fibre, wire or rod. In these structures, the deformation is reversible. Like a fishing pole, the rod wants to remain a rod. Or, if forced into an arc, it is forever trying to become a rod again. As we put arcs into conflict with other arcs, one presses on another, which presses on another, in a reciprocal manner that develops form and structure through an equalisation of tension throughout the network. Much like traditional weaving, it is the reciprocity in these structures that gives them form. Because the rods act essentially as springs, these simple structures are ideal for simulating in a live physics environment. In the simulation environment, we tested network arrangements to understand whether they were properly constrained or whether they might spring open and become unstable. As we bounced back and forth between digital and material experiments, each approach iteratively informed the other. Over time, this process challenged and then trained our instincts until the design of the bending-active networks became practised and intuitive.

Though the design of these structures conforms to the same lattice as before, the localised instructions for their fabrication are even simpler. In this case, it is only necessary to keep track of member lengths and connection points. The arc itself is a product of the geometric frustration of foreshortening a member's length through a fixed connection to other members. Once the digital design is output as a set of these paired length/connection attributes, only the constellation of connection points in local space (one rod to another) needs to be satisfied in order to recuperate the original three-dimensional design from an array of cut-to-length rods. A variety of materials were tested: spring steel wire, natural-fibre bundles of the desert plants bear grass and yucca, commercially produced fibre-composite rods, and combinations thereof.

Design and Improvisation

All of our techniques were developed under the collective construction rubric that we inherited from the weavers. Each design evolved within feedback loops intended to emulate the ritualistic design systems of our collaborator. While basic fabrication rules were set during the initial design phase, individual team members were free to adapt these as needed or desired. For example, the underlying spatial grid with its connection patterning would be determined in advance, perhaps along with the path of the primary coil to ensure basic stability. But other things would be left undetermined. This opening up of the designs through a directed yet improvisational fabrication process led to unanticipated expressions that enriched the project overall. Material choices, substructure, weaving and bundling pattern, for example, were left open and led to discoveries that were in turn absorbed into the core design instructions.

As an extension of this most recent collaboration with Terrol at MOCA, we are currently working to scale this distributed and collective construction approach to develop a number of experimental community structures on the Tohono O'odham reservation. Building on the experiments of the MOCA show, screen material is woven into the coiling's loops to provide a surface for the application of concrete. In this way, the coiled basket structure becomes the formwork for a conventional, permanent architectural material, on which unskilled but motivated tribe members might build sophisticated architectural structures for themselves with minimal instruction.

top: Seed vault model. The team is currently experimenting with the application of concrete to the coiled framework as can be seen here in this large-scale material test.

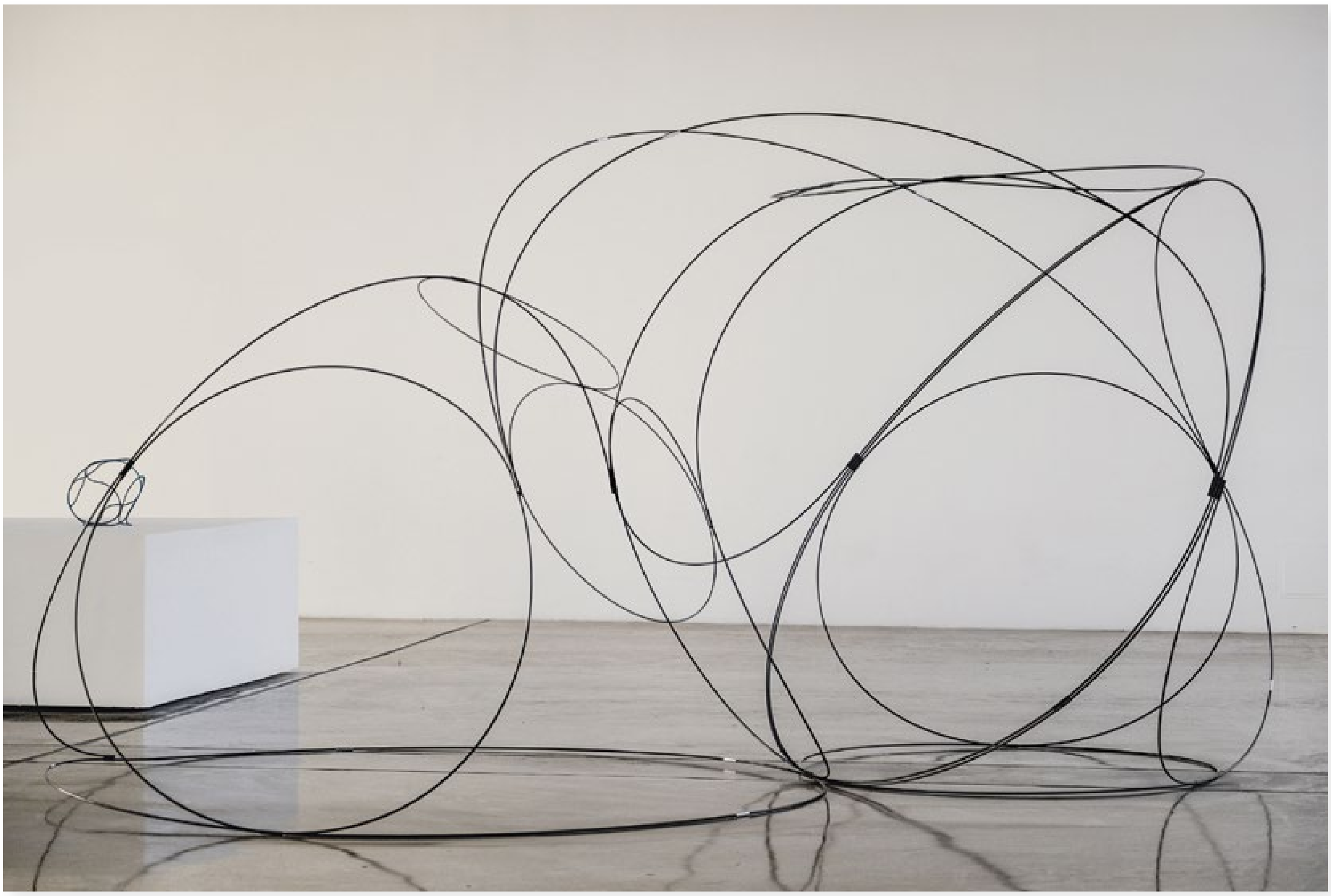
left and above: Traditional and industrial materials were mixed together in this grass coil piece.

We are also speculating on how we might further augment these rich and productive human networks with machine intelligence and robotic construction. Behaviour-based robotics, which uses sensors and machine vision to privilege adaptive behaviour over preprogrammed actions, seems to suggest a congruent extension of the design practices described here. As part of a human-in-loop computing paradigm, behavioural robotics proposes a kind of augmented construction process that echoes the traditional one in that knowledge is not entombed in unbending rules or static design specifications, but continually drawn out during construction and re-input to reinvigorate the overall process. As new generations of makers extend age-old material practices, it is important to recognise that contemporary technologies necessarily enter into the design and construction ecosystem. These innovations should be understood as an enrichment of human design culture, while at the same time we must remain vigilant of their disruptive and alienating potential. One way to guard against alienation is to recognise that contemporary fascinations such as algorithmic design, often perceived as something very new, are intimately connected to the rich and ancient traditions of one of the world's oldest material practices – weaving and basketry. When architecture learns from baskets, it becomes clear that conventional divisions between craft and technology, and between historical and contemporary techniques, are actually best understood as a continuum. ⌂

Notes
1. From Bruce Bernstein, *The Language of Native American Baskets: From the Weavers' View*, National Museum of the American Indian (Washington DC), 2003, p 27.
2. *Ibid.*

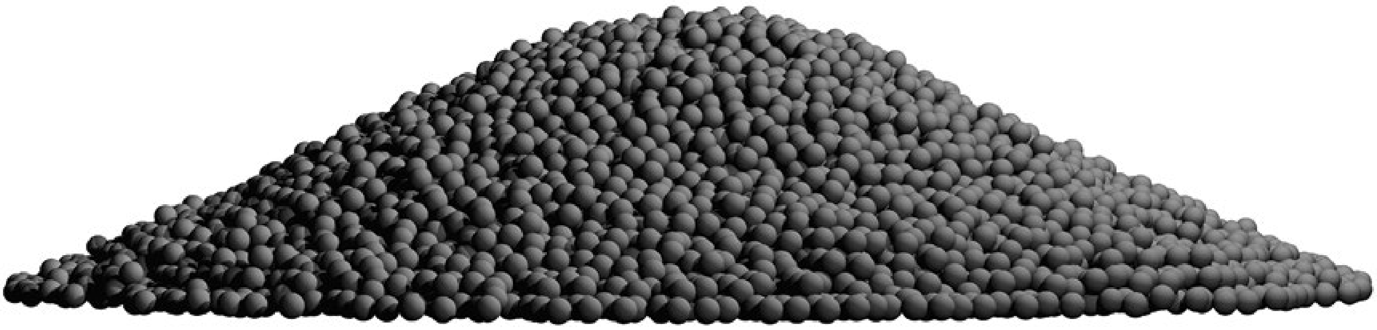
In addition to plant fibres from the Sonoran Desert, the team experimented with other traditional materials, in this case horsehair.

Material choices, substructure, weaving and bundling pattern, for example, were left open and led to discoveries that were in turn absorbed into the core design instructions.



Architectural-scale wire-nest structure made from fibreglass rod.

Kieran Murphy, Leah Roth, Dan Peterman and Heinrich Jaeger

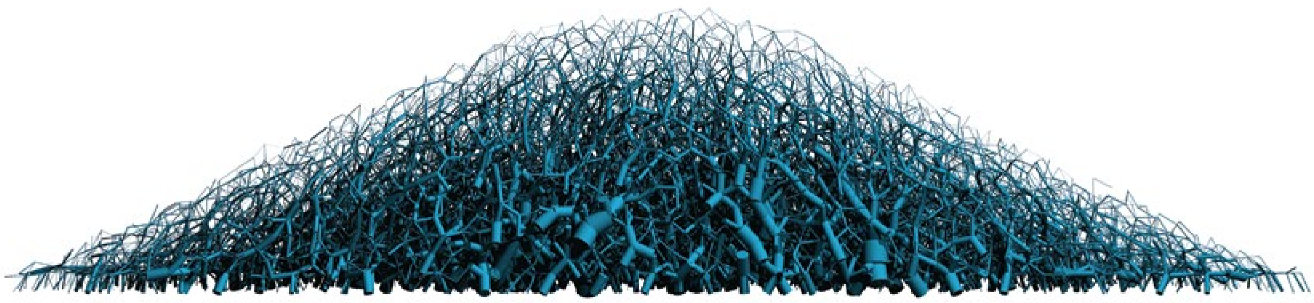


Aleatory Construction Based on Jamming

Stability Through Self-Confinement

Kieran Murphy, Leah Roth and Heinrich Jaeger,
Adaptive granular networks,
JaegerLab,
James Franck Institute,
University of Chicago,
2016

As granular particles are poured into a pile (*above*),
they form and continuously re-form a complex network of contact forces (*opposite*) until a stable configuration is reached.
This simulation of 20,000 spheres grants detailed information about the strength of the local forces,
indicated by the thickness of the lines.



The physical process of jamming could take architectural sustainability/recyclability to a whole new level. It involves achieving structural rigidity through the crowding of particles within a confined space, rather than by permanent bonding. Project Z-Form, a collaboration between a team of physicists from the JaegerLab at the University of Chicago – including PhD students **Kieran Murphy** and **Leah Roth** and professor **Heinrich Jaeger** – and artist **Dan Peterman**, sets out to develop a pourable material that not only self-supports but can also bear loads. Here they explain the project and the concepts behind it.

With traditional building methods, structural stability is attained through detailed preplanning and precise placement of components. Is it possible to engineer a material that can produce its own stability purely through interactions among the constituent parts, without external intervention? Aleatory construction, an emerging approach to this problem, uses randomly assembled elements that autonomously configure to attain loadbearing capability. In physics, the transformation from a loose collection of non-cohesive particles into a disordered solid is referred to as the jamming transition, which describes how micro-scale interactions generate macro-scale rigidity. Generally this occurs through confinement: the available volume is shrunk until there is not enough room for particles to rearrange, and the aggregate locks up spontaneously. The autonomy of this jamming process supplants preplanning, and the democratisation of design at the scale of individual building blocks opens up the potential for adaptability and recyclability beyond traditional methods. At the same time the disorder and configurational ambiguity inherent to jamming serves to introduce structural and textural complexity.

Aleatory construction applies these fundamental principles to designing constituent elements so that the properties of jamming, and thus the stability of the aggregate, emerge via self-confinement. The ongoing work in the JaegerLab at the University of Chicago's James Franck Institute takes these ideas further by removing the need for fastening or bonding agents. The goal has been to identify particle shapes that link to each other solely by friction and geometric entanglement, enabling architectures that can be rapidly deployed by pouring into a mould and easily recycled afterwards to be used anew. In using Z-shaped particles to create basic loadbearing structures such as freestanding columns and arches, the work lays a foundation for further explorations in aleatory architecture.

Jamming as a Route to Rigidity

The idea of jamming is a familiar one in everyday life. Pour coffee beans into a bag and they will flow like a liquid until they settle into a stable yet random arrangement. This configuration is fragile: a squeeze of the bag will easily cause the beans to shift and reconfigure. However, once the particles become just slightly more confined and are given less space for rearrangement, for example upon vacuum sealing, a deeply jammed aggregate is generated that can sustain significant force before deforming.

There are two important points to be highlighted. First, the flowable nature of the unjammed material allows it to be poured, quickly filling arbitrarily shaped volumes. No planning for the placement of the individual elements is needed: after providing an overall form or mould, the specific adjacencies among particles become aleatory – that is, they involve an element of chance. Second, the transition between flowable and rigid states is easily controlled via the degree of confinement. The highly irregular and disordered configuration of the particles causes them to lose their ability to move past one another upon only a slight decrease in aggregate volume, jamming the aggregate and making it rigid to external loads. Once the confinement is removed, the material can flow again and is ready to take the next shape into which it is poured.

Most assembly and construction methods, on molecular as well as architectural scales, create rigidity by carefully bonding together specific subunits. Jamming operates in a fundamentally different way: subunits press against each other due to their randomly generated adjacencies, and rigidity is achieved solely by imposing external constraints on the material as a whole. In granular media, as found in railway beds and harbour breakwaters, the individual subunits

Kieran Murphy, Leah Roth, Dan Peterman and Heinrich Jaeger, Project Z-Form: engineered disorder, Experimental Station/Peterman Studio, Chicago, 2016

Z-shaped particles, fabricated from recycled plastic, pour like sand into formwork but jam into a rigid yet highly disordered state. Upon removing the external confinement, a solid structure remains standing, ready to support weight or be recycled and used again.

Herzog & de Meuron, Gabion wall, Dominus Winery, Napa Valley, California, 1998

View from the interior of the winery. Confinement of granular material by gabions provides a means to create loadbearing walls.

rearrange to balance force and torque autonomously until they jam under their own weight. This allows the jammed granular aggregate to adapt and accommodate significant changes in mechanical load without compromising its integrity.[1]

The vein-like, highly interconnected network of stress paths inside a granular pile demonstrates the origin of this adaptivity: any local rupture in one of the links can easily be taken up by forming new connections that reroute forces through neighbours. Particles throughout the material then rearrange until all movement is arrested. The extreme disorder and heterogeneity that characterises a jammed material at the local scale thus provides an important benefit, namely the ability to rapidly reconfigure and self-heal.

The absence of cohesive bonds between particles also implies that jamming is fully reversible. Jammed granular structures that are quickly and easily deployed, starting by simply pouring the material, come apart equally easily when unjammed. This provides opportunities for creating rigid yet non-permanent structures whose elements can be recycled completely and reused.

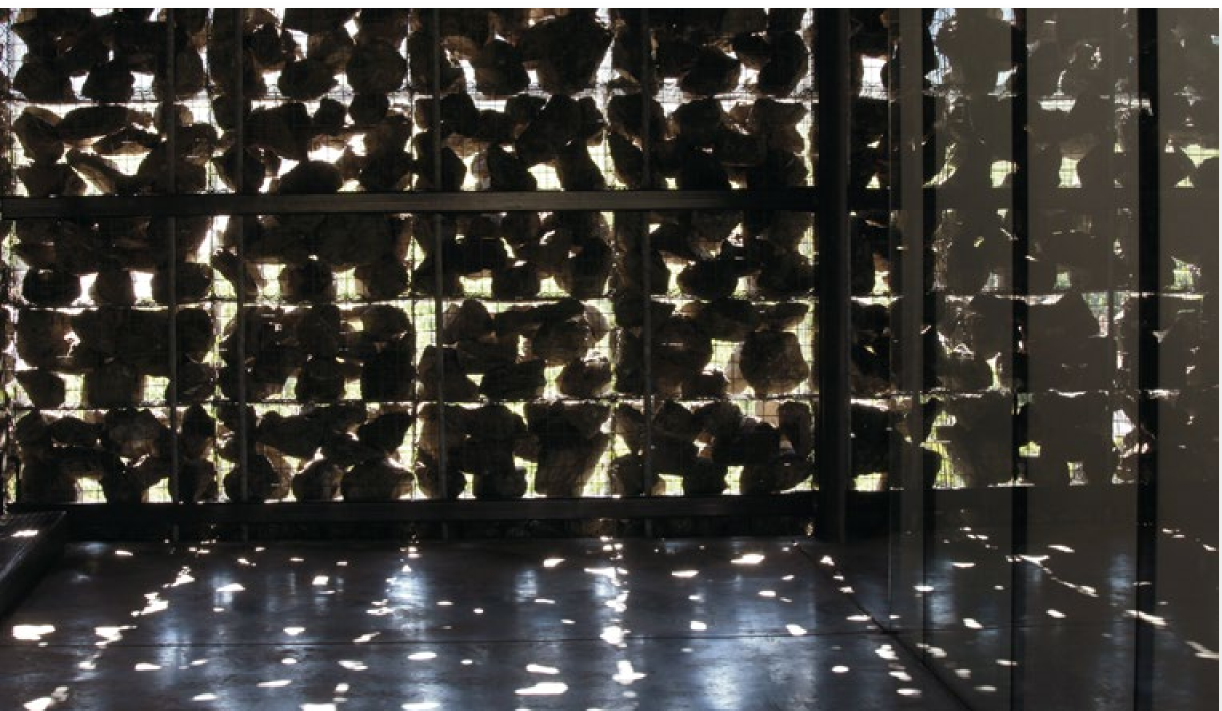
Aleatory Architectures

Cohesionless granular materials that are widely available as bulk commodities, such as sand or gravel, offer only a limited range of options for aleatory construction. Without external confinement to contain them or binding agents to provide cohesion, these materials only allow for mild slopes, as in mounds, dams or embankments. This puts severe constraints on the overall form of any structure made from such materials. In particular, it precludes the creation of freestanding structures such as slender vertical columns or arches. To create freestanding structures from cohesionless granular matter, therefore, requires further confinement.

One possibility is the use of a thin, impermeable outer membrane that allows for rigidly jammed forms by vacuum-sealing the interior, as with the coffee beans mentioned earlier. An example is the footbridge constructed as part of the Deflateables project by Ulrich Knaack and his team at the Delft University of Technology. Another option is to confine the loose material by wire cages or gabions, which have been used to construct whole buildings such as Herzog & de Meuron's Dominus Winery in Napa Valley, California (1998). However, the gabions, as well as the footbridge's membrane, play a prominent role both structurally and aesthetically, and they limit reconfigurability and recyclability.

Ulrich Knaack, Tillmann Klein and Marcel Bilow, Vacuum-jammed bridge, Architectural Engineering and Technology, Delft University of Technology, Delft, the Netherlands, 2007

Vacuum-induced confinement of granular packing inside an impermeable membrane can be used to form stable structures such as the footbridge shown here, which was part of the Deflateables project.



Over the last years several groups of scientists, architects and engineers have developed innovative ideas that can go beyond these limitations, creating initial examples of jamming-based aleatory architecture.[2] Rather than using external confinement, they have explored mechanisms internal to the particle assemblage. Gramazio Kohler Research at ETH Zurich have used string for this purpose. In Rock Print (see pp 82–6 of this issue), a large freestanding structure by Gramazio Kohler Research in collaboration with the MIT Self-Assembly Lab for the Chicago Architecture Biennial (2015), the string is laid in a preprogrammed pattern by a robotic arm and then becomes sandwiched between layers of gravel as it is poured, thereby providing tensile strength.[3] Alternatively, particle shapes that enable neighbours to interlock or entangle can provide autonomous self-confinement, simply through their geometry. Prime examples are the star-shaped particles used by Karola Dierichs and Achim Menges of the Institute for Computational Design at the University of Stuttgart in their extensive work on aggregate architecture (see also their article on pp 88–93 of this issue).[4]

Project Z-Form

A collaboration between physicists in the JaegerLab at the University of Chicago and artist Dan Peterman, who is also on the faculty of the University of Illinois at Chicago, Project Z-Form seeks to engineer a pourable granular medium that both provides its own confinement and is able to bear structural loads. The Z-shape is one of the simplest geometries able to sustain inter-particle tension, torsion, compression and shear. Variations on the prototypical Z-particle were explored in computer simulations designed to measure the resulting aggregate's ability to self-confine and withstand loads, which were then 3D-printed at centimetre scale and tested in the laboratory.[5]

Of all the Z-shapes tested, the non-planar form, with two arms pointing at 90 degrees to each other, exhibited the most dramatic properties. Snapshots from simulations show how these particles interlock, sustaining the tensile forces needed to hold the aggregate together when the column is under axial compression. Movement is frustrated due to these tensile forces and the structure is unable to collapse. From a simple shape thus emerges robust self-confinement.

Though there are multiple particle shapes capable of self-confinement, few are able to withstand additional loads beyond self-weight. Remarkably, instead of weakening under axial load, columns of Z-shaped particles strengthen and jam more deeply. In fact, as long as the column remains under compression – thus staying sufficiently jammed – the particle entanglement is secure enough to allow the entire structure to be picked up and rotated horizontally.

Testing the structural integrity and self-confinement of these shapes on an architectural scale requires larger particles. To this end, Z-forms, each 14 centimetres (5.5 inches) along their length, were cut from planks of recycled post-consumer plastic (PET), then heated and twisted into the non-planar Z-shape. Created by pouring the particles into wooden formwork and consolidating the assemblage by tamping, the jammed structures turned out to be remarkably sturdy and mechanically stiff, as well as capable of bearing significant loads. The special entangling qualities of the non-planar Z-forms lend themselves to assembling arches and spans simply by pouring the particles over inserts embedded within the mould that are later removed. As the inserts are withdrawn, the jammed structure adapts to the changing loading conditions and reconfigures in order to reroute the forces to the legs of the arch.

Kieran Murphy, Leah Roth, Dan Peterman and Heinrich Jaeger, Project Z-Form: strengthening under load, Experimental Station/Peterman Studio, Chicago, 2016

A column composed of Z-shaped particles, standing without external confinement, is able to support significant axial loads. This structure was assembled by pouring the particles into formwork and tamping to compress the aggregate before removing the confinement.

Kieran Murphy, Leah Roth and Heinrich Jaeger, Project Z-Form: geometric entanglement, JaegerLab, James Franck Institute, University of Chicago, 2016

Simulations show how tensile forces can be supported by entangled particles. The column of non-planar Z-forms (*below left*) is unconfined on all sides but the top and bottom, yet it remains rigid and loadbearing due to a minority of particles tugging their neighbours inwards (*below right*).

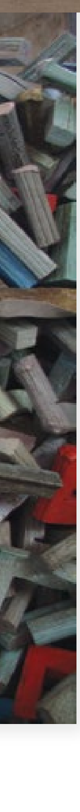
Kieran Murphy,
Leah Roth
and
Heinrich Jaeger,
Project Z-Form:
3D-printed prototypes,
JaegerLab,
James Franck Institute,
University of Chicago,
2016

below: Experiments with different 3D-printed Z-forms showed that a variant that has its two arms positioned at 90 degrees to each other exhibits surprisingly strong geometric cohesiveness: when assembled into a column, the structure is able to sustain both axial and non-axial loads, as demonstrated here by rotating the column.

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

above: To create an arch, non-planar Z-forms were poured over a spacer insert in the formwork, which initially supported much of the central weight of the structure. Upon removal, rapid restructuring of the force network occurred, yet the particles remained rigidly jammed and autonomously adapted to the significant change in confinement.

right: Close-up image of the central portion of the arch.



Project Z-Form highlights the subtlety of the structural differences that transform flowing into rigid particle configurations as the jamming transition is crossed. Whereas crystallisation reorganises the disordered internal arrangement of a liquid into the perfectly ordered lattice of a regular solid, jamming transmutes one disordered state into another through changes that are visually imperceptible. In this way, an aleatory construction produced by jamming effectively retains the particle arrangement of its unjammed precursor. The result is the intricate and highly irregular texture of a particle fluid arrested in motion.

The fluid-like particle arrangement in the jammed state suggests precariousness, yet a jammed aggregate exhibits remarkable robustness precisely because of the inherent disorder. By removing a few particles from the structure, material is locally released into its unjammed state. The aggregate flows, rearranges and quickly locks back into place. In this way, the disorder associated with aleatory construction facilitates self-healing.

Reconfigurability and Recyclability

Aleatory architecture subverts the customary hierarchy of design, suggesting a fresh perspective on how one approaches materials and forms. The dialogue between material and function is given a new edge: the architect is able to engineer the mould, but must surrender a certain amount of control and rely on the particles themselves to give shape to the structure. Tension between simplicity and complexity is at the heart of Project Z-Form. The blueprint for this novel building material contains nothing more than the simple, scale-free geometry of a single Z-shaped particle, yet emergent rigidity arises from a complex web of entanglements in the aggregate.

Jamming-based aleatory structures evoke questions not only about the traditional linkage between structural order and mechanical stability, but more generally about the quest for permanence in architecture. Where traditional construction creates resilience and permanence by fastening or bonding together individual building components, jamming uses only geometrical entanglement and friction. This makes jammed structures more transient, and at the same time opens up new opportunities: driving the aggregate back into its unjammed state, by releasing the mechanical load or toppling a column, returns the material to its flowable state, available for immediate reuse. Such recycling makes it possible to reconfigure jammed assemblages, giving them new form or rebuilding them elsewhere.

In Project Z-Form, these ideas assume an additional conceptual role. Fabricating the particles from recycled material mirrors the complete reconfigurability of the structure itself, tying the transition between jamming and unjamming to the changing of forms and states. The dual nature of the particles, composed of a recycled material and also comprising a larger structure that can be fully recycled, points towards a cycle of invention, production and generation with echoes in ecological responsibility and petrochemical dependency. In this way, aleatory architecture is placed prominently into the larger context of a materials life cycle that minimises waste and emphasises reusability.[6] ⅅ

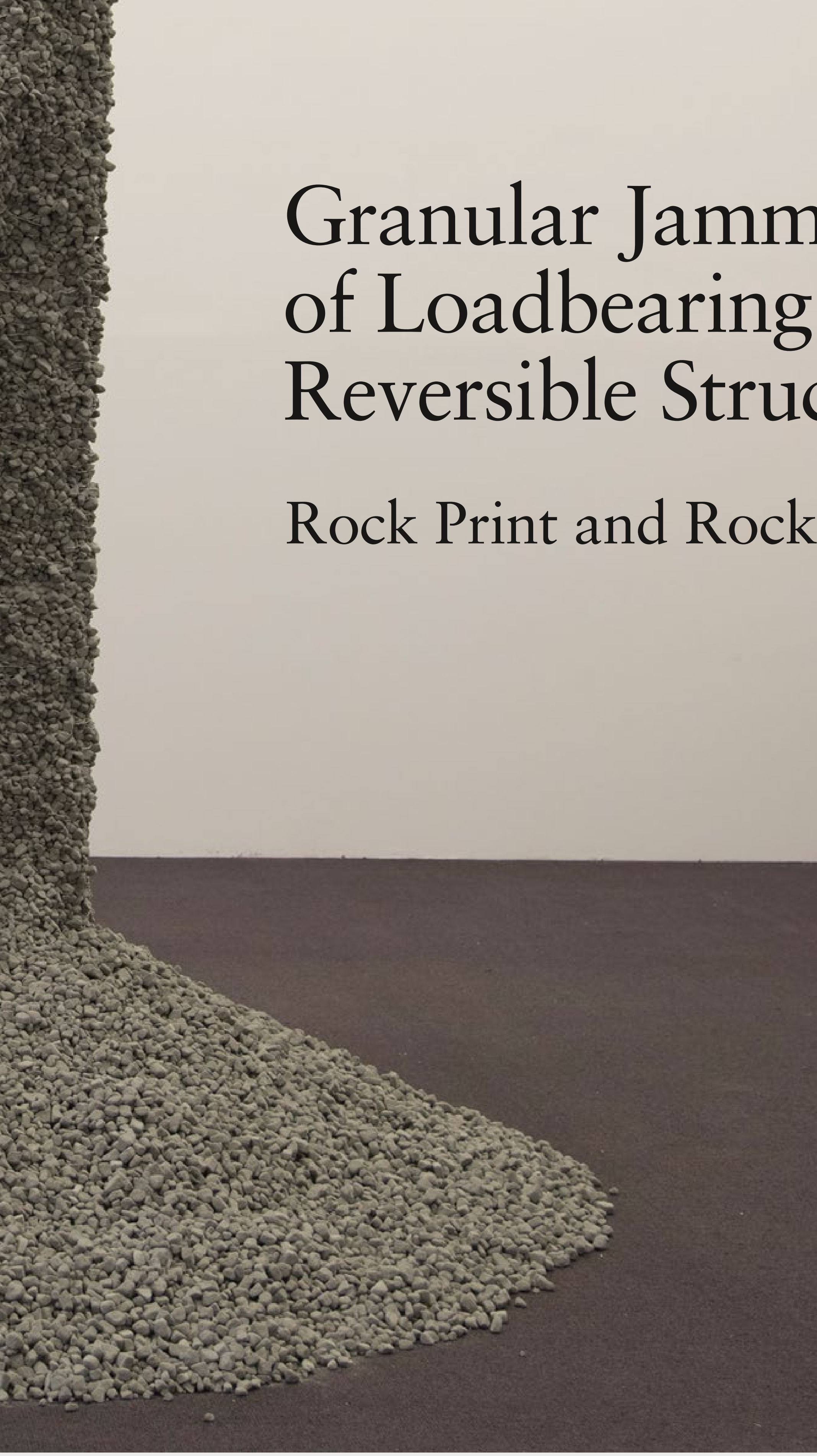
Notes

1. Heinrich M Jaeger, 'Toward Jamming by Design', *Soft Matter*, 11, 2015, pp 12–27.
2. Sean Keller and Heinrich Jaeger, 'Aleatory Architectures', *Granular Matter*, 18, 2016, article 29.
3. Petrus Aejmelaeus-Lindström *et al*, 'Jammed Architectural Structures: Towards Large-scale Reversible Construction', *Granular Matter*, 18, 2016, article 28.
4. Karola Dierichs and Achim Menges, 'Aggregate Structures: Material and Machine Computation of Designed Granular Substances', in Achim Menges, ⅅ *Material Computation: Higher Integration in Morphogenetic Design*, March/April (no 2), 2012, pp 74–81; Karola Dierichs and Achim Menges, 'Towards an Aggregate Architecture: Designed Granular Systems as Programmable Matter in Architecture', *Granular Matter*, 18, 2016, article 25.
5. Kieran Murphy *et al*, 'Freestanding Loadbearing Structures with Z-shaped Particles', *Granular Matter*, 18, 2016, article 26.
6. HMJ acknowledges support from the National Science Foundation through grant CBET-1605075. Project Z-Form was made possible by a grant from the Graham Foundation for Advanced Study in the Fine Arts.

**Petrus Aejmelaeus-Lindström,
Ammar Mirjan, Fabio Gramazio
and Matthias Kohler (ETH Zurich)
and
Schendy Kernizan, Björn Sparrman,
Jared Laucks and Skylar Tibbits
(MIT Self-Assembly Lab)**

Granular Jamming of Loadbearing and Reversible Structures

Rock Print and Rock Wall



Gramazio Kohler Research (ETH Zurich) and the Self-Assembly Lab (Massachusetts Institute of Technology - MIT), Rock Print, Chicago Architecture Biennial, Chicago, 2015

The 4-metre (13-foot) tall installation, with a 3-ton loadbearing capacity, was produced without adhesives or connections. With only loose rock and string, the structure demonstrated the possibility of granular jamming at architectural scales.

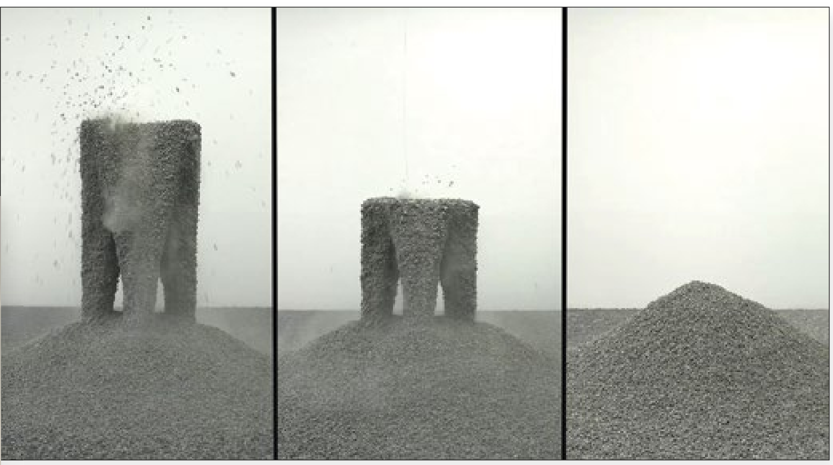
In its more common manifestations, granular jamming relies on vacuums and membranes to bring about liquid-to-solid phase change in materials. **Petrus Aejmelaeus-Lindström, Ammar Mirjan, Fabio Gramazio** and **Matthias Kohler** of ETH Zurich, and **Schendy Kernizan, Björn Sparrman, Jared Laucks** and **Skylar Tibbits** of the Massachusetts Institute of Technology (MIT), describe two projects as members of the two research groups at ETH and MIT that have been collaborating to examine the possibilities of jamming in architecture and construction.

Gramazio Kohler Research (ETH Zurich), Initial studies for Rock Print, ETH Zurich, 2015

To encourage granular jamming with rocks and fibres, a six-axis robotic arm was utilised to deposit string in precise patterns, layer by layer, in between the loose gravel. The rocks acted in compression while the string took the tension, its pattern instigating the jamming of precise three-dimensional shapes.

Traditional methods of construction, including bricklaying and cast-in-place concrete, often require long lead times and manual labour, and lack reversibility or recyclability. Recent investigations in materials science, however, have focused on granular jamming, a phenomenon that has the ability to instantly and reversibly change phase from solid to liquid and back.[1] Though unusual, it can be found in a number of everyday scenarios. These include packaged coffee that behaves like a solid when its amorphously arranged particles, when subjected to vacuum pressure, come into contact with each other and get stuck – or jam – but pours like a liquid when opened.

Unfortunately, the fragility of the membrane and need for constant vacuum mean that traditional applications of granular jamming have significant limitations for architectural structures. However, the collaborative work of Gramazio Kohler Research at ETH Zurich and the Self-Assembly Lab at the Massachusetts Institute of Technology (MIT) has recently explored a new type of architectural-scale granular jamming utilising loose rocks and fibres, without a vacuum or membrane, that enables nearly instantaneous and reversible loadbearing construction through a solid-to-liquid phase-change.



Gramazio Kohler Research (ETH Zurich) and the Self-Assembly Lab (Massachusetts Institute of Technology - MIT), Rock Print, Chicago Architecture Biennial, Chicago, 2015

opposite: The structure's geometry was designed specifically to exhibit the capabilities of granular jamming principles. Smaller at the base with slender columns that converged in a much broader apex, the tower displayed a negative angle of repose that is not naturally found with loose granular material.

above: The project was disassembled by simply removing the string in a single continuous process.

Rock Print

Rock Print, an architectural-scale prototype realised for the inaugural Chicago Architecture Biennial in 2015, combined granular jamming with robotic fabrication to realise complex architectural structures that could be fully reversed. By interlacing the granular material with string, it was possible to solidify the composite where desired. The string created a confinement around the loose aggregates and forced them to jam. Using a robotic fabrication system to deploy the string, the process defined where the material solidified and where it remained as a liquid in a controlled manner.[2] As such, the making of complex architectural structures composed of crushed rock and string can be directly linked to a digital design. The material principle works with a large variety of aggregates, allowing jammed architectural structures with local building material. Pulling the string separates the aggregates from it, allowing reconfiguration of the material into different architectural structures.

Rock Print was 4 metres (13 feet) tall and stood on four slender legs. The legs grew upwards together into a large solid design, accommodating the mass required to create the compressive force and needed to stabilise the assembly. The foundation of the tower, a pile of leftover aggregates inherited from the fabrication, created a barrier between the exhibition piece and the visitors. The structure was fabricated with a lightweight robotic arm, coupled with a string-laying end effector, mounted on a gantry system. The robot deployed the string into a container, followed by the manual pouring and packing of a thin layer of aggregates. Packing was conducted with a concrete compactor to activate the string. To assure the structural integrity of the material system, the string had to be in tension. Therefore, the pattern of the deployed string was based on circles, because of their relation between area and circumference. It was also layer-based, forming horizontal layers of string and rock. To be able to compensate for articulated geometries, such as sharp edges or overhangs, it was necessary to maintain a continuity of circles between the layers. The structure was built from the ground up and the container was extended incrementally following the vertical aggregation. The final structure was comprised of 200 fabrication layers with a thickness of 20 millimetres (approximately three-quarters of an inch) each. Once fully assembled, the container was removed, revealing the final structure. At the end of the exhibition, Rock Print was dismantled by pulling the string in one continuous process, restoring the building material into a pile of rocks and a spool of string.

Rock Wall

The Rock Wall project extended the fundamental principles developed in Rock Print to promote granular jamming of architectural structures, while exploring the speed of deployment realised in Mountain View, California in 2016. In order to increase speed, two main factors were tested: (1) a redundancy of fibres that could be quickly layered into the structure without precise placement; and (2) a slip-casting method used to continuously pour jammable walls with modular moulds, rather than printing and unmoulding the entire structure at once.

Unlike masonry construction, the aim here was to create a system that offered a faster moulding process and eliminated the need for reinforcement to provide tension within it. Tension was achieved instead by the use of loose coconut fibres within the rock deposition. Through systematic testing it was discovered that the following qualities were required for the system to work. The rocks should be at a minimum 13 millimetres (half an inch) in diameter with relation to the size of the fibres and the width of the mould. Coconut fibres were specifically used to maximise the dry friction between the fibres and were long enough to be entangled with other members while spanning the width of the wall.

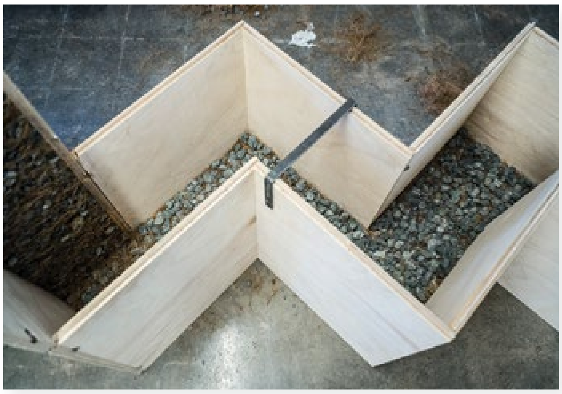
The materials were deposited in alternating layers within a modular frame. The fibre bed needed to be dense enough to create a thin even layer, but not so thick as to create patches or mounds. The same technique of thin layers was applied to the rock deposition. As the layers stacked up, hand pressure and the weight of the material allowed for the composition to solidify.

Unlike concrete forms, which must stay in place many hours while cement cures, granular jamming formwork may be removed as soon as the material has been poured. Capitalising on this property, a modular system was devised which allows incremental construction of a continuous structure with a limited number of identical elements.

Self-Assembly Lab (MIT),
Rock Wall,
Mountain View,
California,
2016

The L-shaped forms featured rare earth magnets on their vertical edges, allowing them to easily snap together into a zigzag shape. Interlocking grooves on their top and bottom edges allowed them to be stacked vertically to create tall walls. C-shaped metal brackets held the forms at a set distance from each other. While the forms could be arranged in many configurations, adequate structure is provided by the 'L' shape of the forms themselves.

Eight forms were required for the resulting wall prototype. This was enough to construct a wall with a maximum height of 1.2 metres (4 feet) – two forms tall – but with theoretically infinite length. As sections of the wall reached their maximum height, those forms were removed and repositioned on the unfinished end of the wall where construction continued. This dramatically increases the speed of the process and, through the use of the modular mould, allows for custom wall configurations.



A slip-casting process was developed using modular L-shaped walls that could be linked together, filled with the rocks and fibres to promote jamming, then moved to the end of the line to continue pouring the wall.

The depth of the continuous geometry resulted in a final wall that was strong in compression and stable under lateral force. It also supported the continuous aspect of the slip-casting method, allowing future sections to be added to the wall.

Surface details of the Rock Wall revealing the densities and patterns of the coconut husks. Given the short-term nature of the installation, and the need for extreme speed of production, the system was consequently composed of varying densities and rock-to-string ratios, while still maintaining a precise and stable structure.

Continuing Explorations of Granular Jamming

The projects here demonstrate two unique methods for granular jammable principles applied to architectural-scale applications, which avoid the traditional constraints of construction relying on either precisely placed building blocks or long cure-times and non-reversible concrete. Granular jamming was also explored with unconventional materials, at significantly large scales and without a reliance on pneumatics or vacuum-sealed membranes. The first process included robotically placed fibre for precise control over form and function, while the second slip-casting process included reconfigurable moulds and the redundancy of fibres to increase speed for fast/low-cost scenarios. Both of these methods go far beyond today's labour- and energy-intensive construction processes. Future work by Gramazio Kohler Research and the Self-Assembly Lab will aim to continually improve speed, repeatability, scalability and design freedom through granular jamming, aiming for truly instant and reversible loadbearing structures. ⌀

Notes

1. Chaoming Song, Ping Wang and Hernán A Makse, 'A Phase Diagram for Jammed Matter', *Nature*, 453 (7195), 29 May 2008, pp 629–32.
2. Petrus Aejmelaeus-Lindström et al, 'Jammed Architectural Structures: Towards Large-scale Reversible Construction', *Granular Matter*, 18 (2), 2016, pp 1–12.
3. The authors would like to thank their supporters at ETH Zurich and the Department of Architecture as well as the ETH Zurich Foundation. The work was co-supported by MIT's Department of Architecture, the MIT International Design Center, and an MIT International Science and Technology Initiative (MISTI) grant. We would also like to thank the selected experts: Professor Dr Hans J Herrmann and Dr Falk K Wittel (ETH Zurich), Professor Heinrich Jaeger and Kieran Murphy (Chicago University), Walt + Galmarini AG and the researchers at MIT and ETH who have contributed to the presented projects: Andreas Thoma (project lead Rock Print installation), Volker Helm, Sara Falcone, Lina Kara'in, Michael Lyrenmann, Georg Varnavides, Carrie McKnelly, Stephane de Weck, Jan Willmann, Dimitrios Mairopoulos, Mary Davidge, Drew Wenzel, Frances Ball, Michelle Kaufmann and Nash Hurley.

Using local rock and coconut husks, the continuous wall was built in under eight hours, the speed and precision of which indicate a future scenario of instant and reversible granular jammable construction methods.

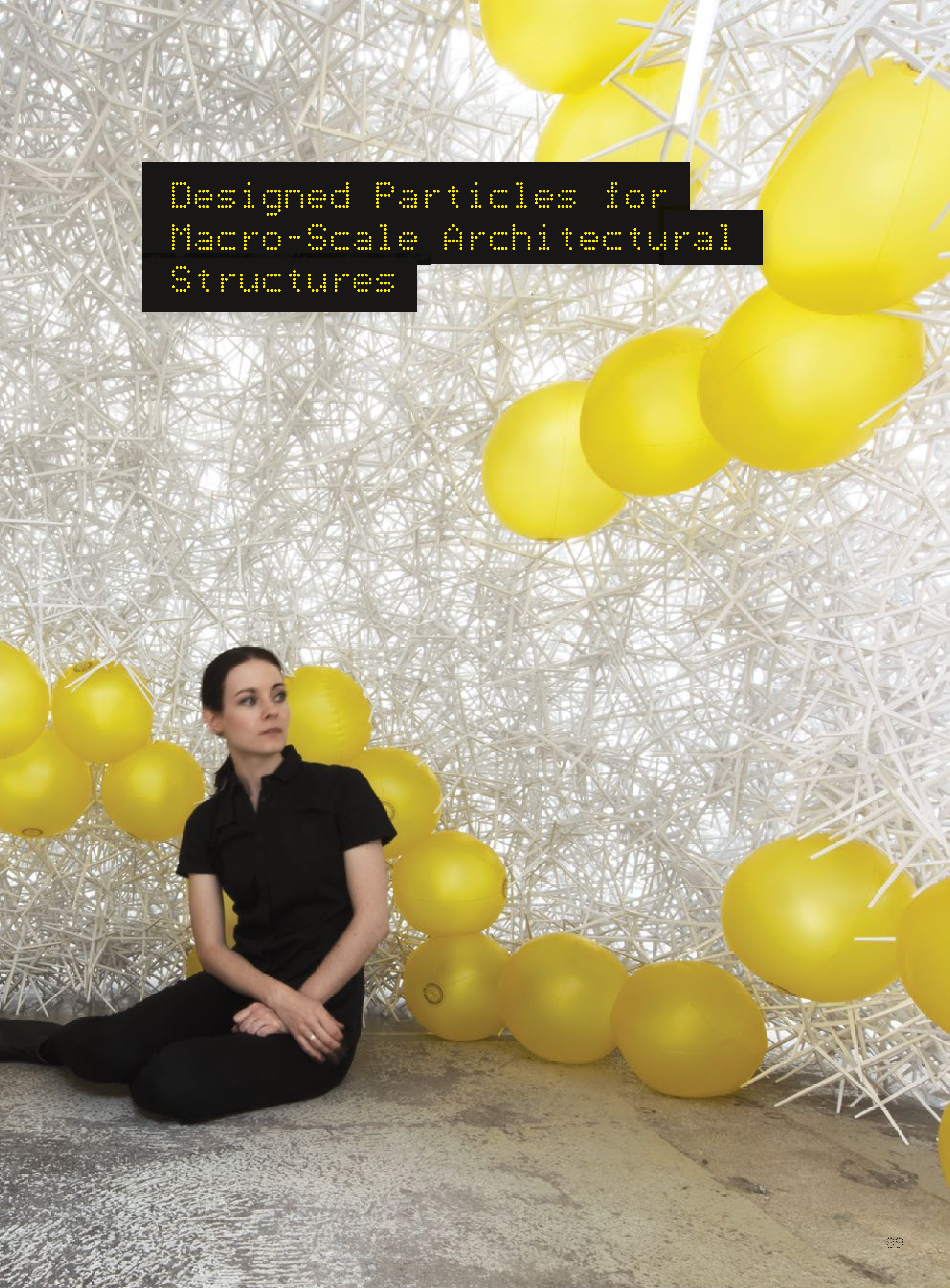
Karola Dierichs and Achim Menges

GRANULAR CONSTRUCTION

Karola Dierichs/ITECH Master Class, Prototype for the ICD Aggregate Pavilion 2017, Institute for Computational Design (ICD), University of Stuttgart, 2016

Highly non-convex particles are poured over a formwork made from convex inflatable ones, which allows for the formation of large-scale spatial enclosures.

Designed Particles for Macro-Scale Architectural Structures



Designing the individual particles of granular materials defines novel material characteristics of the overall granular system. This opens up a range of possibilities for architectural applications that are fully reconfigurable as the particles are not bound to each other. **Karola Dierichs** and **Achim Menges** of the Institute for Computational Design (ICD) at the University of Stuttgart provide an overview of recent research conducted at the Institute in this field. Autonomous construction is integrated into these systems through using either extrinsic autonomous machines or intrinsic autonomous particles.

Karola Dierichs,
Designed granular materials,
Institute for Computational Design (ICD),
University of Stuttgart,
2015

The behaviour of a granular material can be designed by defining the morphology of the composing particles.

Granular materials are vast amounts of unbound particles. They radically differ from other physical systems as they can have both solid and liquid states.[1] If deployed in architectural construction, these material systems fundamentally challenge known paradigms of design: while an architectural structure is usually fully defined and controlled in terms of its components, its assembly and its resulting overall geometry, in granular materials the particles form larger stable structures by themselves, without the need – or actually the possibility – of exact geometric control of the overall system. However, if the geometry and the material of those individual composing particles are designed, the behaviour of granular systems can be tuned. Thus granular substances of designed particles can perform as macro-scale architectural construction materials.[2] Here, granular materials become designer matter.[3]

Since their individual particles are not bound by a matrix, granular materials are fully reconfigurable and recyclable. Consequently they can be reused after each construction phase, and infinitely rearranged to allow for change and adaptation during a structure's lifetime. If the individual particles are designed, their behaviour can also be adjusted to satisfy a range of architectural construction criteria. Designed granular materials consequently embrace the relevant existing properties of granular systems and enhance them through the added effects of newly developed characteristics. Design in this context is understood as the interrelation between cause and effect – between particle morphology and granular behaviour, and between form and performance.[4]

What is distinct about any granular material, designed or not, is its ability to self-construct to a large extent. Whereas in conventional assembly each part needs to be carefully placed and joined, in a granular system each particle finds its own place in the overall structure. By their very nature, granular materials thus lend themselves to autonomous construction. Their characteristics can be calibrated and their constructional behaviour steered through the design of their particles.

Given their specific properties, granular materials require an entirely different set of design tools and technologies that can be adapted from other fields such as granular physics and statistics.[5] Both analogue experiments and digital simulations need to be integrated to arrive at a comprehensive understanding of designed granular materials. Analogue experiments frequently serve to establish first principles and proof-of-concept design models. Digital simulations allow for analysis of these results and, in a second step, for the prediction of potential behaviours of the overall system if parameters are altered. However, methods need to be developed that directly link the analogue and the digital realms in order to arrive at reliable models for such predictions and eventually for design. Since granular systems show a high degree of variance between one probe and another, these experiments and simulations need to be conducted in statistical series in order to produce reliable results.

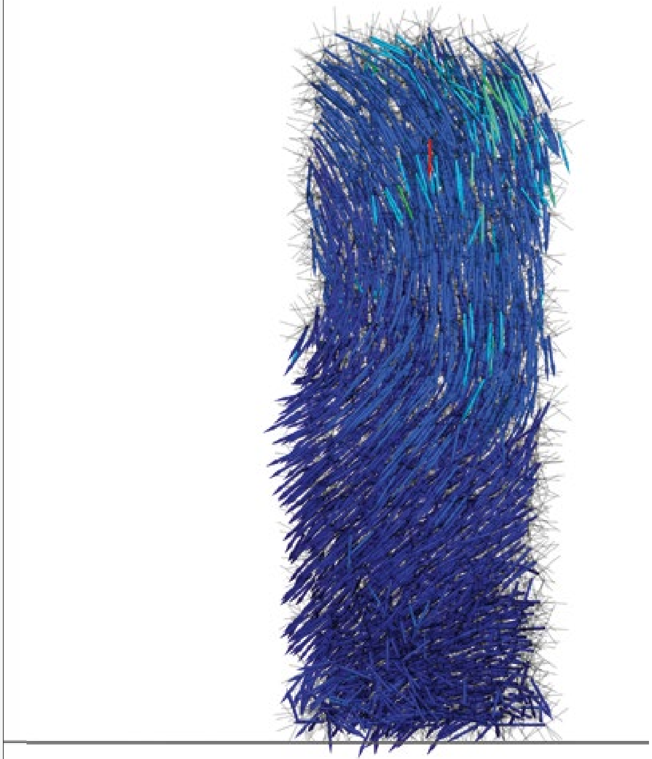
Macro-Scale Granular Systems

Designed granular materials are well suited to macro-scale construction. In principle there are no size limits to the material system, as small elements of the same type can be infinitely amassed. An example in the natural world are deserts being made from vast numbers of small sand grains. This represents a radically different approach from known assembly systems, where scaling up frequently denotes increasing the size of the elements and consequently of the fabrication processes. Furthermore, scaling up of a granular system can also be conducted in a relatively open-ended manner by simply adding more material, whereas in a controlled assembly process the final size of the structure needs to be defined at the outset. Due to the self-forming properties of granular materials, fabrication processes do not need to be very refined; the machines can even become embedded in the granular system itself, as will be shown later. Machines for fabrication are thus not as much of a scale-confining factor as in conventional construction methods. Designed or not, granular materials are also rapidly deployable; large structures can thus be quickly constructed, reconstructed and deconstructed.

In the ICD Aggregate Pavilion 2015, realised by the Institute for Computational Design at the University of Stuttgart, the material properties of the granular material were calibrated to form vertical structures that depart from the sloped angle of repose typical of naturally occurring granular systems like sand. This was achieved through the use of highly non-convex particles that geometrically interlock.[6] After initial testing of small 3D-printed particle series, three different injection-moulding tools were cut based on an economic ratio of cost-effectiveness and packing density. Altogether, 25,000 six-armed particles and around 5,000 four-armed ones were cast from recycled plastics. Several macro-scale prototypes were then tested in a laboratory setting, investigating the functional grading of columns, arches and cantilevers with different particle classes and geometric variants of these.

The project also required the custom design of a cable-driven parallel robot for macro-scale construction that could be adjusted to a range of site conditions. Initial test runs were conducted inside a scaled-down framework within an industrial production hall before the pavilion was eventually sited in an existing urban courtyard on the university campus. Here, four trees allowed for the ad-hoc and in-situ installation of the cable-driven parallel robot, which was calibrated for precise positioning and fitted with a custom radial gripper. The robotic setup consequently enabled the full-scale construction and deconstruction of the final pavilion's vertical granular structures that formed both its spatial and visual enclosures.

In parallel to the macro-scale prototyping, discrete element modelling (DEM) simulations were employed to observe particle motions and contact forces in the column formation to investigate pouring sequences for the next phase of the research.

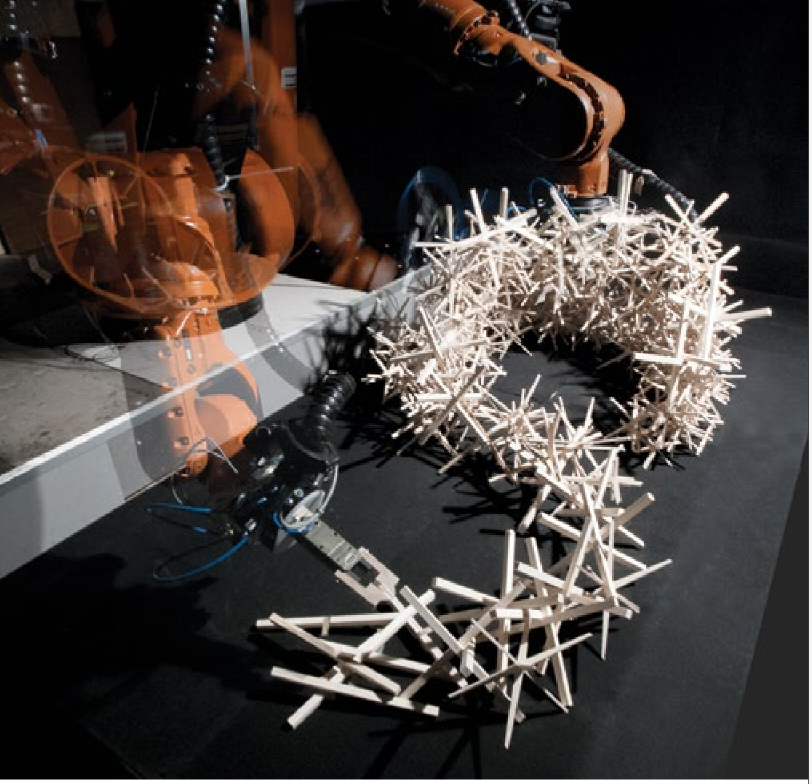


Karola Dierichs,
Simulation for the ICD Aggregate Pavilion 2015,
Institute for Computational Design (ICD)
with Itasca Education Partnership (IEP),
University of Stuttgart,
2015

Discrete element modelling (DEM) simulations are used to analyse speeds and contact forces in a granular column consisting of highly non-convex particles.

Karola Dierichs,
ICD Aggregate Pavilion 2015,
Institute for Computational Design (ICD),
University of Stuttgart,
2015

The ICD Aggregate Pavilion 2015 explores vertical granular structures as macro-scale space-defining elements.

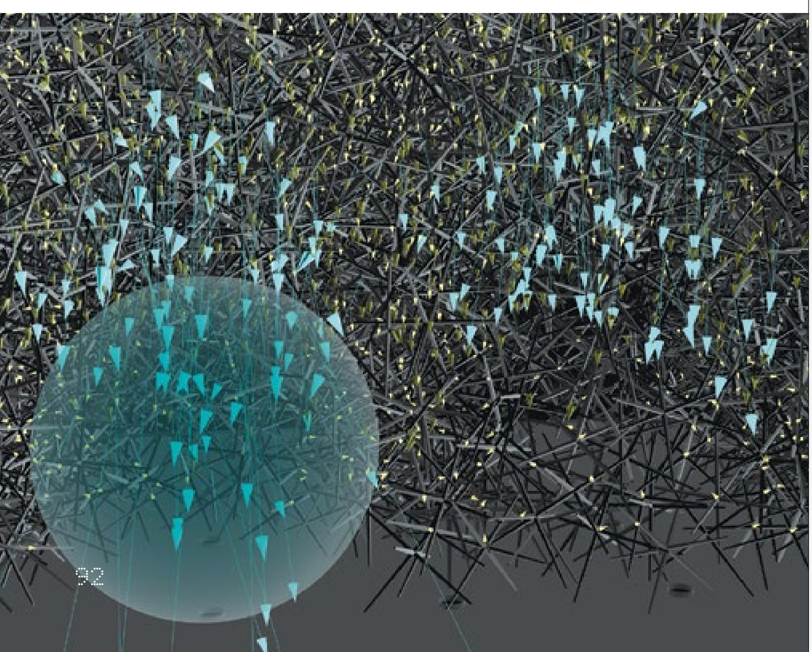


Ondřej Kyjánek and Leyla Yunis,
Regenerative Matter,
Integrative Technologies and Architectural Design Research (ITECH) master's thesis,
Institute for Computational Design (ICD),
University of Stuttgart,
2014-15

A six-axis robot with one external axis is programmed to fabricate, aggregate and disaggregate designed particles using both non-sensory and sensory controlled processes.

Gergana Rusenova,
Emergent Space,
Integrative Technologies and Architectural Design Research (ITECH) master's thesis,
Institute for Computational Design (ICD) with Itasca Education Partnership (IEP),
University of Stuttgart,
2014-15

DEM simulations are used in a feedback loop with a pneumatic formwork to analyse and control spatial formations in designed granular materials.



Autonomous Granular Construction

In the ICD Aggregate Pavilion 2015, designed granular materials were used as autonomous construction materials, whereby the particles do not need careful placement but rather self-arrange under gravity. Looking ahead, the ICD is currently exploring two further tracks to turn construction with designed granular materials into an autonomous process.

The first focuses on the development of autonomous machines that act on the granular material. The machine, be it an industrial six-axis articulated robot or a custom-made construction system, needs to be imbued with ‘intelligence’ that allows for more advanced processes of constructing with granular materials. In their Integrative Technologies and Architectural Design Research (ITECH) master’s thesis project Regenerative Matter (2014–15), Ondřej Kyjánek and Leyla Yunis established a complete loop of fabricating, aggregating and disaggregating designed granular materials. The loop combines non-sensory and sensory controlled procedures using a six-axis articulated robot with one external axis. Their approach is highly relevant for autonomous machinic granular construction since it deploys both the fast and precise production capacity of the robot for the making of the particles, as well as its ability to react to an emerging material formation for the aggregation and disaggregation of the granular system. A single machine integrates all of the diverse production processes required when working with designed granular materials. Incorporating this full loop into a large-workspace robotic system, such as a cable-driven parallel robot, might be the next step in full-scale autonomous machinic construction with designed granular materials.

In her ITECH master’s thesis project Emergent Space (2014–15), Gergana Rusenova investigated the integration of an adaptive pneumatic formwork for a designed granular material with a DEM simulation in a feedback loop. Here, the overall system of the inflatable formwork and the particles becomes an autonomous machine that can react to statistical data input from a simulation environment.

Autonomous machines enable a wide range of information and construction principles to be introduced into building processes with designed granular materials. To some extent they are indispensable, as granular materials are statistical entities that do not allow for pre-planned production procedures, but rather require the operating machine to interact with their formation.

The ICD’s second track of research explores autonomous particles, where the particles themselves are imbued with intelligence for construction and deconstruction. Matthias Helmreich’s ITECH master’s thesis project Hygrogates (2014–15), which was later part of an ICD workshop at the Domaine de Boisbuchet in Lessac, France, in 2016, is based on hygroscopic actuated particles. The particles have time-variable geometries that turn a convex shape – a stick – into a double non-convex form that has hooks. This geometric change occurs under variations in the moisture content of the wood, and is controlled through the lamination conditions of a wood-bilayer material.[7] The ability to change particle geometry over time can be strategically deployed for different stages in the construction process: for example, the packing volume of the granular system increases multiple times under actuation. Furthermore, the material moves from a pourable substance, when the particles are convex, to an entangled mass, when they are double non-convex. The process of geometry change is entirely reversible and can be steered directly through watering, or indirectly through ambient relative humidity, changing the moisture content of the particles.

The combination of actuating with non-actuating particles was explored by Alexander Wolkow in the ITECH master's thesis Mixed Linear Particles (2015–16). This approach is especially suited for large-scale construction as it combines only a few intelligent – and thus costly – particles with cheap and recycled bulk materials. The largest percentage of the granular structure is made from simple sticks cut from leftover wood materials. Only a small portion of hygroscopic actuating particles is distributed throughout the system to allow for a wider range of load cases, such as tension or shear, to be integrated.

Outlook: Robotic Granular Matter

Turning particles into autonomous entities is one of the most pertinent ways forward for macro-scale granular construction, with the promise of overcoming the need for external machines by embedding them within the granular substance itself. The autonomous particles would work either as a mass, transforming as a whole, or constitute individual agents that locally trigger changes in the behaviour of the overall system. Here, the passively actuating particles would be distributed machines acting on the very system they are embedded within. In both cases, the granular material would become robotic matter that can sense, process and react to external information and thus perform some or all of the constructional and adaptive operations itself. ◬

Notes

1. Pierre-Gilles de Gennes, 'Granular Matter: A Tentative View', *Reviews of Modern Physics*, 71 (2), 1999, pp S374–82.
2. Sean Keller and Heinrich M Jaeger, 'Aleatory Architectures', *Granular Matter*, 18 (29), 2016, pp 1–11; Karola Dierichs and Achim Menges, 'Towards an Aggregate Architecture: Designed Granular Systems as Programmable Matter in Architecture', *Granular Matter*, 18 (25), 2016, pp 1–14; Kentaro Tsubaki, 'Tumbling Units: Tectonics of Indeterminate Extension', in Gail P Borden and Michael Meredith (eds), *Matter: Material Processes in Architectural Production*, Routledge (London), 2012, pp 187–203; Michael Hensel, Achim Menges and Eiichi Matsuda, 'Aggregates 01', and Anne Hawkins and Catie Newell, 'Aggregates 02', in Michael Hensel and Achim Menges (eds), *Morpho-ecologies*, AA publications (London), 2006, pp 262–71 and 274–83.
3. Pedro M Reis, Heinrich M Jaeger and Martin van Hecke, 'Designer Matter: A Perspective', *Extreme Mechanics Letters*, 5, 2015, pp 25–9.
4. Avni Jain, Jonathan A Bollinger and Thomas M Truskett, 'Inverse Methods for Material Design', *American Institute of Chemical Engineers Journal*, 60 (8), 2014, pp 2732–40; Michael Hensel and Achim Menges, 'Performance als Forschungs- und Entwurfskonzept: Begriffe und Bezugssysteme', *Archplus*, 41 (188), 2008, pp 31–5.
5. Karola Dierichs, Desislava Angelova and Achim Menges, 'Modelling Aggregate Behaviour', in Mette Ramsgaard Thomsen *et al* (eds), *Modelling Behaviour*, Springer (Cham, Heidelberg, New York, Dordrecht, London), 2015, pp 5–15; Eric Winsberg, 'A Tale of Two Methods', *Synthese*, 169 (3), 2008, pp 575–92.
6. Yuchen Zhao *et al*, 'Packings of 3D Stars: Stability and Structure', *Granular Matter*, 18 (24), 2016, pp 1–8.
7. Dylan M Wood *et al*, 'Material Computation – 4D Timber Construction: Towards Building-scale Hygroscopic Actuated, Self-constructing Timber Surfaces', *International Journal of Architectural Computing (IJAC)*, 14 (1), 2016, pp 49–62.

Karola Dierichs and Dylan Wood with Matthias Helmreich and David Correa,
Hygroscopic Particle,
Institute for Computational Design (ICD),
University of Stuttgart,
2014-16

A hygroscopic actuated particle can change geometry over time under alternating environmental conditions, thereby allowing for variable characteristics of a granular material in different stages of the construction process.

Alexander Wolkow,
Mixed Linear Particles,
Integrative Technologies and Architectural Design Research (ITECH) master's thesis,
Institute for Computational Design (ICD),
University of Stuttgart,
Stuttgart,
2015-16

Granular materials made from bulk products, such as wood sticks, can be strategically reinforced with actuating particles, which is an entirely reversible process.

Philippe Block, Matthias Rippmann and Tom Van Mele

Block Research Group/ETH Zurich with Ochsendorf DeJong & Block Engineering and the Escobedo Group, Armadillo Vault, 'Beyond Bending', Venice Architecture Biennale, 2016

Compres Asse

Bottom-Up Performance for a New Form of Construction

Comprising 399 individually cut limestone pieces, unreinforced, assembled without mortar, and proportionally half as thin as an eggshell, the Armadillo Vault's funicular geometry allowed it to stand in pure compression.

sive

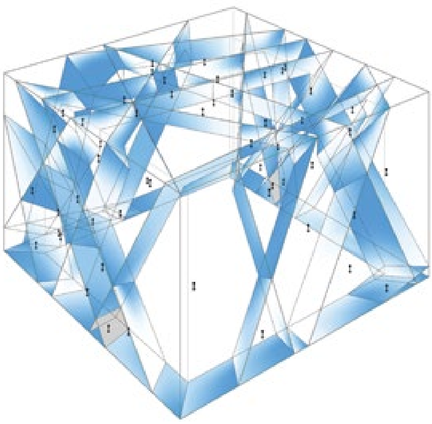
mblies

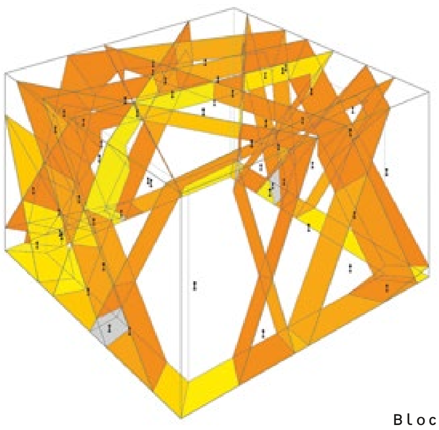
From Inuit igloos to Roman arches to Gothic cathedrals, builders have long used friction and balance to make structures hold together. The Block Research Group at ETH Zurich is involved in ongoing research that investigates historical techniques and fuses them with the latest technologies, including robotics and 3D printing, to establish new methods of architectural assembly. Group founder **Philippe Block**, co-director **Tom Van Mele** and team member **Matthias Rippmann** explain.

In distributed structures such as the Roman arch, components work together collectively to create a stable whole. Remove one component and the entire structure collapses. Each part is essential to the achievement of something greater – truly the sum of its parts. This form of bottom-up performance presents opportunities beyond traditional hierarchical structural systems to develop new forms of construction and to introduce alternatives to steel, concrete or timber.

The ongoing work by the Block Research Group at ETH Zurich revisits historical references and technologies to demonstrate that paradigm-shifting innovations can be achieved with distributed structures such as discrete-element assemblies by favouring compressive flows during and after assembly. It shows that the logic of compression-only geometry provides the opportunity to minimise or even totally eliminate falsework, simplify connection details, use weak materials, and fully embrace novel fabrication technologies such as 3D printing to significantly reduce the energy embodied in constructions.

As an extreme example of these principles, the Armadillo Vault, part of the 'Beyond Bending' exhibition by the Block Research Group with Ochsendorf DeJong & Block Engineering and The Escobedo Group at the Venice Architecture Biennale in 2016, defies the commonly assumed limitations of masonry and stone engineering and, by extension, the geometric limitations associated with discrete-element structures.[1] However, realising the shell required extensive falsework. To fully exploit the potential of discrete structural systems in pure compression and to clarify opportunities beyond their literal application in masonry, construction logics, sequencing and optimisation therefore need to be addressed.





Block Research Group, Discrete-element assemblies, Institute of Technology in Architecture, ETH Zurich, 2015

Surprising discrete-element assemblies can be designed by controlling the location and orientation of the interfaces between the elements; for example, an unreinforced, 'vaulted' box standing only due to compressive and frictional contact forces.

Reducing Falsework

Discrete elements such as bricks or stone blocks can be assembled into stable structures without mechanical connections or 'glue' at the interfaces, not only through the formation of arches, but also by using friction and/or corbelling or balancing. When fully embracing all of these structural actions, even a box can become a 'vaulted', unreinforced discrete assembly.[2] Furthermore, in combination with informed construction logics, falsework for these kinds of assemblies can be reduced or even eliminated. An igloo, for example, can be built without a supporting structure by cutting the ice blocks so that they can be placed in a spiralling sequence. Masonry domes can also be built without falsework by working in stable sections; with every completed ring of bricks, the structure is stable, and during construction of the ring the mortar's adhesion prevents the individual bricks from sliding.

For geometries that cannot be built using a spiralling or circular logic, Gothic builders developed systems using ropes, counterweights and pulleys to assemble and construct vaults with minimal supports, effectively cantilevering out in space, providing temporary reaction forces with the ropes.[3] Similar approaches could theoretically be extended to the construction of discrete, 'freeform' shell structures, using only a finite number of hooks and anchor points.[4] Although this solution is perhaps a bit optimistic and/or academic, the relevance of such research lies in finding strategies and optimisation algorithms to assemble discrete structures with the minimum amount of support or, even better, with only a few 'helping hands'.

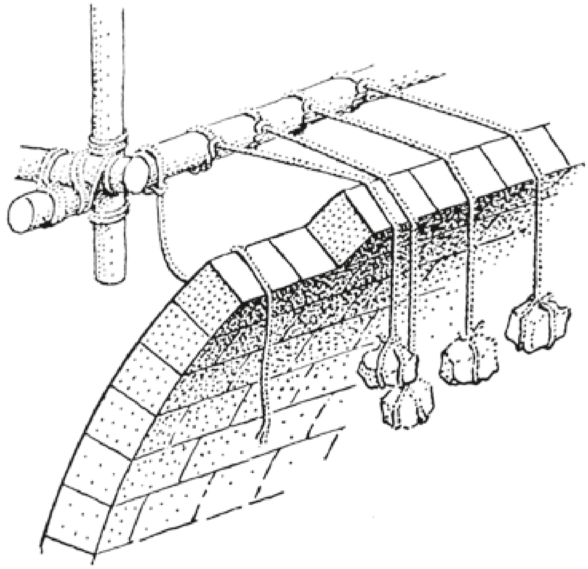
Taking this literally, the Block Research Group, in collaboration with the Autonomous Systems and Robotic Systems Labs at ETH Zurich, is investigating how complex discrete-element structures and aggregations can be assembled using only two robotic arms. These provide intermediate support where needed to maintain stability at each stage of the build until the assembly is completed. The objective of these robotic, 3D-puzzle-building exercises is to discover surprising new masonry forms and to develop efficient ways to build them with only temporary supports. In addition, the obtained knowledge can be used to optimise the construction sequence of, for example, large-scale shell roofs such that they can be safely installed from large pieces without falsework and using only a limited number of cranes on site.

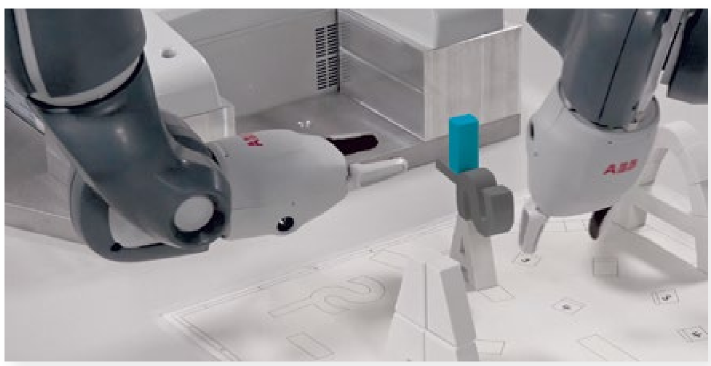
The cupola of the Sports Palace in Tbilisi, Georgia, for example, was erected in 1961 by the alternating placement of precast modules with custom, stepped-element geometries according to a specifically designed assembly sequence. The structure, with a span of over 75 metres (246 feet), could therefore be constructed without scaffolding or falsework using only two cranes placed inside the building.[5] Although the cupola has a simple domical shape, it serves as an inspiration for how smart construction logics could be applied to more complex architectural forms to optimise the erection process.

If discrete-element assemblies are designed to have only compressive and frictional contact forces at the interfaces between the discrete parts, the assembly process can be further simplified by designing the interfaces or even the entire parts so that they facilitate building in stable

John Fitchen,
System of ropes and counterweights,
1981

Gothic builders reduced the need for falsework by using a system of ropes and counterweights. From John Fitchen, *The Construction of Gothic Cathedrals: A Study in Medieval Vault Erection*, University of Chicago Press, 1981.





Autonomous Systems Lab,
Robotic Systems Lab and
the Block Research Group,
Robotic Discrete
Assemblies, National
Centre of Competence in
Research – Digital
Fabrication,
ETH Zurich,
2016

Robotic assembly of a discrete model structure using two collaborative robotic arms to temporarily support and position block elements until a new equilibrated configuration is formed.

sections with little or no temporary support required. They can be designed, for example, to be self-registering to simplify placement and alignment of the discrete elements. Furthermore, their geometry and/or that of their parts can be tailored to prevent local sliding failure and to guarantee stability in intermediate construction states, without the need for mortar or other forms of 'assembly glue'.

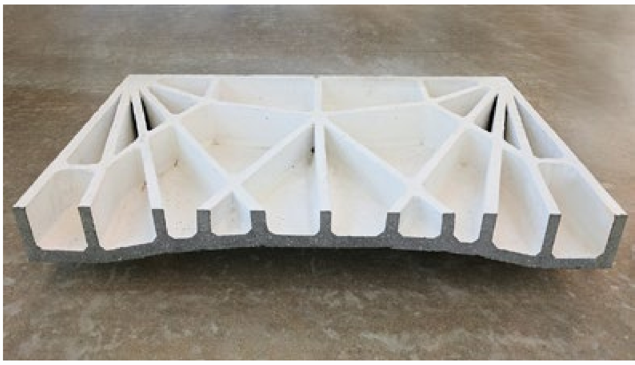
Controlling Force Flow

Following the geometry and logic of compressions, to design and discretise structures results in low stresses and therefore allows for the use of less, and even weak, material: more specifically, materials that take (humble amounts of) compression, but no tension or bending, such as stone, brick, unreinforced concrete, adobe, compressed soil and recycled waste. It also enables the removal of (steel) reinforcements, which are subject to corrosion and/or fire damage, and therefore contribute to the detriment of many structures. This presents opportunities in developing or generally resource-constrained environments where high-performance materials are often unavailable.

By 'pre-cracking' these structures to create hinges that determine the location of thrust lines in all load cases, their behaviour can be dictated further to avoid bending at all times. This principle was used, for example, by Robert Maillart when designing the Salginatobel Bridge (1930) in Schiers, Switzerland, as a three-hinged arch. Otherwise, the state of the structure is indeterminate and per definition unknown to the designer. In a manner of speaking, the structure will decide how it stands and will develop cracks accordingly in zones of tension. This is exemplified by the large radial cracks in the Pantheon in Rome,[6] or in the microcracks that develop in beams subjected to bending to activate the tensile reinforcements.

Embracing New Fabrication Technologies

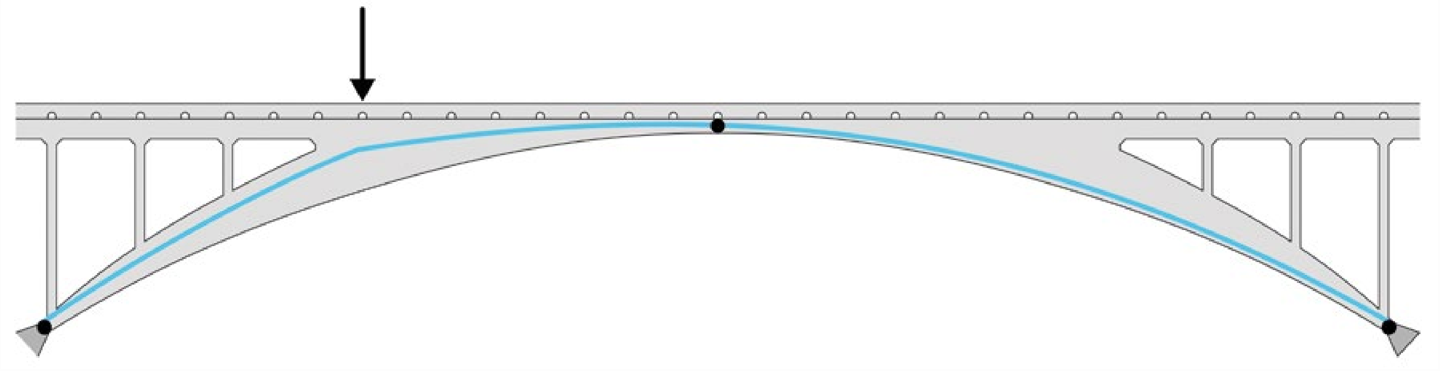
The significant potential material savings achievable through the logic of compression is demonstrated in an unreinforced concrete funicular floor developed by the Block Research Group. With a 2-centimetre (0.8-inch) thick stiffened shell, the floor required 70 per cent less material than a conventional floor slab and thus resulted in a weight reduction on the beams, columns and foundation.[7] Cavities between the shell and the stiffeners can also be used to embed low-energy heating and cooling, media and other services in places that would typically be filled up by material (in conventional systems).[8] Therefore, by integrating functions into the floor rather than layering them on top, the height of the floor can be reduced significantly. In certain contexts this results in one building level gained for free every three to four floors.[9] However, the prefabrication of this optimised structural geometry is expensive, requiring the making of double-sided moulds and therefore limiting the application to a repeated-unit or modular system.



Block Research Group, Unreinforced concrete floor, Institute of Technology in Architecture, ETH Zurich, 2013

Cross-sectional cut of the unreinforced concrete floor system with a thickness of only 2 centimetres (0.8 inches) for spans up to 6 metres (19.7 feet).

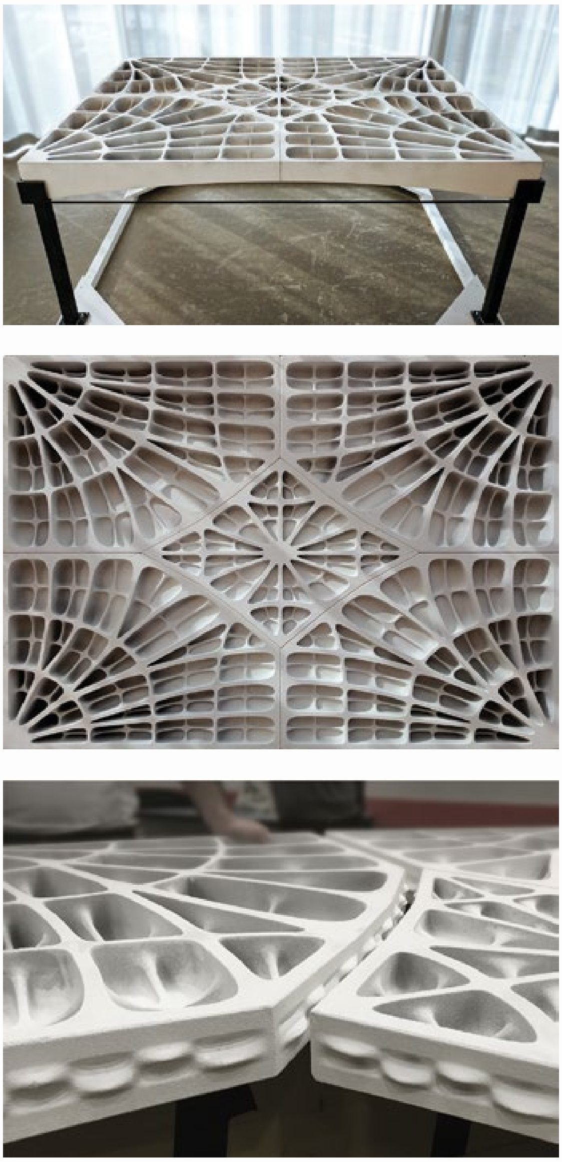
By 'pre-cracking' these structures to create hinges that determine the location of thrust lines in all load cases, their behaviour can be dictated further to avoid bending at all times.



Robert Maillart, Salginatobel Bridge, Schiers, Switzerland, 1930

The bridge was designed as a three-hinged arch to determine the location of thrust lines in all loading cases, and thus control the compressive force flow. Redrawn by the authors/Block Research Group.

In comparison, powder-based 3D printing has several advantages: it is bespoke; it does not require a mould, making it possible to print cantilevers, undercuts and so on; and it is highly precise, with a resolution literally that of a grain of sand. However, this method also brings limitations. It is challenging to integrate reinforcement, and the current maximum print size is 4 x 2 x 1 metres (approximately 13 x 7 x 3 feet). Furthermore, the printing materials are weak, with acceptable compressive strength but negligible bending capacity. As discussed above, these apparent constraints can be avoided through the use of funicular geometry and by designing pre-cracked structural systems with discrete parts.



Block Research Group, Ribbed 3D-printed floor, Institute of Technology in Architecture, ETH Zurich, 2016

The unreinforced, structural floor consists of five discrete elements with externalised tension ties. The rib pattern and discretisation layout are aligned with the 'force flow'. Male–female interlocking features on the interfaces guarantee proper alignment between neighbouring elements.

Further Potential

The concepts presented here are thus a perfect match for new fabrication technologies such as 3D printing, since complex structural components shaped by the local force flow and sophisticated, stereotomic interfaces can be printed to the highest precision. Additionally, and with the same effort, the integration of other functions and media is possible, and material can be carefully placed for room and vibro-acoustical performance and optimisation.[10]

If we are able to make 3D-printing materials safer and more eco-friendly, the results could lead to a significant reduction in the carbon footprint of our buildings and a potential paradigm shift in the construction industry. Floors would become much lighter and more compact, include integrated features, demonstrate higher comfort, and even be more aesthetic and longer lasting.

Research on the design and development of discrete-element assemblies acting predominantly in compression also creates possibilities for the development of self-supporting, stay-in-place formworks, for example for concrete surfaces and spatial structures without the need for scaffolding (and therefore foundations) to support the wet concrete.

Employing a 'masonry model' as the underlying structural principle thus not only provides the opportunity to reduce or even totally eliminate falsework, even for non-funicular final geometry, but also to optimise construction processes in general, and to discover structural applications for new technologies.

Notes

1. See Philippe Block *et al*, 'Armadillo Vault: An Extreme Discrete Stone Shell', *DETAIL*, 10, 2016, pp 940–42; Matthias Rippmann *et al*, 'The Armadillo Vault: Computational Design and Digital Fabrication of a Freeform Stone Shell', *Advances in Architectural Geometry*, 2016, pp 344–63; and Philippe Block, Matthias Rippmann and Tom Van Mele, 'Structural Stone Surfaces: New Compression Shells Inspired by the Past', in Achim Menges, *AD Material Synthesis: Fusing the Physical and the Computational*, September/October (no 5), 2015, pp 74–9.
2. Ursula Frick, Tom Van Mele and Philippe Block, 'Decomposing Three-dimensional Shapes into Self-supporting Discrete Element Assemblies', in Mette Ramsgaard Thomsen *et al*, *Modelling Behaviour: Design Modelling Symposium 2015*, Springer International (Cham), 2015, pp 187–201.
3. John Fitchen, *The Construction of Gothic Cathedrals: A Study of Medieval Vault Erection*, University of Chicago Press (Chicago), 1981.
4. Mario Deuss *et al*, 'Assembling Self-Supporting Structures', *ACM Transactions on Graphics: Proceedings of ACM SIGGRAPH Asia 2014*, 33 (6), 2014, pp 214:1–224:10.
5. DI Kadzhaya, 'Precast Spherical Cupola Roof for Sport Palace in Tbilisi and its Erection by Overhang Method', in *Symposium on Problems of Interdependence of Design and Construction of Large-Span Shells for Industrial and Civil Buildings*, IASS (Leningrad), 1966.
6. Jennifer Zessin, Wanda Lau and John Ochsendorf, 'Equilibrium of Cracked Masonry Domes', *Proceedings of the Institution of Civil Engineers – Engineering and Computational Mechanics*, 163 (3), September 2010, pp 135–45.
7. Andrew Liew *et al*, 'Design, Fabrication and Testing of a Prototype, Thin-vaulted, Unreinforced Concrete Floor', *Engineering Structures*, 137, 2017, pp 323–35.
8. Gearóid P Lydon et al, 'Coupling Energy Systems with Lightweight Structures for a Net Plus Energy Building', *Applied Energy*, 189, 2017, pp 310–26.
9. Arno Schlueter *et al*, '3for2: Realizing Spatial, Material, and Energy Savings Through Integrated Design', *CTBUH Journal*, II, 2016, pp 40–5.
10. Tomás Méndez Echenagucia, Bert Roozen and Philippe Block, 'Minimization of Sound Radiation in Doubly Curved Shell Structures by Means of Stiffness', in Ken'ichi Kawaguchi, Makoto Ohsaki and Toru Takeuchi (eds), *Proceedings of the 2016 IASS Symposium* (Tokyo), 2016.

Hannes Mayer, Fabio Gramazio and Matthias Kohler

Using a pneumatic shooting apparatus, walls were built up remotely from clay projectiles. An expression of ballistic accuracy that extended the tradition of building with clay and adobe.

Disarmed Strategies

With the aid of a scanning device and the integration of its feedback into the control of the shooting apparatus, slender walls could be accurately built. Their minimum thickness depended on their angle in relation to the direction of shooting. Learning from such inherent rules helps to establish new forms and architectural expression based on the unique construction process.

New Machines and Techniques for an Era of Computational Contextualism in Architecture

A close-up of the wall reveals the deformation of the clay projectiles and is testimony to a building process based on ballistic energy.

Digital fabrication to date has typically been blind to context. But this need not be the case – as demonstrated by the experiments of **Gramazio Kohler Research**, based at ETH Zurich. They have developed systems that employ robotic arms and flying machines with feedback control to adapt the fabrication process as it progresses. From the ballistic projection of clay in a cutting-edge version of adobe, to the interlacing of string to form suspended structures in space, **Fabio Gramazio**, **Matthias Kohler** and **Hannes Mayer** outline some of their inventions here.

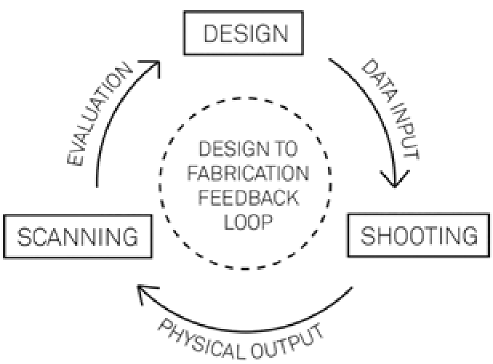
Gramazio Kohler Research/ETH Zurich,
Remote Material Deposition,
Sitterwerk,
St Gallen,
Switzerland,
2014

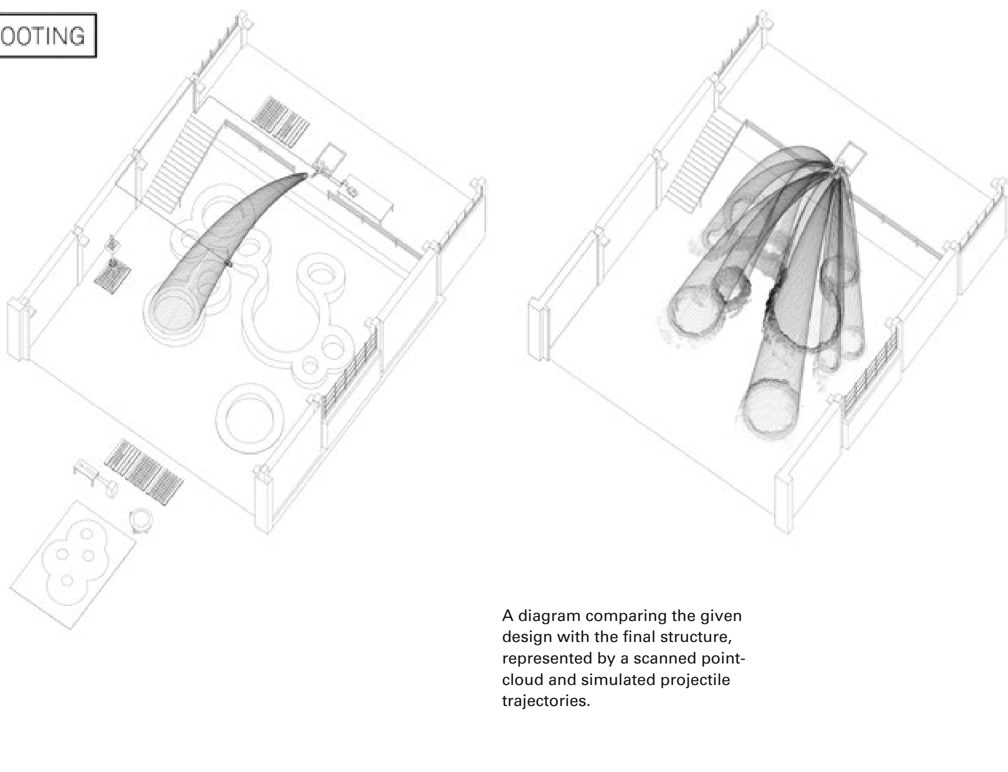
The arm robot with its projectile holder on a pneumatic cylinder.

Since 2005 Gramazio Kohler Research has established the robotic arm as a powerful instrument in the toolbox of architecture. Today, robotic arms are common sight at architecture faculties and increasingly used by the building industry to realise complex construction tasks. Their versatility has supported a rapid diversification of applications, adding many material processes to the early seminal brick pick-and-place projects. Yet, despite their worldwide success, problems such as their limited work space remain and call for strategies. The recently inaugurated Robotic Fabrication Laboratory at ETH Zurich developed by Gramazio Kohler pushes these boundaries to a volume of 45 by 17 by 6 metres (148 by 56 by 20 feet) in which four robotic arms suspended from gantries can cooperate. A different approach is explored together with ETH's Agile and Dexterous Robotics Lab: the location-aware mobile in-situ fabricator (2014–18) combines a robotic arm with a base on crawler tracks.[1] In contrast to these projects, which could be described as heavy-handed and industrial, the two Gramazio Kohler Research projects presented in this article – Remote Material Deposition and Aerial Construction – formulate lightweight alternatives with disarming qualities.

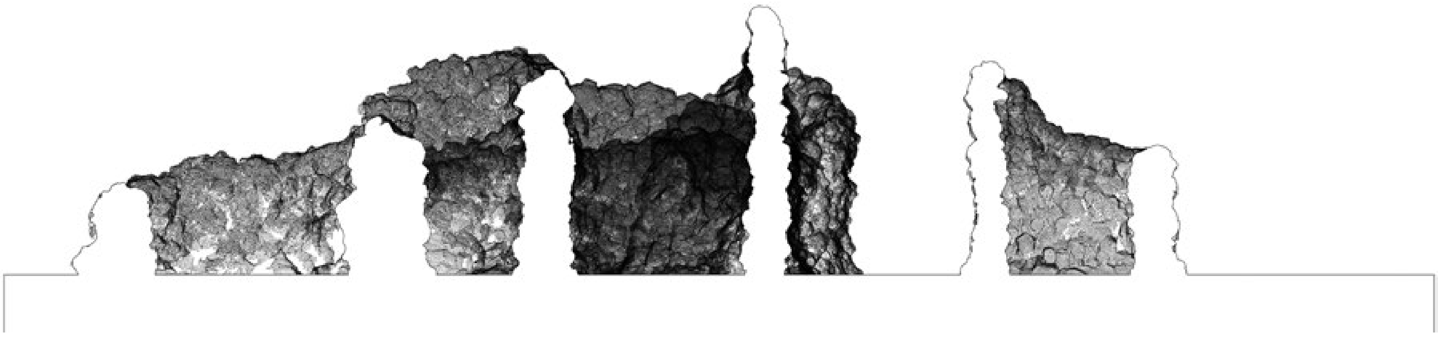
Remote Material Deposition (RMD) was constructed in June 2014 during a student workshop at Sitterwerk, an art foundation near St Gallen, Switzerland. RMD is based on the ancient human insight that throwing increases the reach of an arm. Yet, releasing the firm grip on the building material means challenging one of the core ambitions of digital fabrication: accuracy. Thus, while RMD can be situated within a group of projects that try to expand the work space of digitally controlled building machines – whether robots or 3D printers – to the scale of a building, its process and performative presence cannot be reduced to a purely quantitative and operational goal. RMD has its roots partly in the vernacular and owes its existence not least to an artistic process. It invokes the early work of Swiss artist Roman Signer, who in 1992 synchronously catapulted stools out of the second-floor windows of a vacant hotel in Weissbad, only 25 kilometres (16 miles) away from Sitterwerk. Signer's work is a peaceful reminder that in the past, from catapults to modern missiles, throwing and launching 'material' has resulted in destruction. RMD reverses this process by employing ballistics, the science of calculating and predicting the trajectories of projectiles, for construction: it 'civilises' ballistics.

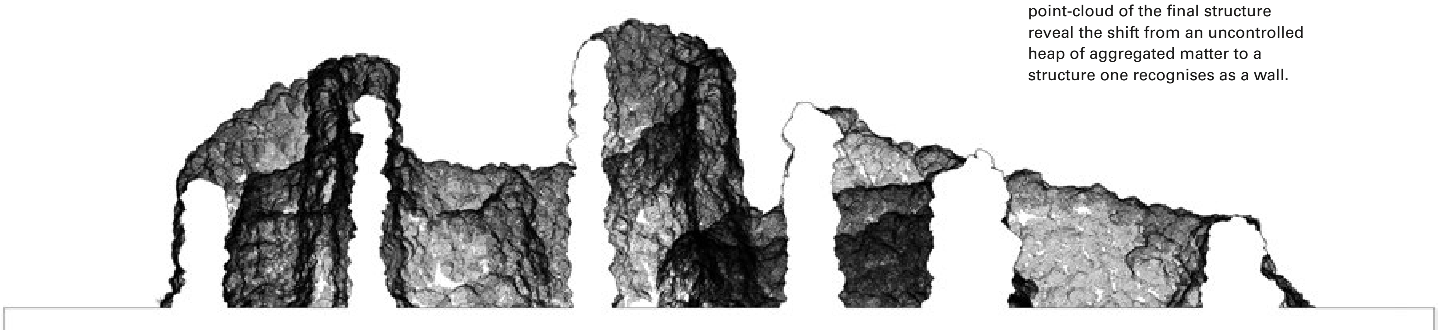
A diagram explaining the design fabrication loop, allowing for a simple learning process. Such control is the basis for turning a process susceptible to error into a powerful architectural tool, sensing the environment as a precondition for computational contextualism.





A diagram comparing the given design with the final structure, represented by a scanned point-cloud and simulated projectile trajectories.





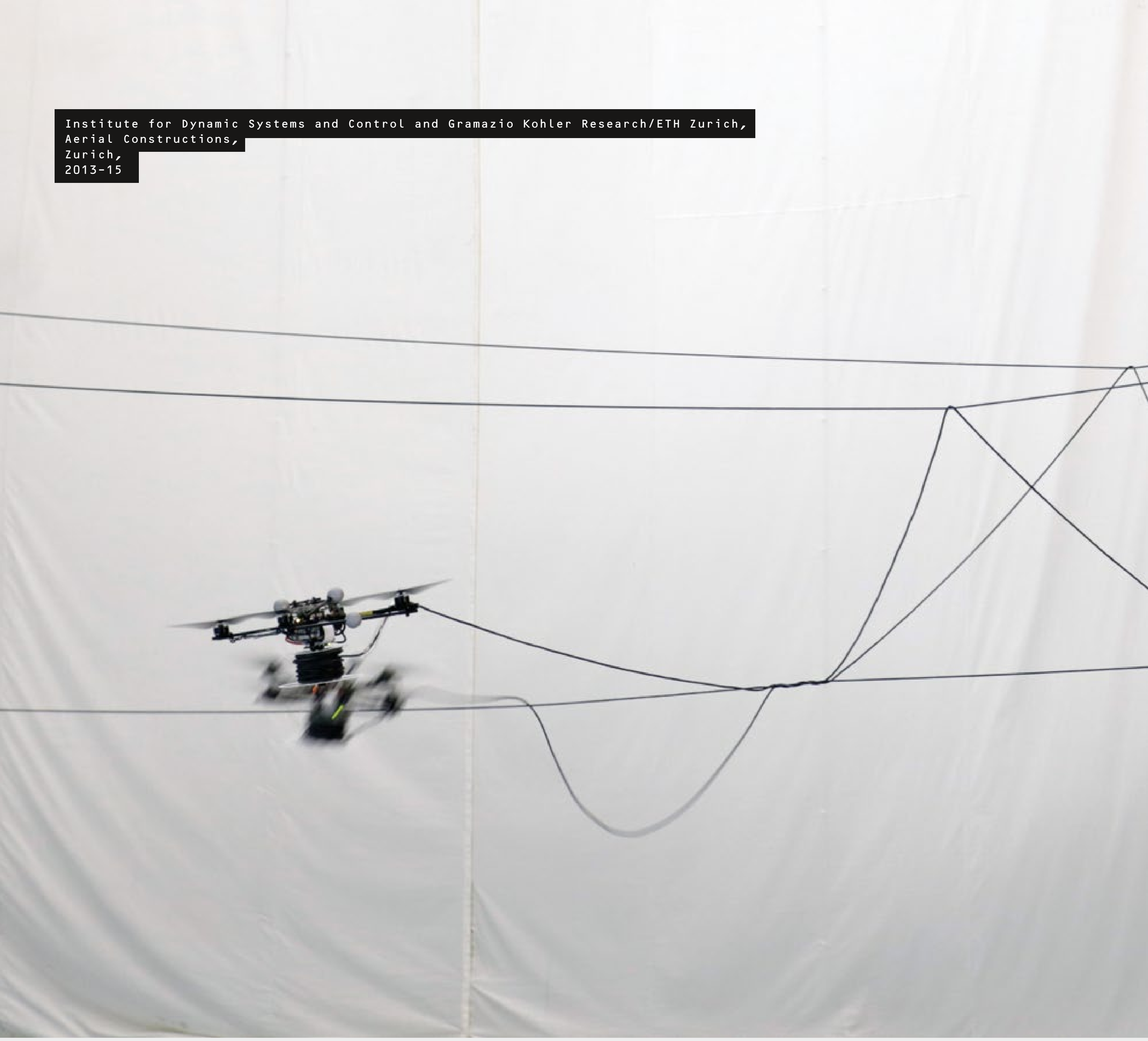
Two sections through the scanned point-cloud of the final structure reveal the shift from an uncontrolled heap of aggregated matter to a structure one recognises as a wall.

On Neutral Grounds of Architecture

Moreover, RMD reconciles two positions of architecture that have been constituted as opposing poles in the architectural discourse of the past years: those advocating digital design and those promoting social design. For the latter camp, earthen buildings designed by architects – such as Francis Kéré's teacher's housing in Gando, Burkina Faso (2004) or Anna Heringer's METI school in Rudrapur, Bangladesh (2006) – have acquired a highly symbolic meaning, the latter having featured prominently in manifesto exhibitions such as the New York Museum of Modern Art's 'Small Scale Big Change' (2011). In its search to find an appropriate building material that allows for certain tolerances, RMD adds a digitally controlled new method to the ancient technique of building with rammed earth, thereby bridging the two camps in architecture. At the same time, it reintroduces a material sensuality and self-expression to the digital while also emphasising the performative aspect of the building process.

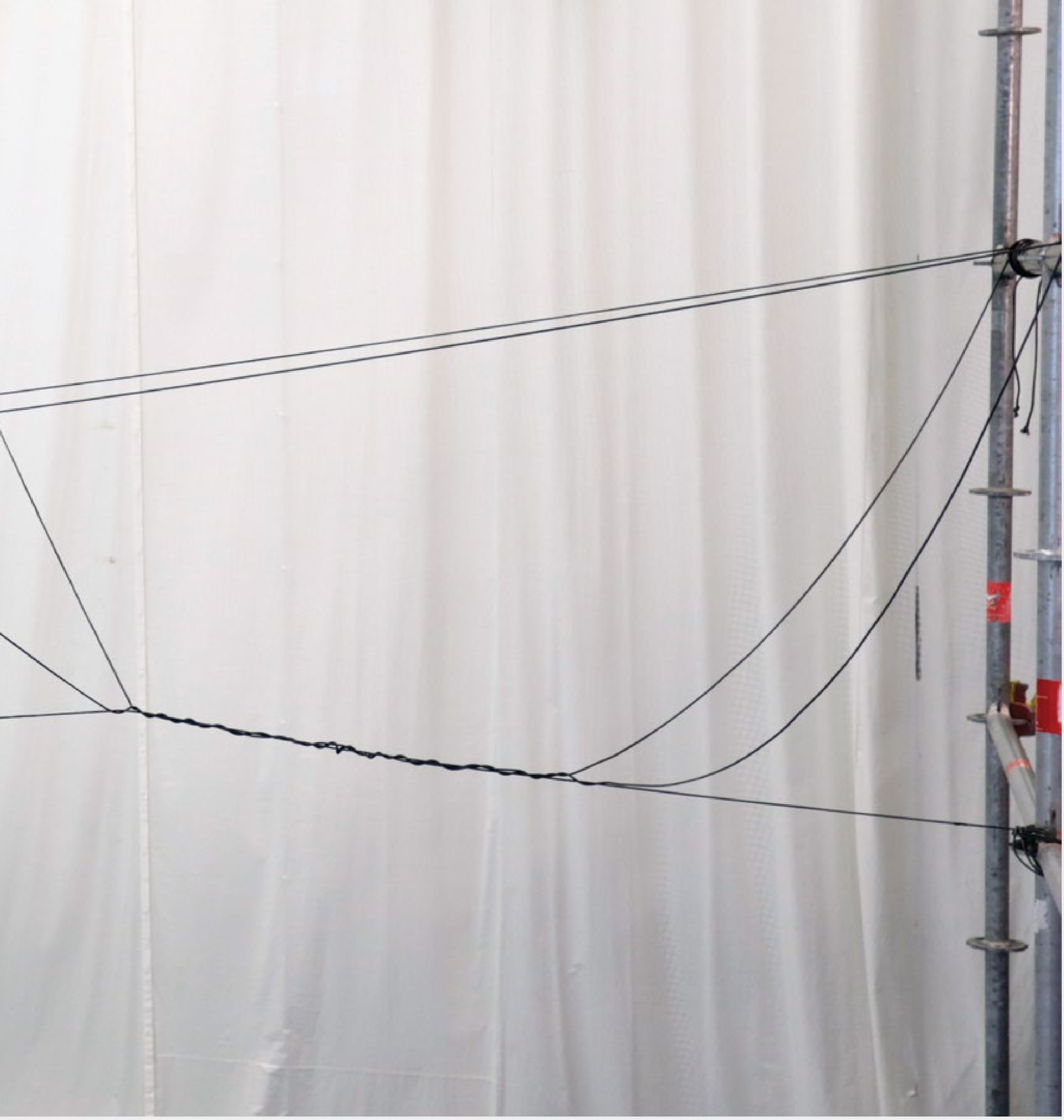
The Spectacle: From Projectile to Project

Whereas robotic fabrication environments are commonly associated with pristine factory spaces void of employees, RMD literally started off as a dirty endeavour. After months of investigating the behaviour of different clay and loam mixtures with respect to water content, hardening times, deformation and aggregation, 25 tons of clay were ordered from a local pit, mixed with sand and cut into roughly 16,000 150-millimetre (6-inch) long cylindrical projectiles with a diameter of 83 millimetres (3¼ inches). The robotic setup consisted of a pneumatic shooting apparatus and a small robot manufactured by Danish firm Universal Robots that would pan and tilt the launcher. The robot was mounted on a gallery 7 metres (23 feet) above the exhibition space at Sitterwerk and accelerated the clay projectiles to a speed of 7.8 metres (26 feet) per second from its elevated position, which resulted in a circular building area of 11 metres (36 feet) in diameter. A scanner attached to the ceiling constantly monitored the topography of the shot structure, sending feedback to the control of the robot to adaptively determine new target points and to adjust the ballistic curve by recalculating the tilt angle. A 3D-modelled design, based on extruded circles that form undulating walls and topographical ridges, was given as a target input. To improve the building process the design anticipated 'ballistic shadows', spatial areas that cannot be accessed due to material deposited earlier in the production process. Such preconceived design was key for 'civilising' the ballistic architecture robot and for understanding the principles of ballistic architecture.



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

Air space had become addressable by coordinates and therefore a part of the rational world, space itself turned into constructible territory by means of digital control.



Two quadrocopters tying together the footrope and handrail ropes. In contrast to the assembly of parts, which requires a high level of precision and stable positioning, the continuous loose-fit 'weaving process' perfectly matches the capacity of the flying machines.

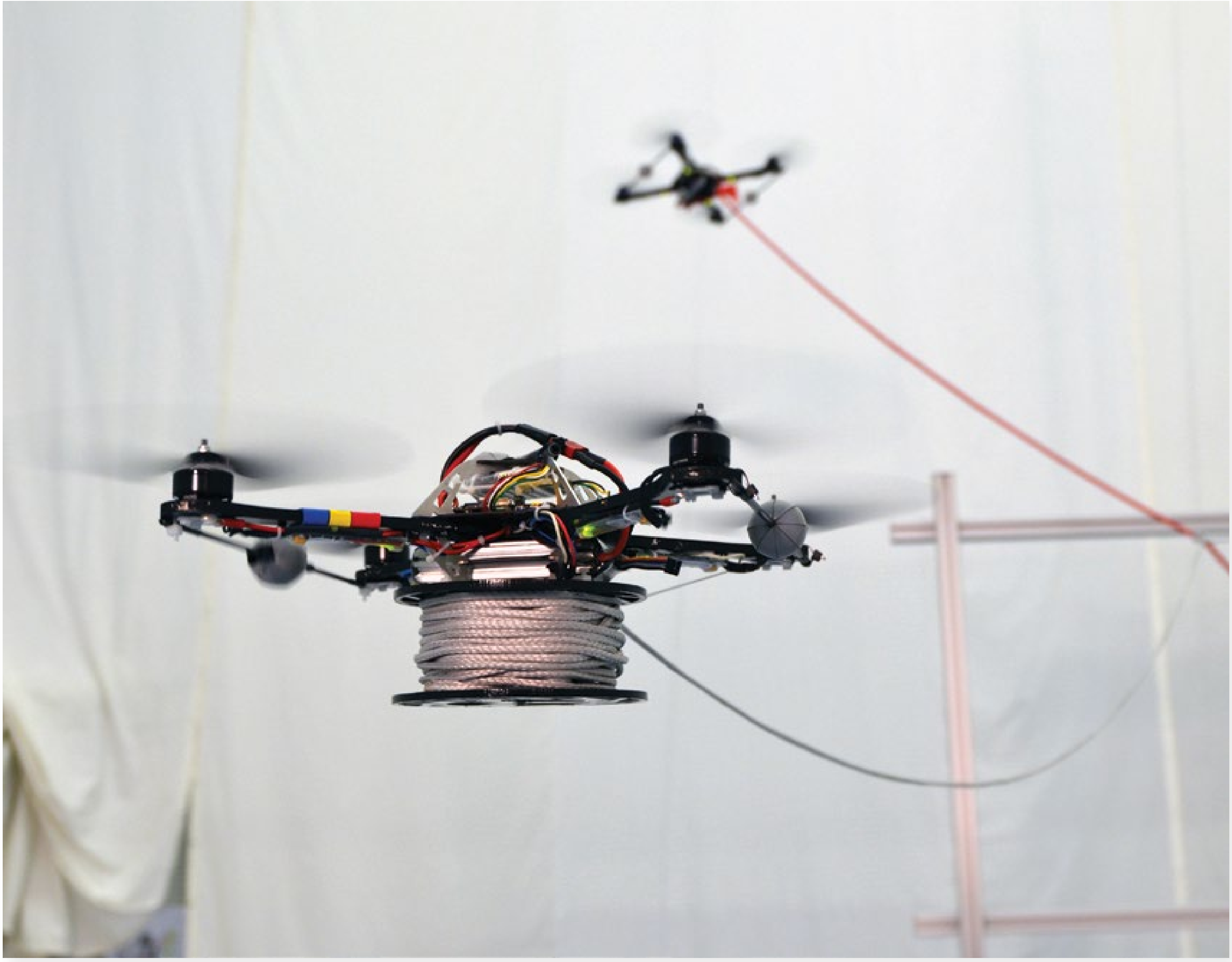
Compression as Expression

The geometric rigour of the forms made any deviation clearly visible, both when looking at the scans during the process and at the final built structure: the offsets of perfect circles were pushed outwards in shooting directions, leading to a radial stretching of the overall structure with the robot acting as the centre. Following the same logic, walls that ran in ballistic directions would be emphasised in its surprising slenderness. Through the feedback of the constant scanning process, the accuracy of the setup in shooting the design was incrementally improved and allowed for wall heights of up to 2 metres (6 feet 6 inches). The legible overall form emphasised the material expression based on compression and deformation, a frozen state of ballistic impact.

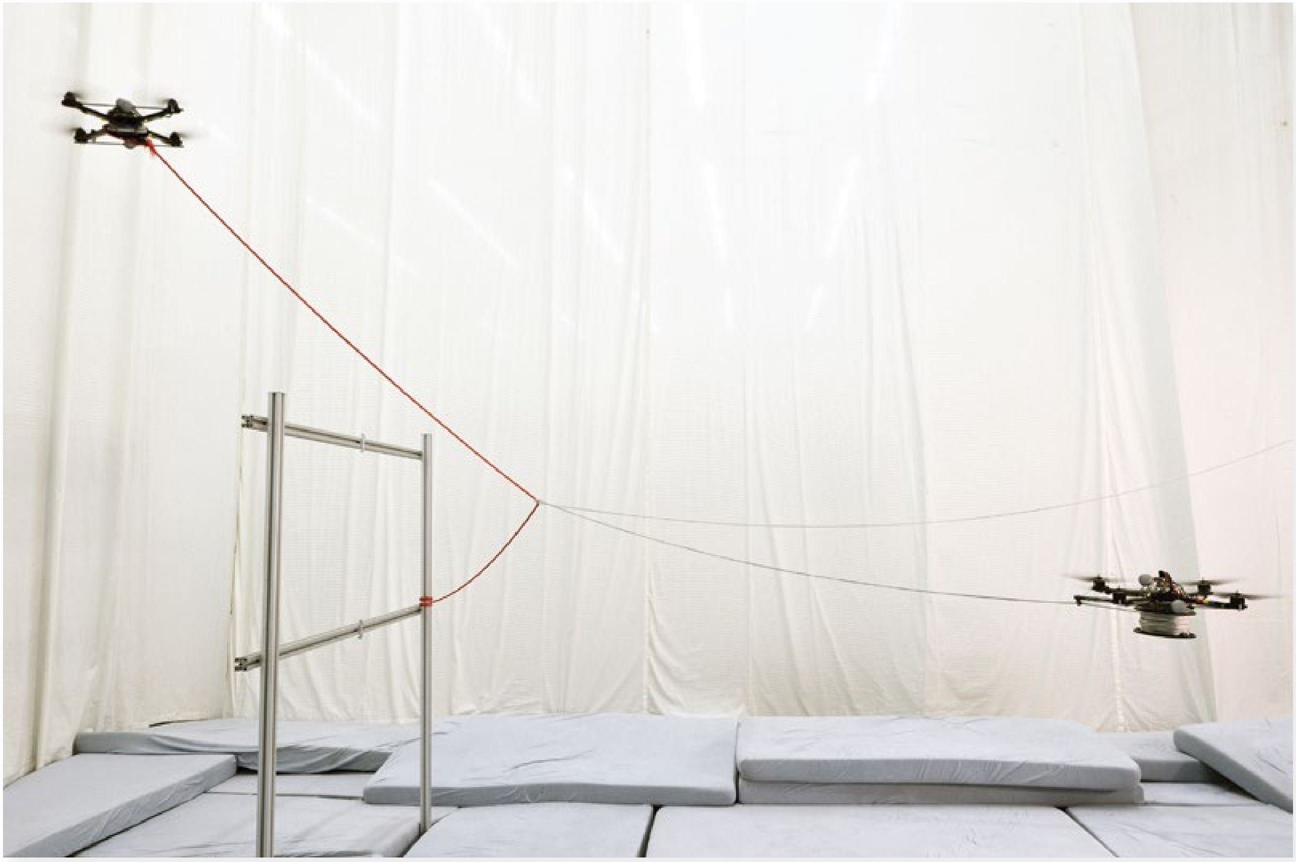
From Autonomous Construction to Autonomous Design

Despite the process's emphasis on energy, it is controlled by a design agenda that is closer to the Baroque garden with its focus on perfect form and absolute control than to the contemporary understanding of open and dynamic systems with its accent on uncertainty. Thus, in a next step the ballistic potential of RMD in regard to emergent forms – or, more precisely, non-determined structures that are governed by the inherent logic and flaws of the process – would need to be explored. What spatial aggregations could be built if the design was not preconceived, but would instead fully exploit the material deposition feedback control? How would architects design if they had to translate their typological repertoire into a design system consisting of energy and material? In its first phase, RMD has elevated the hitherto formless heap to a state of architectural significance through remote fabrication of recognisable building elements. In a second phase, RMD could challenge the tectonic architectural conventions and its formative principles using the knowledge gained throughout its first project phase leading to the exhibition at Sitterwerk.

Close-up of one of the quadrocopters during flight, autonomously building a rope bridge at the flight arena of the Institute for Dynamic Systems and Control at ETH Zurich.



By continuously unwinding string during flight, the flying machines performed truly spatial operations, gradually densifying and defining, interlacing a suspended structure.



above: Two quadrocopters flying a first node during the construction process of the rope bridge. Their flight paths were calculated so as to allow for tolerances of the inherently unstable flying machines.

Flying Through Space, Building In Space

In its current state RMD operates best indoors. Without much airflow or turbulence, the ballistic trajectory can be calculated accurately. Such idealised conception of space goes back to the early days of modern architecture when Rudolph Schindler, disciple of Frank Lloyd Wright and one of the founding fathers of Pacific Modernism, introduced space as the medium architecture has to master, highlighting it as 'a new medium of art distinct from all other arts'.[2] Here, space was understood as the negative to the positive, it was a binary understanding of mass and void. When in 2012 Gramazio Kohler together with Raffaello d'Andrea realised Flight Assembled Architecture at FRAC Centre in Orléans, France, it demonstrated yet another step towards the mastery of architecture´s primary medium. Since airspace had become addressable by coordinates and therefore a part of the rational world, space itself turned into constructible territory by means of digital control. Using ultra-light flying machines that have detached themselves from the massive body, firm stand and kinetic restrictions of a robotic arm, it was at this point that architecture's primary medium – space – stopped being reliant on the ground from where architecture is built up. Flight Assembled Architecture masked this shift due to the sheer presence of the tower being built element by element from bottom to top. Its follow-up research project Aerial Construction (2013–15), discarded such conventions.[3] By continuously unwinding string during flight, the flying machines performed truly spatial operations, gradually densifying and defining, interlacing a suspended structure, in this case a cable bridge.

Based on a dialogue between environment and technology, disarmed machines can move out of the laboratory and venture into open systems, like gliders that gracefully play with airstreams.

Detail view of the rope bridge, showing flown nodes and braids: a structure that could extend far beyond a laboratory and beyond a purely functionalist understanding. A Victorian perception of structure and ornament could be extended to constructions in airspace.

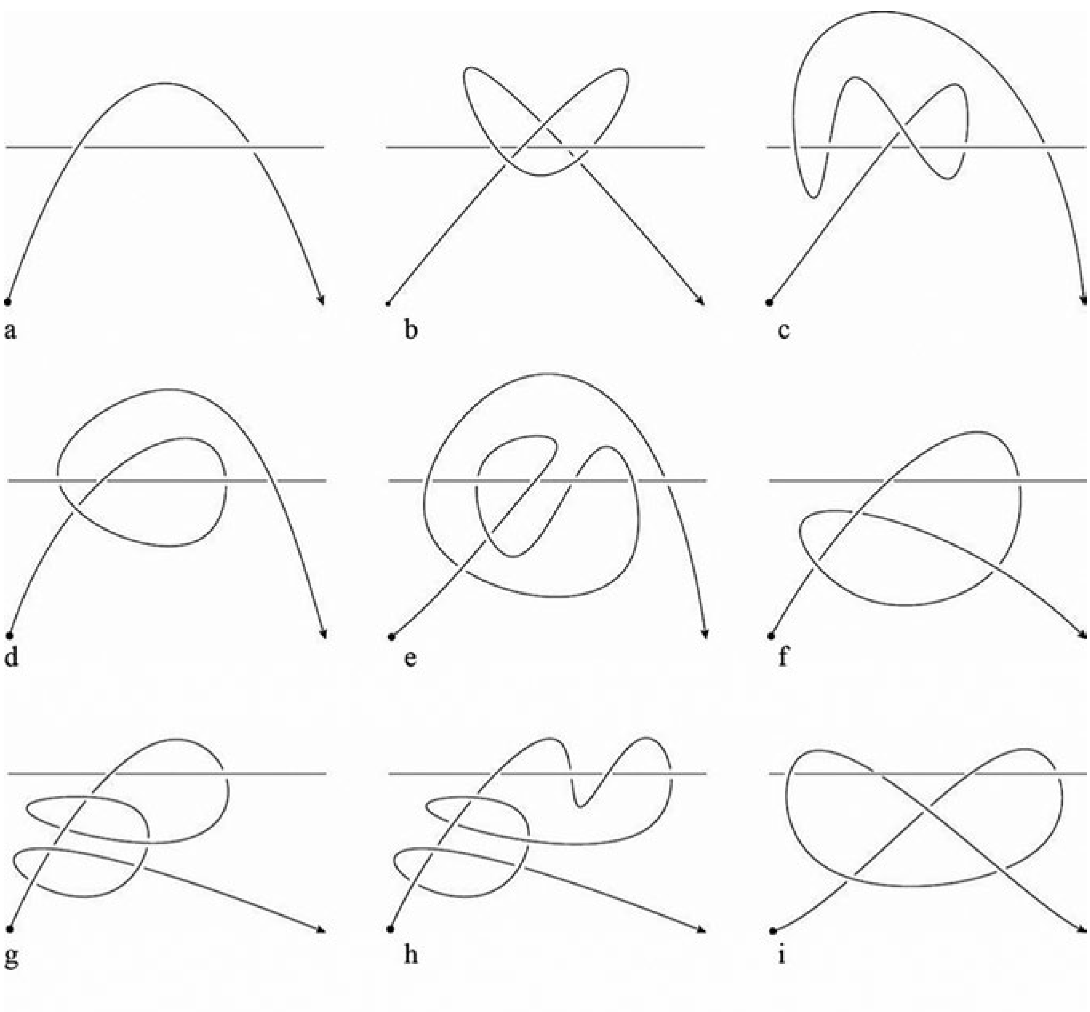
Computational Contextualism

Similar in its set-up to RMD, Aerial Construction tasked its flying machines with a predefined design, which proved robust enough to compensate for tolerances due to the material behaviour and the inherent instability of the flying robot. Consequently, Aerial Construction was still about establishing certainty within a medium largely governed by uncertainty. Yet, its development documents the shift from the modern understanding of space as void, to the contemporary perception of it as air that has become digitally tangible due to the comprehension of its dynamics and the improvement of sensorial observations and algorithmic control. With the integration of the latter into the design and fabrication process, the understanding of space and time in architecture enters a new level. At first, this is likely to serve an operational mode to tame the dynamics of the environment and to execute a predefined design without deviances. However, in a second phase the digitally enhanced awareness of and interaction with the environment will lead to a departure from a classical design paradigm that understood digital fabrication as the contextually blind execution of a predefined and pre-calculated design. Local conditions will start to impact on the design decision-making process, turning initially digitally tangible phenomena into physically tangible construction. Propelled by the race for resolution in sensing and control, computational contextualism fully exploits gained control in millimetres and microseconds, as well as further sensorial feedback, by understanding the architectural agency of the dynamic forces acting in the context of disarmed machines. Based on a dialogue between environment and technology, disarmed machines can move out of the laboratory and venture into open systems, like gliders that gracefully play with airstreams. D

Notes

1. Kathrin Dörfler *et al*, 'Mobile Robotic Brickwork – Automation of a Discrete Robotic Fabrication Process Using an Autonomous Mobile Robot', in Dagmar Reinhardt, Rob Saunders and Jane Burry (eds), *Robotic Fabrication in Architecture, Art and Design 2016*, Springer (Vienna), 2016, pp 204–17.
2. Bruno Zevi, *Towards an Organic Architecture*, Faber & Faber (London), 1950, p 128.
3. Mirjan Ammar, *Aerial Construction: Robotic Fabrication of Tensile Structures with Flying Machines*, unpublished PhD thesis, ETH Zurich, 2016.

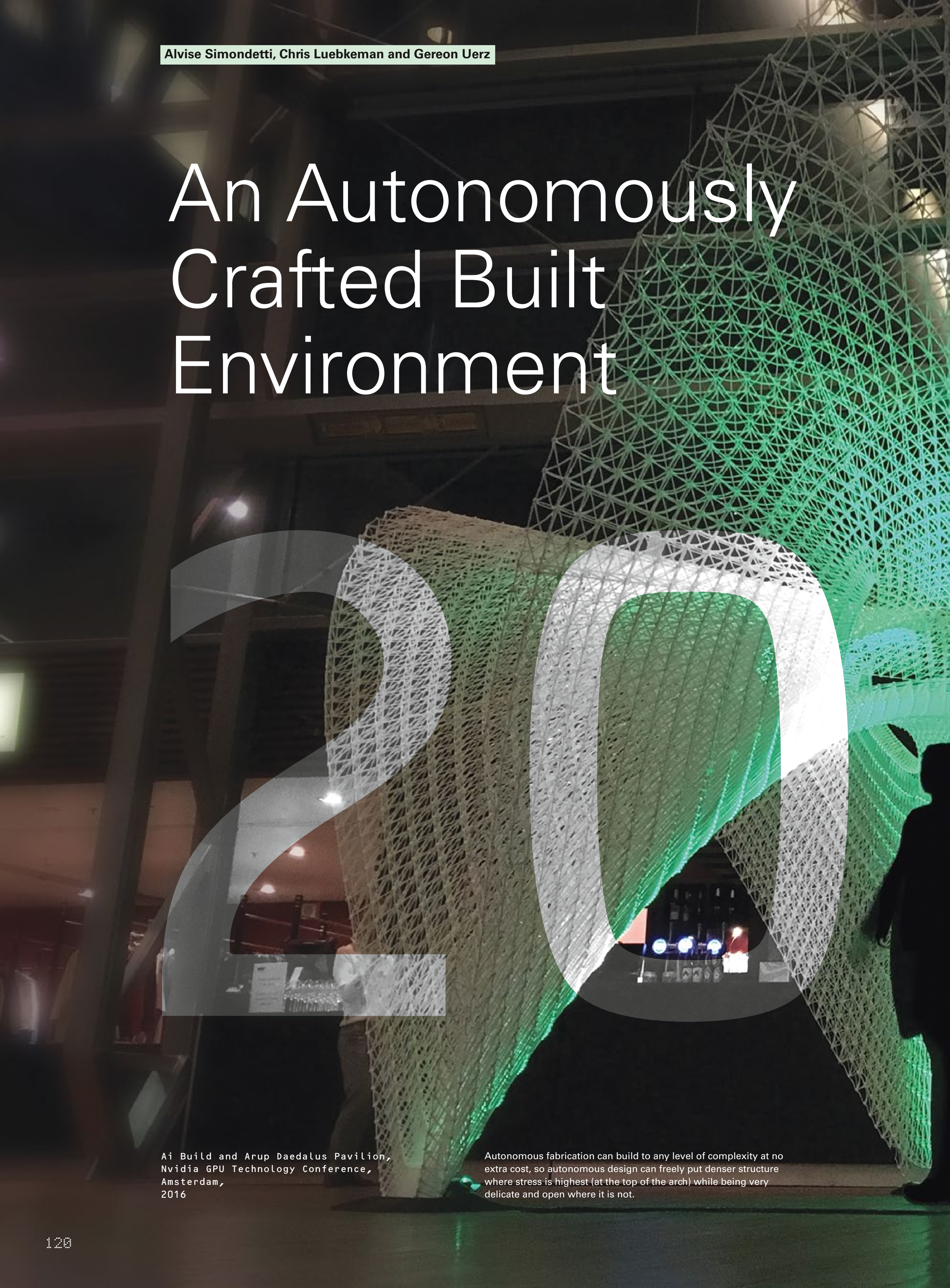
A catalogue of nodes that can be flown by quadrocopters, showing the agility of the quadrocopter in a series of diagrams.



Alvise Simondetti, Chris Luebkeman and Gereon Uerz

An Autonomously Crafted Built Environment

20



Ai Build and Arup Daedalus Pavilion,
Nvidia GPU Technology Conference,
Amsterdam,
2016

Autonomous fabrication can build to any level of complexity at no extra cost, so autonomous design can freely put denser structure where stress is highest (at the top of the arch) while being very delicate and open where it is not.

By 2060, smart technology will allow every aspect of our surroundings to be optimised for efficiency and customisable to our desires. From street lighting, to building maintenance, to hotel interiors, to flood protection – this is the future as imagined by **Alvise Simondetti**, **Chris Luebkeman** and **Gereon Uerz** of **Arup's Foresight + Research + Innovation team**. After setting out their vision of what lies ahead, they highlight several recent projects that they have worked on with high-profile architects around the globe: projects that pave the way to a world where fine crafting and intelligent design are for the masses rather than the few. This is all set in context by a piece that outlines the evolutionary steps that have been triggered by disruptive technological shifts.

It is the spring of 2060. The influence of computers, and specifically their ability to work independent of human intervention, has impacted people's lives dramatically. Computers are the reason why most governments in the Western Hemisphere now guarantee a basic income for all citizens. This became necessary when autonomous technology fully took over in 2040, and human workers were replaced in so many sectors. Nearly 70 per cent of professions became redundant. For example, 3.5 million driving jobs in the US evaporated because of computer intervention. Now, in 2060, all of the three 'D's of life – work that is dull, dirty or dangerous – as well as managerial tasks are done exclusively by robots.

Sensitive Relationships

What do people do instead? With so much of the 'doing' of life taken over by machines there is a freedom to concentrate on feeling and relating. People dedicate more of their time to caring for each other and being social. It seems that human contact, empathy and real attention cannot yet be replaced by machines, and so the care-giving field and other areas of compassion work remain incredibly robust.

This is not to say that objects and infrastructure are not hard at work striking up relationships with humans. Houses sense body temperature, heart rate or temperament, and can turn on the heat or choose a particular music to make the environment more comfortable.

All transport, whether leisure or business, goods or people, light or heavy, happens in shared autonomous vehicles. In fact, the sharing economy rules. The closed, secretive business technology model has been replaced with open source. Innovation happens so much faster because of it.

Portable Preferences

All people use miniaturised, high-tech, high-touch, customisable communication platforms able to do a wide range of ancillary functions in addition to simple conversations. These personal devices carry all human preferences within them, and through sensors can understand moods and needs as well as wants. They measure the ambient and direct humidity, vibrations and temperatures. They understand the implications of fluctuations in heart rate and blood-sugar levels. These devices interact with buildings to create an optimised personal experience – if chosen to do so.

Because homes, buildings and urban infrastructure are connected and self-aware through smart components, design updates occur automatically. Inefficient and wasteful scheduled maintenance schemes were replaced in 2050 by machine learning with its 99 per cent successful predictive or preventive maintenance. A scenario is described to the machine, and it simply does the rest.

Customised Solutions

Autonomous systems are a mandatory part of living with climate extremes in 2060. When a storm approaches, a machine that has studied flooding patterns autonomously retracts any drain covers affected by its trajectory before the rain even begins. It recovers only those manholes that pour out excess water.

Designers and data scientists work together to continuously contribute insights to ensure the variety and sheer volume of data needed to create these kinds of adapting and preferred scenarios. The scenarios, in turn, train machines to produce the most sensitive and customised design solutions. A continuous feedback loop from the environment and users ensures success.

Participatory design means consumers are producers at the same time. Everyone is a designer able to choose their own characteristics for items through Fab Labs located throughout cities. Self-building is also massively popular as building experience is not needed to construct housing.

Site Feedback

Building sites are prepared and levelled by large, autonomously driven machinery, moving earth around by using their on-board digital terrain model. Because ground composition is often unknown, and foundations are one of the most delicate and uncertain parts of construction, autonomous feedback is continually used. Sensors are embedded in the concrete as it is injected into the ground, and they provide feedback on the effectiveness of the pile. Based upon 24/7 data from the first piles, the machine autonomously makes immediate decisions to increase the number of piles in the ground until the required performance of the foundation is met. The machine knowledge uses a relatively small number of relevant samples at first, but as it works across the building site its decisions get wiser and wiser.

This has greatly improved the foundation speed, cost and quality over techniques existing in the 2020s. At that time, data from sensors in the first pile would go to a base station, and be displayed on a dashboard for a human (during working hours) to compare with the required performance. Often some 24 hours later, the human would instruct the automated machine, which by then had moved on to a different foundation, to return to the site and add a fourth pile.

Autonomous pump trucks also pour the main concrete core, columns and slabs and the primary skeleton of the building is erected. These portions of the building are heavier, longer term and built on site to a lesser tolerance. Once the slabs are in place, the edge of the slab is measured and compared with the construction model to ensure accuracy. The secondary facade structure is built off-site to much higher tolerances, as it must water-proof the spaces, ensure air-tightness for thermal barrier and finally provide a high-quality aesthetic and tactile finish. The computer therefore compares the as-built model with the construction model, and every time a discrepancy is found an autonomous local decision is made to update the construction model within the design rules.

A first step towards the autonomous construction techniques of 2060 happened at the beginning of the century when contractor Skanska built the Ray and Maria Stata Center at the Massachusetts Institute of Technology (MIT) in Boston, designed by Frank Gehry. To manage the risk of overspend and overrun in the schedule, the contractor, client and architect all agreed that, within limits, the inevitable discrepancies between the built form and the construction model would be absorbed by the design. (The design was parametric in nature.) At the time, the 3D-scanned positions of the edge of the slab were manually inserted by the operator in the polyline that guided the assembly of the entire facade cladding. The new parametric facade design adapted to the built form, here and there making it a little more bulky, or slimmer. This way the complex building was magically delivered on time and on budget.

Frank Gehry,
Ray and Maria Stata Center,
Boston,
Massachusetts,
2004

The completed building design elegantly accommodates the discrepancies between the as-built and digital construction model. It remains true to the design intent as a result of the designer's robust rules of conspicuously avoiding co-planarity, co-axiality and perpendicularity between the architectural surfaces.

Adaptive Construction

Finished construction in 2060 has three levels of adaptability. The 'chassis' is the permanent external structure, made to last 20 to 100 years appropriate to the specific local context and its speed of change. The building 'body' is customised to the particular tenant, programmed with dynamic lighting and audio/visual displays enabling monthly or yearly rebranding in sync with the ups and downs of a business. Particular signage, soft lighting and warm, sensual colours for one business or high contrast and sharp colours for another are transformed with a keystroke, allowing a hotel, for example, to change owners or style every two to 10 years. The third level of adaptability is focused on the individual. At the Universal Pop Up Hotel, a seven-star luxury brand in Milan, the room 'interface' personalises to each traveller every night. Picture frames and interactive paint autonomously connect to a guest's phone, so room imagery (think family photos or modern-art masterpieces) and video-chat connections are left to their discretion to make travellers feel literally at home.

City infrastructure also uses such adaptability. Personalisation means the street knows when an elderly gentleman out walking his dog would appreciate more light.

Historical Futurescape

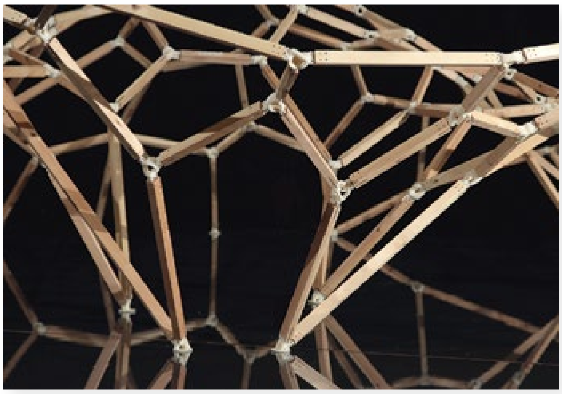
Let us come back to this reality, today, in July of 2017. Great progress towards the exciting ideas outlined above has already begun.

Indeed, in a 2005 example of autonomous operation, Portuguese architects Alvaro Siza and Eduardo Souto de Moura created a temporary summer pavilion outside London's Serpentine Gallery in Kensington Gardens. The curvaceous structure of timber, metal and semi-opaque polycarbonate panes used a decentralised lighting solution by Arup's Steve Walker devoid of wiring. A small solar-powered panel and bulb were centred on each roof plate for lighting the pavilion at night. Because the materials used to build were all unique in shape and size, every panel had its own orientation towards the sky. As dusk fell, each pane's sensor automatically and independently illuminated when it hit the target darkness in a beautifully organic, and autonomous, display.

Alvaro Siza and Eduardo Souto de Moura with Arup, Serpentine Gallery Pavilion, London, 2005

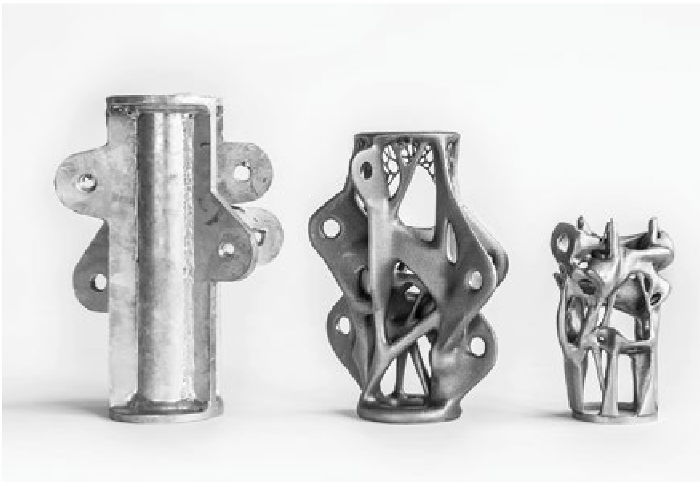
above: Wireless, individually solar-powered lights placed on semi-opaque roof panels provided an early example of autonomous operation in the 300-square-metre (3,230-square-foot) Serpentine Gallery Pavilion cafe.

right: As dusk fell over Kensington Gardens, each light illuminated one by one, depending on its orientation to the sky. The result was wholly organic and completely autonomous.



RMIT University, also in collaboration with Arup, employed autonomous design and additive fabrication through the use of 3D printing for the Smart Nodes Pavilion at the Engineers Australia Convention, Melbourne, in 2014. Research focused on improving weight efficiency in building materials by using individually designed nodes unique to their location in a structure. Very large-span roofs, like the one built in 2014 at the Singapore Sports Hub in Kallang, are uniquely sensitive to self-weight. The weight of the nodes is a considerable proportion of the roof self-weight. Pure weight optimisation of nodes, generally considered unsustainable in most structures, in this application kick-starts a virtuous cycle: the forces on the structural nodes are reduced as the nodes are optimised.

Weight efficiency is also critical for tensegrity structures. Arup, researching in collaboration with Altair, WithinLab (now Autodesk Within) and 3D Systems, and inspired by the design for a lighting installation for the Grote Marktstraat in The Hague, Netherlands, has explored the design of nodes used in conjunction with rods and cables. In the first iteration in 2014, the computer was asked to carry out topological optimisation, and put the steel only where it was truly needed without impacting strength. In later iterations the following year the designers went further by removing ring shape constraints at one end of the node. The end result is a structural node designed to carry the same load and force, half the size of the original and weighing 75 per cent less.[1] An overall reduction in weight of the total structure of more than 40 per cent with these types of gains is possible.



RMIT University and Arup,
Smart Nodes Pavilion,
Engineers Australia Convention,
Melbourne,
2014

above top: An iterative design and analysis process for the Smart Nodes Pavilion assembled by hand at one-fifth scale had three goals: maintain straight and untwisted two-by-four cut timber members, keep the resulting panels approximately planar, and maintain reasonable angles for the three, four and five members coming to each node. The processes produced all the unique nodal forces to generate the smart nodes.

above middle: The polymer smart nodes, printed with fuse deposition modelling (FDM), are based on strength, bespoke at every single location within the pavilion, and autonomously designed using light topological optimisation starting from a 60,000-voxels solid spherical volume. Autonomous design removes the need for the designer to rationalise and simplify geometry, or make it more repetitive.

above bottom: To create the full-scale (220-millimetre/8.5-inch size) stainless-steel nodes printed with a selected laser sintering (SLM) technique, a topological optimisation algorithm called BESO (Bi-directional Evolutionary Structural Optimization) autonomously added and subtracted material starting from a solid sphere, and following the load paths of the forces between the members. Beginning with a half-million-voxel solid spherical volume, it took two and a half days to compute.

Arup, Altair, WithinLab (now Autodesk Within)
and 3D Systems, Evolution of design optimisations
for a 3D-printed structural node in metal,
2015

Autonomous design can drastically change the shape and amount of material used in building resources. The two stainless-steel node iterations for a lighting structure on the right vary dramatically in volume and weight yet are full sized and equally functional to the original on the left.

Rapid Formation

Arup also worked with Ai Build, a UK startup specialising in artificial intelligence and 3D-printing applications, to create an elegant and structurally efficient form with an optimised distribution of material. What made the Daedalus Pavilion autonomous fabrication project so revolutionary was the scale and speed of the build. The beautiful structure was unveiled at the GPU Technology Conference in Amsterdam in September 2016.

The pavilion was constructed by a robotic arm and a mechanism that deployed corn-based plastic raw material. Algorithms and cameras acted as eyes to see if and where discrepancies were made, and the robot, with a feedback mechanism, corrected itself as it went along. While the robotic arm reach allowed for the greater print size, this locally approximate (but globally accurate) deposition method enabled a massive increase in depositing speed necessary to make the large-scale print practical. This approximation made the pavilion look more like a hand-knitted jumper from one's grandmother than mass-produced and purchased in a shop.

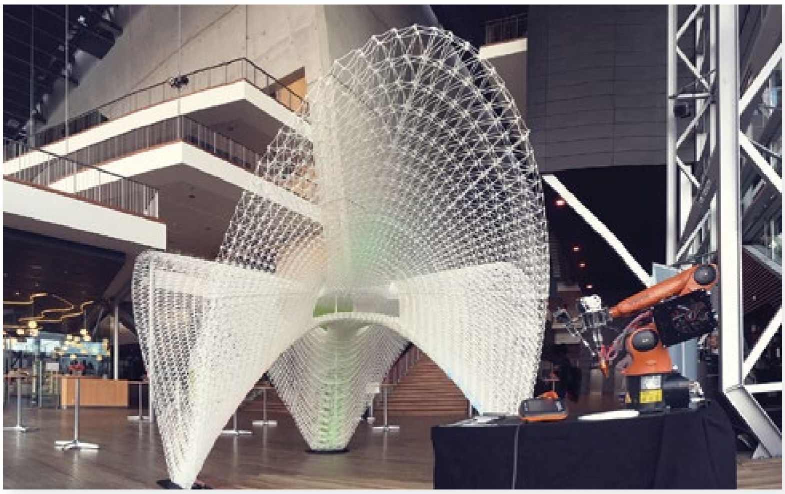
The feedback loop was the main innovation, made possible because the robot could see what it was printing and adapt. It used advanced computer vision algorithms to detect how the printing was going, and if there was a mistake adapted the next layer to compensate. What could have taken many months on a classical 3D printer was completed in just two and a half weeks, a 10-fold improvement in speed.[2]

Thoughtful Creation

Arup Foresight believes that in 2060, humankind – a billowing population of more than 10 billion people living under extreme climate behaviour – will enjoy a built environment that is carefully and autonomously crafted. It will be appropriate to its locality and able to adapt in a timely fashion to the shifting culture of our fast-changing world. Before the Industrial Revolution, only a lucky few enjoyed thoughtful creations or finely crafted solutions that improved their lives. In the post-industrial revolution, with its automation of thinking and making, the promise is to provide thoughtful creations for all.

Notes

1. Salomé Galjaard *et al*, 'New Opportunities to Optimize Structural Designs in Metal by Using Additive Manufacturing', in Philippe Block *et al* (eds), *Advances in Architectural Geometry 2014*, Springer (Cham), 2015, pp 79–93.
2. Freddie Dawson, 'Can 3D Printing Transform Construction?', *Forbes*, 30 September 2016: www.forbes.com/sites/freddiedawson/2016/09/30/can-3d-printing-transform-construction/#19c5fc713574.



Ai Build and Arup
Daedalus Pavilion,
Nvidia GPU
Technology
Conference,
Amsterdam,
2016

Breaking apart the idea that 3D-printed projects are small in stature and slow to build, a custom Ai Build printer head-mounted on a KUKA industrial robot created this 5-cubic-metre (176-cubic-foot) sculptural pavilion in less than three weeks.

Machine learning is not perfection – but it is consistent improvement. As seen in the slightly bent lines, the robot used cameras to see how far its landing position was from the design position before correcting itself. The intelligent feedback loop allowed it to be quicker by being more adventurous.

THE EVOLUTION OF REVOLUTIONS

Homo sapiens' every evolutionary step has required a shaping of the environment. New tools and technologies, whether made of stone or silicon, resulted in leaps of potential and expression. At times seamless or quite disruptive, and all too often both simultaneously, the built environment and technology have always had a symbiotic relationship.

The Industrial Revolution of the 18th century established centralised processes that standardised, modularised and automated manufacturing. Mankind monetised time and segmented the day according to a timepiece rather than the movement of the sun. Automation efficiently addressed the strains of population growth, urbanisation and social change.

The Second Industrial Revolution, known as the Technological Revolution, from the second half of the 19th century until the First World War, introduced steam and advanced automation. Production harnessed increasingly concentrated energy, allowing shipbuilding, construction and later the automotive industries to embrace their speed of change. Automation, and better understanding of the behaviour of building materials, allowed mankind to push against the tyranny of distance and the limits of gravity that had bound humanity to earth's surface for eons. The ever-taller buildings of Chicago and New York scraped the sky. These tall, thin edifices were the ideal treat for the Modernist architectural movements that were also trying to rationalise urban life and living with similar industrial-revolution paradigms. Such industrialised solutions are still produced around the world today, found in every latitude, weather type, political system and economy. Generic living solutions, they are the residence of millions of citizens.

The Third Industrial Revolution – the Digital Revolution – began in the late 1950s and boasted advances in computational power that digitised processes to further rationalise them. Calculations previously requiring 150 engineers/designers could now be completed by a mainframe computer in seconds. The potential to understand the performance of space and place took a massive leap forward.

And now, **the Fourth Industrial Revolution**, incorporating the decentralisation of manufacturing with machine learning, is another huge step. Advances in autonomous assembly powered by machine learning offer appropriateness, timeliness and scalability of solutions. There are radical new ways to tackle population growth, urbanisation and speed of change. Indeed, the smartphone app revolution enables instant access to a whole manner of services, from taxis to accommodation to food delivery.

Architects, engineers and construction professionals will benefit greatly from machine learning, and will be well served to fully integrate and incorporate autonomous assembly into their design and construction vocabulary.

Autonomous Assembly as the Fourth Approach to Generic Construction

COUNTERPOINT 04/2017 No 248

Andong Lu

The three major approaches to generic construction tested since the advent of prefabrication – element assemblage, layer stratification and module composition – all maintain a separation between manufacturing and assembly. Autonomous assembly, in contrast, coalesces these into a single method of collective production. But – as **Andong Lu**, Professor at the School of Architecture and Urban Planning, Nanjing University, argues – for such innovative approaches to inspire the future of architecture, it is crucial to connect technology, design and people, based on a comprehensive understanding of construction.

The concept of autonomous assembly has perhaps brought us closer than ever to realising the ideal vision of generic construction, where the production of buildings is fully programmed and regulated, and the on-site part of the process minimised. The past century has witnessed continuous endeavours to adopt a modern mode of production in architectural design. 'Machine' or 'furniture' became metaphors for a new architecture that presumed to be able to be mass produced and easily assembled. 'Prefabricatable', 'reproducible', 'demountable' and 'movable' became its catchwords and lasting criteria. More recently, advanced manufacturing and digital fabrication have allowed us to make almost anything in highly regulated industrial spaces. The construction of buildings, however, still mostly takes place in real spaces that are site specific, labour intensive, and subject to uncertain scenarios and undulating conditions.

Will autonomous assembly prove to be the final step in achieving this utopian idea of generic construction? Will it follow the threads of previous endeavours, or instead require an entirely new mindset? Is generic construction the future of architecture, and how might it change a discipline that is profoundly anchored to the idea of Baukunst (the art of construction)? In response to these questions, this article investigates the mindset that underlies autonomous assembly as an innovative approach to generic construction in relation to earlier (but still active) approaches to incorporating real-space construction within the design phase.

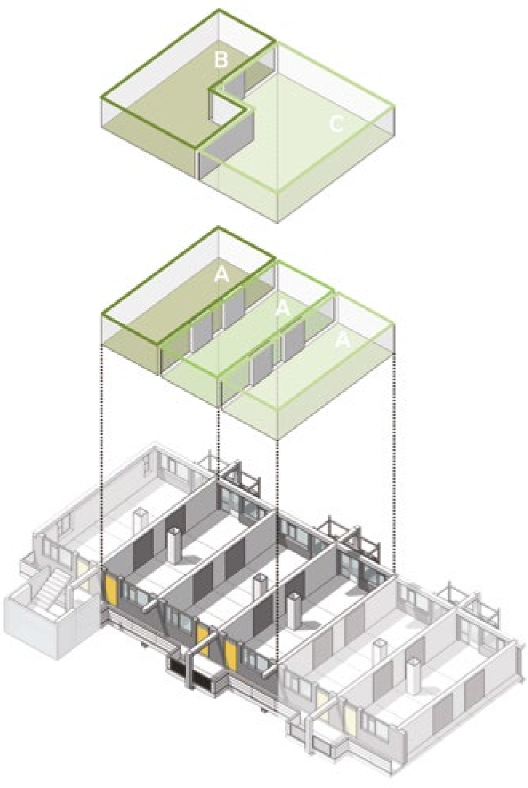
Localisation and the Element-Assemblage Mindset

Perhaps the most basic difference between manufacturing and construction is that while the former can be executed in a generic non-place (where, for example, temperature and humidity can be controlled), the latter has to be conducted locally and is therefore subject to site-specific contextual conditions. For manufacturing to take 'place' – to adapt to the different local conditions of each construction task – its process has to be reprogrammed each time and resilient enough to allow for all uncertainties. In most circumstances we cannot produce buildings in the way we produce cars.

A typical approach to addressing the issue of localisation is the prefabrication of standard building elements, so that a large proportion of construction work can be carried out off-site. Elements are enduring individual units which, when amalgamated, turn a building into a performative whole. As Rem Koolhaas has put it: 'The fact that these elements change independently of each other, according to different cycles and economies, and for different reasons, turns each building into a complex collage of the archaic and the current, the site-specific and the standard, mechanical smoothness and the spontaneous.'[1]

The element-assemblage approach is most often applied in the industrialisation of architecture, where its flexibility allows for a mix of both the standardised and the site specific. Basic elements can be easily assembled into versatile forms when combined with on-site construction. On the other hand, its economy and practicality depend largely on the standardisation and synchronisation of various engineering systems made possible with the use of tools such as building information modelling (BIM), GIS or the Internet of Things (IoT). The approach is often governed by the building codes and standards of top-down governance, and therefore applied mainly in the housing realm.

In 2016, in a bid to conserve energy, save resources and upgrade the construction industry, the Chinese government announced its target of having prefabricated structures account for 30 per cent of all new buildings in the next decade.[2] This significant shift was anticipated by the country's leading real-estate developers such as Vanke, which in 2013 adopted a set of prefabrication principles including 'enhancing quality, increasing efficiency, and reducing reliance on workers'.[3] The global shortage of housing, and particularly affordable housing, combined with the decrease in labour productivity in the construction sectors of countries including the US as well as China, mean prefabrication is now becoming a crucial issue.

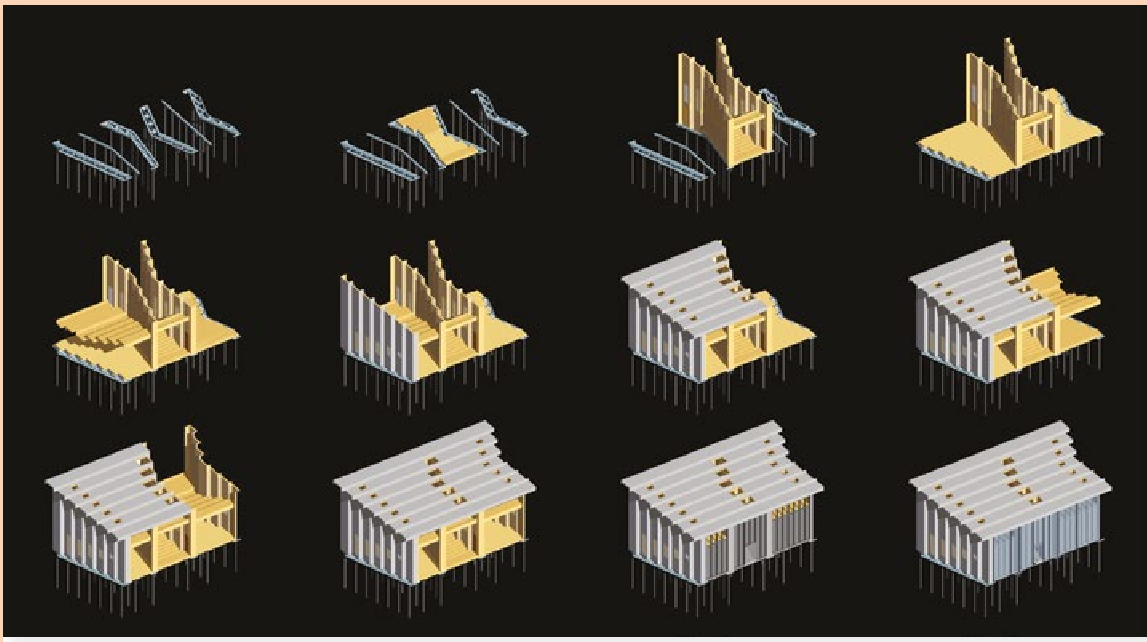


Liu Dongwei/ China Institute of Building Standard Design & Research, Prefab public rental housing based on a skeleton-infill system, Daxing, Beijing, 2014

Exploring the architectural systems and key technologies employed in the industrialisation of affordable housing, the researcher here completely separated the prefabricated structural system and the highly industrialised infill component system to achieve greater interior flexibility.

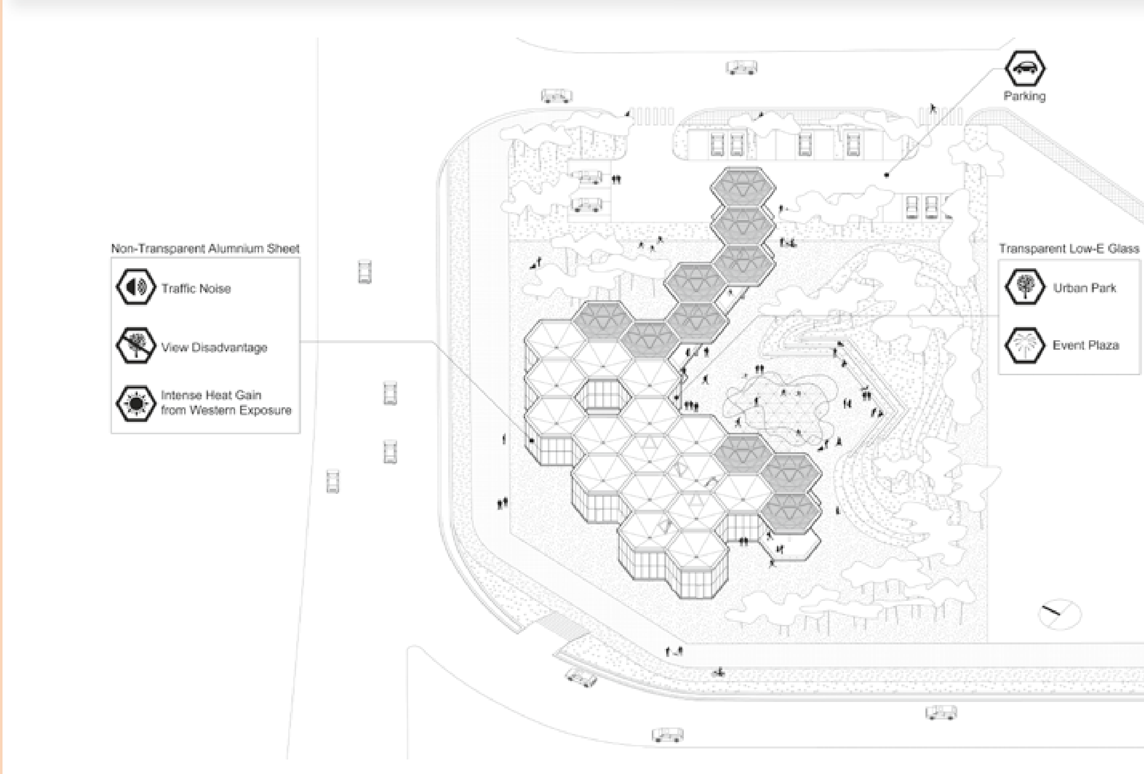
Zhu Jingxiang,
Z-Panel System,
New Lawuga
Charity School,
Yushu,
Qinghai,
China,
2015

Using lightweight prefabrication, the building was constructed in just one month. The Hong Kong-based design team used a BIM platform to coordinate 90 per cent of its production in a timber factory in Chengdu, Sichuan. The diagram shows a clear layer mindset.



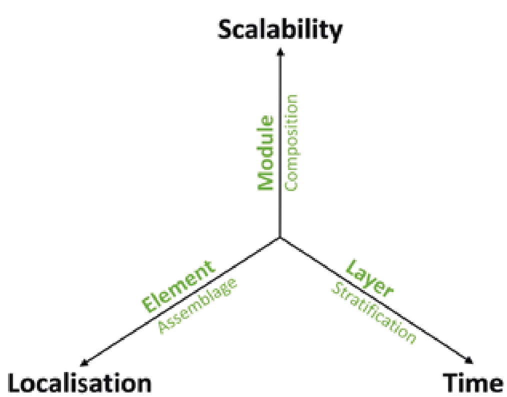
OPEN Architecture,
HEX-SYS,
Guangzhou,
China,
2015

In response to the phenomenon of short-lived buildings, the architects developed a modular building system that is light, industrialised and flexible. It enables speedy construction, and can be disassembled after each use and reassembled in another location.



Andong Lu,
The triad mindsets
of generic
construction,
School of
Architecture
and Urban Planning,
Nanjing University,
Nanjing,
China,
2017

Localisation, time and scalability are the major factors that prevent the total integration of construction within the manufacturing process. Different mindsets have gradually evolved to try to address these issues with the goal of incorporating real-space construction within the design phase.



Autonomous assembly casts new light on the challenges of generic construction in a fourth approach, and has the potential to redefine the whole concept of construction itself.

Time and the Layer-Stratification Mindset

Though time is an indirect dimension of construction, it is no less important than localisation. It calls for consideration of often-overlooked factors such as occupancy, flexibility and the lifecycle of different materials, and the related issues of the replacement and recyclability of building components, which might also be determined by changing values, tastes and lifestyles.

This requires a new mindset that focuses on the long-term performance of a building rather than how it is put together. According to Frank Duffy, quoted in Stewart Brand's book *How Buildings Learn* (1994), 'there isn't such a thing as a building. A building properly conceived is several layers of longevity of built components.'[4] Duffy's concept of shearing layers was further elaborated by Brand in his proposal of six differently paced systems of Site, Structure, Skin, Services, Space Plan and Stuff.[5] The pace levels of these layers have different effects on the whole: 'the quick processes provide originality and challenge, the slow provide continuity and constraint'.[6] Layers are not therefore material elements, but rather conceptual frames that allow building designs to accommodate technological and organisational change. Disconnection or intervals between layers are essential for them to be free and changeable.

Scalability and the Module-Composition Mindset

Scale is an intrinsic dimension of construction. As its Latin etymology shows (*com* means 'with, together' and *struere* means 'to pile up'),[7] the very concept of construction is about accumulating small-scale units to form larger-scale objects, systems or organisations. In this sense, construction can also be understood as the art and science of making by scaling up.

The module-composition mindset responds to this understanding of construction. In order to make the piling-up easier, the basic units need to be identical or in a limited number of different types. They then follow some simple rules of neighbouring to grow. The resulting composition is often non-hierarchical in structure, and its units are both attachable and detachable. The basic units are self-sufficient cells and can be mass-produced. While they may be simple, with a few generative steps they can compose highly sophisticated forms. As Stephen Wolfram has argued in his book *A New Kind of Science* (2002), great complexity can be achieved through the iteration of elementary rules.[8]

It is the mathematical rules of composition or the geometrical shapes of the units – often rectangular, hexagonal or octagonal – that differentiate the module approach from those of element assemblage and layer stratification. Le Corbusier's Quartiers Modernes Frugès housing development (1925–6) in Pessac, France, or Aldo van Eyck's cellular experimentation in the 1970s can be considered early precedents of the approach. OPEN Architecture has applied and experimented with this idea in a contemporary context in a number of recent projects, such as the Xihuafu Sales Pavilion (Beijing, 2013) and its HEX-SYS hexagonal modular building system (Guangzhou, 2015).

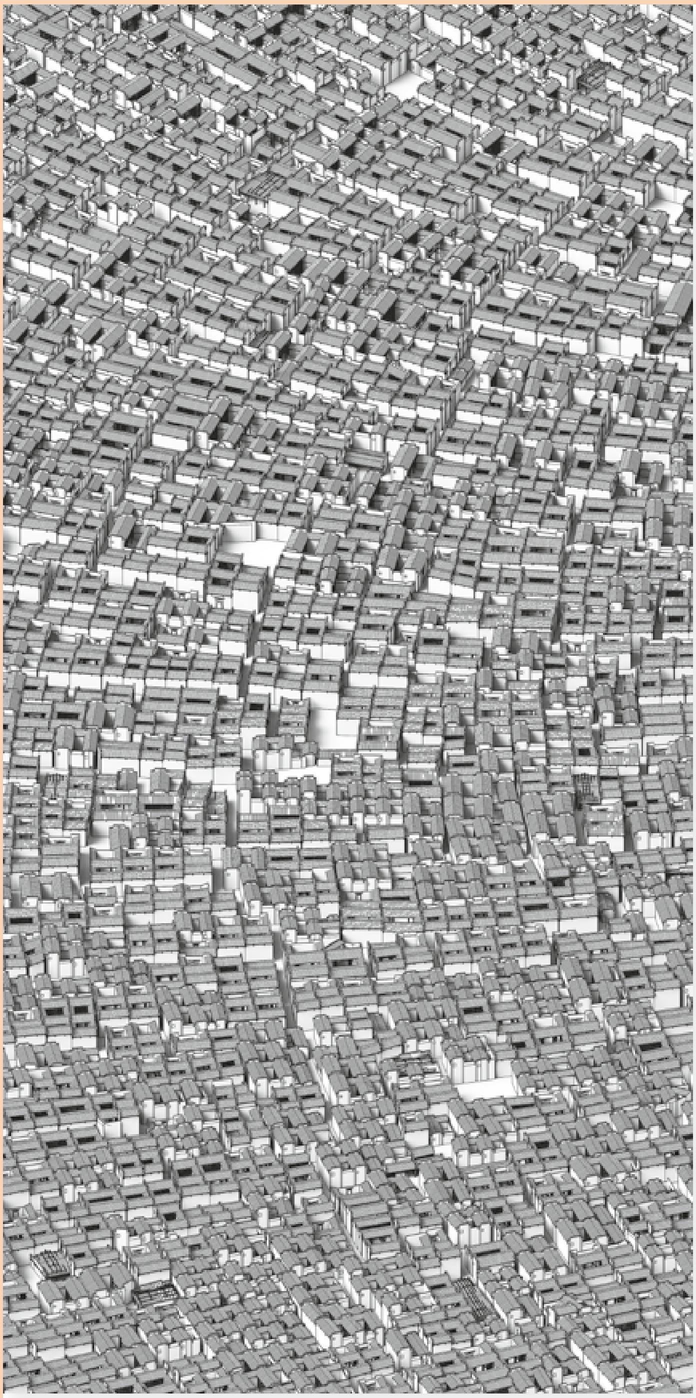
Generic Construction and the Autonomous Assembly Approach

Although architects may think freely of buildings in terms of elements, layers, modules or a combination of these, the shared aim of the mindsets described above is nonetheless to break down the ad hoc issue of construction into standard subsets and substructures to make them prefabricatable and mass producible – in other words, generic construction. However, they also have different characteristics. For example, the layer mindset, more properly called 'shearing layers', focuses more on the well-tempered interior environment and follows an introversive logic. It is not a coincidence that the theory of layers was originally developed for the interior design of commercial buildings. On the other hand, the module mindset is more concerned with the organising pattern, which serves as an extroversive framework that allows the whole system to be seemingly infinitely expandable. The modular system therefore has the capacity to extend beyond architecture into urban and geographic realms, as forecast by the Japanese Metabolist architect Kisho Kurokawa's Agricultural City project (1960) in which he envisioned the natural growth of the agricultural city underpinned by a grid system, based on which the living units multiply spontaneously without any hierarchy.

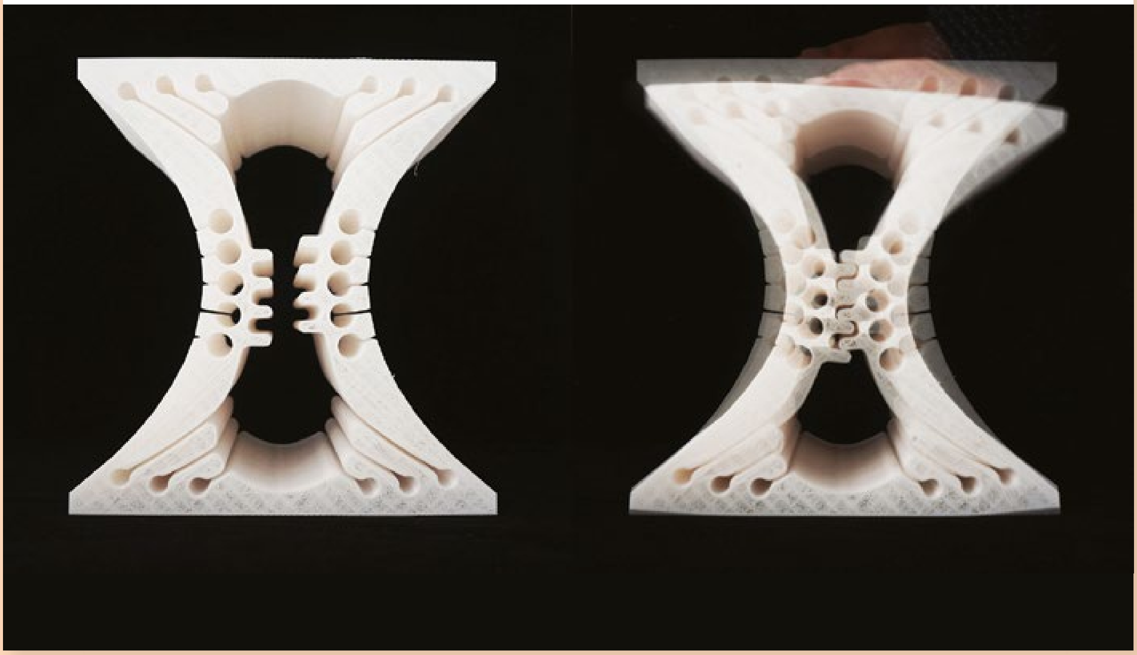
Instead of separating the processes of manufacturing and assembly, autonomous assembly casts new light on the challenges of generic construction in a fourth approach, and has the potential to redefine the whole concept of construction itself. Early precursors include transformable structures such as mobile deployable systems or retractable roofs, which have already been widely applied in architectural engineering. It applies the theory of self-assembly in chemistry, biology and natural systems, and material science to human-scale construction by programming the materials, components or configuration processes. It considers localisation very much in a thermodynamic sense, as local input of energy, and thus shows a responsive attitude to environmental factors and natural forces. Regarding the dimension of time, autonomous assembly understands construction as a conditioned (re-)configuration based on weak interactions among thermodynamically stable components, and is

Li Biao,
Sand Mapping,
Architectural
Algorithms &
Applications
exhibition,
School of
Architecture,
Southeast
University,
Nanjing,
2016

Optimised collective forms of settlement can be generated in seconds via a computational system integrating the rules of traditional Chinese timber structures, street pattern and distribution of plots. In this project, the evolutionary rules were observed from case studies of historical settlements and encoded by Java programming.



Rather than placing subunits in a desired location following a designated sequence or composition, autonomous assembly involves a bottom-up process in which they work collectively.



Zhong Huaying,
Resilient Fragile
Material,
Year 4 Studio,
School of
Architecture and
Urban Planning,
Nanjing University,
Nanjing,
2015

The morphing capacity of 3D printing was here combined with performance-oriented modelling that optimises the distribution of internal stress to prefabricate a transformable unit using fragile material.

therefore characterised by an intrinsic property of reversibility. On the issue of scalability, though seemingly similar to the module mindset, it adopts a process more like pattern formation in nature. Rather than placing subunits in a desired location following a designated sequence or composition, autonomous assembly involves a bottom-up process in which they work collectively.

Challenges of the Fourth Approach

While autonomous assembly certainly provides a solution for construction in extreme conditions such as unreachable sites, its wider application in the built environment presents a number of challenges that are yet to be sufficiently addressed:

- **Performance:** Architectural construction is about forming a habitable space rather than a structure. The goal of the traditional element, layer and module approaches is improving the environmental performance of buildings by increasing the quality, diversity and level of customisation. Integrating performance-related design within the autonomous assembly process is essential for its application beyond civil engineering and pavilion building.
- **Resilience:** Whilst its intrinsic reversibility means that autonomous assembly is suitable for temporary structures, most architectural construction builds for a longer period of time (years, or even decades) and thus needs to be resilient to countless unavoidable and unforeseeable variables during this period. How can sufficient resilience be achieved while maintaining the weak interaction between the subunits of autonomous assembly?
- **Engagement:** Construction, in the traditional sense, is heavily reliant on local resources and human labour, and hence deeply embedded in the local environment, economy and culture. It is not surprising therefore that it often becomes a ceremonial process or unifying event. Autonomous assembly eliminates the manual work of construction, and with it human engagement. Can new forms of engagement be invented that retain the social agency dimension of construction?

Prefabricated generic construction responds to some of the challenges that are emerging as our cities and buildings become increasingly transitory and building production more systematic, and innovative approaches such as autonomous assembly may inspire new models to connect design, construction and society. However, the establishment of a real working model requires exploration of the possibilities of combining this fourth approach with those of element-assemblage, layer-stratification and module composition, and learning from the long tradition of construction in which, for example, pattern formation is manifested in the collective form rather than single buildings. Perhaps we should bear in mind that construction is always a synthesis of physical production, the material definition of a place on earth, and the agency of interaction and expression. Though separated, these dimensions will never disappear. ⅅ

Dou Pingping, Typology-based demonstrative prefab rural housing, Jiangning, Nanjing, 2015

The project focused on the grouping and configuration of prefab housing units, and provided a construction manual for villagers to select from and follow. When adapted to the complex topography of the landscape, the composition of only a few different types of units achieved a fine balance between collective order and high diversity.

Notes:

1. Rem Koolhaas *et al*, *Elements*, Marsilio (Venice), 2014, back cover.
2. 'Government Turns to Prefab Buildings to Save Resources', *China Daily*, 1 October 2016: www.chinadaily.com.cn/china/2016-10/01/content_26956827.htm.
3. Vanke, *2015 Annual Report*: www.vanke.com/upload/file/2016-04-28/d3380669-9908-46b7-9033-c1aaf783314a.pdf.
4. Stewart Brand, *How Buildings Learn: What Happens After They're Built*, Viking (New York), 1994, p 12.
5. *Ibid*, pp 12–13.
6. *Ibid*, p 17.
7. Online Etymology Dictionary: www.etymonline.com/index.php?allowed_in_frame=0&search=construction.
8. Stephen Wolfram, *A New Kind of Science*, Wolfram Research (Champaign, IL), 2002.

CONTRIBUTORS

ARCHITECTURAL DESIGN

AUTONOMOUS ASSEMBLY

Benjamin Aranda is a partner in Aranda\Lasch, a design practice dedicated to the design of buildings, installations, objects and furniture through a deep investigation of structure and materials. Aranda\Lasch have been winners of the United States Artists Award and Young Architects + Designers Award in 2007, the Architectural Record Design Vanguard Award in 2014, the Architectural League Emerging Voices Award in 2015, Architectural Digest's 2014 AD Innovators, and a Miller Prize finalist in 2016. Aranda is based in the firm's New York office.

Philippe Block is Associate Professor at the Institute of Technology in Architecture, ETH Zurich, where he leads the Block Research Group (BRG) with Tom Van Mele, and is the Deputy Director of the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication. The BRG's research focuses on structural form-finding as well as the optimisation and fabrication of shell structures. He studied architecture and structural engineering at the Vrije Universiteit Brussel (VUB) in Belgium, and at the Massachusetts Institute of Technology (MIT). With the BRG and as partner of Ochsendorf DeJong & Block, he provides structural assessment of historic monuments, and design and engineering of novel compression structures.

Marcelo Coelho is a lecturer at the MIT Department of Architecture and a principal at Marcelo Coelho Studio. Spanning a wide range of media, processes and scales, his work explores the boundaries between matter and information, and utilises programmable materials and digital fabrication to fundamentally expand and enhance the ways in which we interact and communicate. Prior to forming his studio practice, he received a Bachelor in Computation Arts with highest honours from Concordia University in Montreal, and a Doctorate in Media Arts and Sciences from the MIT Media Lab.

Karola Dierichs is an architect and researcher at the Institute for Computational Design (ICD), University of Stuttgart, where she is leading the aggregate architectures research field and developing granular materials as designer matter in architecture. She has taught at the Architectural Association (AA) in London, the Städelschule Architecture Class in Frankfurt, as well as the ICD. Her recent work has been recognised with the Holcim Acknowledgement Award Europe 2014.

Bastien Gallet is a philosopher and writer, and teaches at the Haute École des Arts du Rhin (HEAR) in Strasbourg. He is also managing editor of the French publishing house Editions MF.

Fabio Gramazio is an architect with multidisciplinary interests ranging from computational design and robotic fabrication to material innovation. In 2000, with Matthias Kohler, he cofounded the Zurich architecture practice Gramazio Kohler, which has produced numerous award-winning designs. Current projects include the design of the Empa NEST research platform, a future living and working laboratory for sustainable building construction. In 2015, the partners also opened the world's first architectural robotic laboratory at ETH Zurich, with projects ranging from 1:1 prototype installations to the design of robotically fabricated high-rises. The recent research is outlined and theoretically framed in the book *The Robotic Touch: How Robots Change Architecture* (Park Books, 2014).

Tovi Grossman is a Distinguished Research Scientist at Autodesk Research, located in downtown Toronto. His research on human–computer interaction focuses on software learning and new technologies. His work has led to a number of technologies now used in Autodesk products, such as Autodesk Screencast and Autodesk ToolClip videos, and Autodesk SketchBook Motion. He received a PhD in Human-Computer Interaction from the Department of Computer Science at the University of Toronto.

Mariana Ibañez is an architect and artist who practised in Argentina before studying at the AA in London, after which she worked as a project architect at the offices of Zaha Hadid. She is based in Cambridge, Massachusetts, where she is a principal of Ibañez Kim and Associate Professor of Architecture at the Harvard University Graduate School of Design (GSD). She is also an Associate of the Immersive Kinematics Lab.

Heinrich Jaeger is the William J Friedman and Alicia Townsend Professor of Physics at the University of Chicago. He received his PhD in physics in 1987 from the University of Minnesota, and has been on the faculty at the University of Chicago since 1991, directing the Chicago Materials Research Center from 2001 to 2006, and the James Franck Institute from 2007 to 2010. His current research focuses on self-assembled nanoparticle-based structures, on the rheology of concentrated particle suspensions, and on studies of the packing and flow properties of granular materials.

Simon Kim is a registered architect and designer trained at the AA in London and at MIT. He is Director of the Immersive Kinematics Lab at the University of Pennsylvania (UPenn) and a principal of Ibañez Kim. He has grants from the National Science Foundation and the Pew Center for Humanities, and has taught at Harvard, Yale and UPenn.

Matthias Kohler is an architect with multidisciplinary interests and cofounder with Fabio Gramazio of award-winning practice Gramazio Kohler. He has played an equal part in the practice's research at ETH Zurich, which has been formative in the field of digital architecture, merging advanced architectural design and additive fabrication processes through the customised use of industrial robots. Since 2014, he has also been the founding director of the new National Centre of Competence in Research (NCCR) Digital Fabrication in Zurich (www.dfab.ch).

Chris Lasch is a partner in Aranda\Lasch, based at the Tucson, Arizona office. The practice's early projects are the subject of the book *Tooling* (Princeton Architectural Press, 2006), part of the *Pamphlet Architecture* series. Their firm's collaborative work with Terrol Dew Johnson is part of the permanent collection at the Museum of Modern Art (MoMA) in New York.

Jared Laucks is a trained designer and fabrication specialist. He is currently a Research Scientist and Co-Director at the MIT Self-Assembly Lab. He holds a Master of Science from the MIT Media Lab where he focused on robotic and biological fabrication methods for projects including the *Silk Pavilion*. He obtained a Bachelor of Architecture from Philadelphia University. Prior to MIT, he practised at Interface Studio Architects and THEVERYMANY, and taught a number of architecture courses. He is a regular studio critic for MIT courses. He continues to develop research and project-based work publications and exhibits worldwide.

Andong Lu is Professor at the School of Architecture and Urban Planning, Nanjing University. He holds a PhD in Architecture from the University of Cambridge, and was a Fellow of Wolfson College. He is co-editor of the books *Cities in Transition: Power, Environment, Society* (NAi010, 2015) and *Urban Cinematics: Understanding Urban Phenomena Through the Moving Image* (Intellect Books, 2011). His research focuses on architecture, narrative and digitality. He launched the Investigate-It Workshop and Exhibitions (RIBA, London 2015; OCAT, Shanghai 2016; Melbourne School of Design, 2016), and the Memory Project of the Nanjing Yangtze River Bridge. He is also the founding partner of LanD Studio.

Chris Luebkeman's interest in the built environment blossomed early, propelling him to pursue a multifaceted education, beginning with engineering and culminating in a Doctorate in Architecture from ETH Zurich. He gained valuable experience as the protégé of esteemed Spanish architect Santiago Calatrava. He has taught at several prestigious universities. In 1999 he joined Arup as Co-Director for Research and Development, and a couple of years later formed the Foresight, Innovation and Incubation team, which has evolved into its present form as Arup Foresight + Research + Innovation.

Hannes Mayer is a senior researcher and member of the Board at Gramazio Kohler Research, ETH Zurich, and co-publisher of the architecture magazine *manege für architektur*. He has been a guest professor at the Academy of Fine Arts in Vienna, and taught design studios and postgraduate design research at the Bartlett School of Architecture, University College London (UCL) and at the University of Westminster. He has also served as director and editor-in-chief of the thematic review for architecture *archithese*. He holds a diploma and Master's degree in architecture from the Bartlett.

Robin Meier is an artist and composer who explores the emergence of natural and artificial intelligence and the role of humans in a world of machines. Referred to as 'Maestro of the Swarm' (*Nature*) or 'pathetic' (Vimeo user), his works are shown in institutions such as the Palais de Tokyo, Musée d'Art Moderne de Paris, Art Basel, Shanghai Biennale and the Nikola Lenivets Moscow.

Achim Menges is a registered architect and professor at the University of Stuttgart, where he is the founding director of the Institute for Computational Design (ICD). He was Visiting Professor in Architecture at Harvard GSD from 2009 to 2015. His practice and research focus on the development of integral design processes at the intersection of morphogenetic design computation, biomimetic engineering and computer-aided manufacturing that enables a highly articulated, performative built environment.

Caitlin Mueller is a designer and researcher who works at the intersection of architecture and structural engineering. She is currently an Assistant Professor at MIT, where she holds a joint appointment in the Departments of Architecture and Civil and Environmental Engineering, and leads the Digital Structures research group. She earned a PhD in Building Technology, Master of Science in Computation for Design and Optimization and Bachelor of Science in Architecture from MIT, and a Master's in Structural Engineering from Stanford University, and has practised at several architecture and engineering firms across the US.

Kieran Murphy is a physics PhD student at the University of Chicago. His research focuses on driving disordered, complex systems to failure in order to understand how details at the smallest scales – such as particle shape in jammed granular structures – can play a critical role in macroscopic behaviour. He received his BA in physics and computer science from the University of California, Berkeley.

Radhika Nagpal is a Professor in Computer Science at the Harvard School of Engineering and Applied Sciences, and a core faculty member of the Harvard Wyss Institute for Biologically Inspired Engineering where she co-leads the BioRobotics Platform. The two main focus areas of her research are biologically inspired multi-agent systems (collective algorithms, programming paradigms, modular and swarm robotics) and biological multi-agent systems (models of multicellular morphogenesis and collective insect behaviour). She was named as one of the *Nature*'s 10: top ten scientists and engineers of 2014.

Athina Papadopoulou is an architect and design researcher. She is currently a PhD researcher in the Design Computation Group and the Self-Assembly Lab at MIT. Her research includes the study of spatial sensory interactions and the development of active material environments. It has been published in *Cognitive Processing, Nature Scientific Reports*, *3DPrinting+* and design journals. She has co-organised workshops and conferences, including the Active Matter Summit at MIT, and has taught at MIT and the Boston Architectural College. She holds a Master of Science in Design Computation from MIT, and graduate and undergraduate degrees in architecture from the National Technical University of Athens.

Dan Peterman is an artist whose work combines innovative strategies of local engagement and activism with national and international exhibitions, projects and installations. Among his diverse projects, he explores networks of recycled or discarded materials to produce starkly minimal works that function interchangeably as stockpiles, sculpture, functional objects, and critiques of environmental oversight and neglect. He is a founder of the Experimental Station, an innovative Chicago-based incubator of small-scale enterprise and cultural projects. He is also an associate professor in the College of Architecture and the Arts at the University of Illinois at Chicago.

Kirstin Petersen is an Assistant Professor at the department of Electrical and Computer Engineering at Cornell University in New York. She has a BSc in electro-technical engineering from the University of Southern Denmark, and a PhD in Computer Science from Harvard. Before starting at Cornell, she completed a two-year postdoctoral fellowship at the Max Planck Institute for Intelligent Systems in Stuttgart. Inspired by social insects in nature, her research involves design and coordination of embodied intelligent robot collectives capable of manipulating their shared environment.

Matthias Rippmann has been a member of the Block Research Group (BRG) at ETH Zurich since 2010, where he received his doctorate. In 2015 he joined the NCCR Digital Fabrication at ETH as a postdoctoral fellow. He conducts research in the field of structurally informed design and digital fabrication, and is lead developer of the form-finding software RhinoVAULT. He studied architecture at the University of Stuttgart and the University of Melbourne. He has worked at Behnisch Architekten, LAVA, the Institute for Lightweight Structures and Conceptual Design and Werner Sobek Engineers. In 2010 he cofounded the architecture and consultancy firm Rippmann Oesterle Knauss GmbH (ROK).

Leah Roth is a physics PhD student at the University of Chicago, researching the role of particle shape in designing and controlling the dynamics of granular material through evolutionary algorithms paired with simulation and experiment. She received her BA in physics and computer science at St Olaf College in Northfield, Minnesota.

Jose Sanchez is an architect, programmer and game designer based in Los Angeles. He is a partner at Bloom Games and the director of Plethora Project, a research and learning project investing in the future of online open-source knowledge, and the creator of Block'hood, a city simulator video game exploring notions of crowdsourced urbanism. He is currently Assistant Professor at the University of Southern California School of Architecture in Los Angeles. His research explores generative interfaces in the form of video games, speculating on modes of intelligence augmentation, combinatorics and open systems as a design medium.

Alvise Simondetti, a registered architect in Italy, has been formally educated in architecture, town planning, conservation and computation. He believes that successful design cannot be separated from tools. He is a Fulbright Scholar and a graduate of MIT. From 1997 to 2000 he was Assistant Professor of the School of Design, Hong Kong Polytechnic University. He joined Arup in 2000, were he is now an associate in the Foresight + Research + Innovation team, currently exploring applications of machine learning for the architecture, engineering and construction industries. He is responsible for the business development of synthetic environments.

Gereon Uerz is a sociologist and foresight professional who joined Arup in 2014. He left the University of Freiburg in Germany where he was senior researcher and lecturer at the Institute of Sociology in 2005 to join Z_punkt The Foresight Company as a consultant. From 2009 he was Project Director at Volkswagen Group Research in Wolfsburg. Over the last decade he has been guest lecturing at Hannover University, the University of Vienna, European Business School (EBS) in Östrich-Winkel, and has authored a number of articles and a book. He is currently supporting the establishment of Arup University and Foresight in Europe, as well as focusing on projects with clients from the automotive, engineering and chemical industries.

Tom Van Mele is co-director of the Block Research Group (BRG) at ETH Zurich, where he has been leading research and development since 2010. In 2008 he received his PhD from the Department of Architectural Engineering at the VUB in Brussels. His current research projects include collapse mechanisms of masonry structures, flexible formwork systems for concrete shells, and graphical design and analysis methods such as three-dimensional graphic statics. He is the lead developer of compAS, the open-source computational framework for architecture, structures and digital fabrication.

Zorana Zeravcic is a lecturer and researcher at the École Supérieure de Physique et de Chimie Industrielles at Paris Sciences et Lettres Research University in Paris, having started as Maître de Conférences in 2016. She uses computer simulations and various analytical tools such as statistical physics to study design principles of artificial matter. Her background is in condensed matter physics theory, with a PhD from the University of Leiden. Her interest in biology-inspired design developed during postdoctoral research at Harvard and at Rockefeller University in New York.

What is Architectural Design?

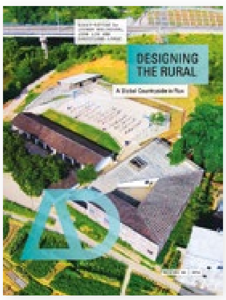
Founded in 1930, *Architectural Design* (AD) is an influential and prestigious publication. It combines the currency and topicality of a newsstand journal with the rigour and production qualities of a book. With an almost unrivalled reputation worldwide, it is consistently at the forefront of cultural thought and design.

Each title of AD is edited by an invited Guest-Editor, who is an international expert in the field. Renowned for being at the leading edge of design and new technologies, AD also covers themes as diverse as architectural history, the environment, interior design, landscape architecture and urban design.

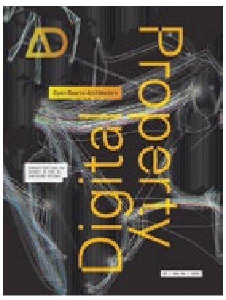
Provocative and pioneering, AD inspires theoretical, creative and technological advances. It questions the outcome of technical innovations as well as the far-reaching social, cultural and environmental challenges that present themselves today.

For further information on AD, subscriptions and purchasing single issues see:

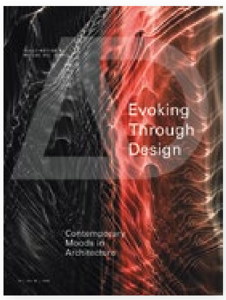
www.architectural-design-magazine.com



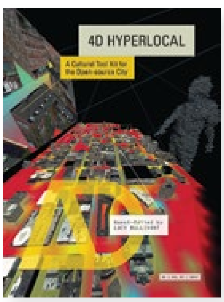
Volume 86 No 4
ISBN 978 1118 951057



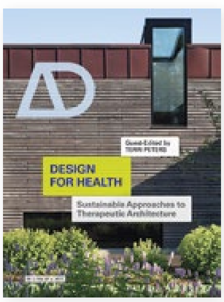
Volume 86 No 5
ISBN 978 1118 954980



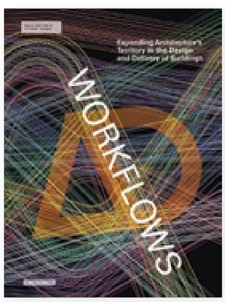
Volume 86 No 6
ISBN 978 1119 099581



Volume 87 No 1
ISBN 978 1119 099581



Volume 87 No 2
ISBN 978 1119 162131



Volume 87 No 3
ISBN 978 1119 317845

Individual backlist issues of AD are available as books for purchase starting at £24.99 / US$39.95

www.wiley.com

How to Subscribe
With 6 issues a year, you can subscribe to AD (either print, online or through the AD App for iPad)

Institutional subscription
£275 / US$516
print or online

Institutional subscription
£330 / US$620
combined print and online

Personal-rate subscription
£128 / US$201
print and iPad access

Student-rate subscription
£84/ US$129
print only

AD App for iPad
6-issue subscription:
£44.99 / US$64.99
Individual issue:
£9.99 / US$13.99

To subscribe to print or online
E: cs-journals@wiley.com

Americas
E: cs-journals@wiley.com
T: +1 781 388 8598
or +1 800 835 6770
(toll free in the USA & Canada)

Europe, Middle East and Africa
E: cs-journals@wiley.com
T: +44 (0) 1865 778315

Asia Pacific
E: cs-journals@wiley.com
T: +65 6511 8000

Japan (for Japanese-speaking support)
E: cs-japan@wiley.com
T: +65 6511 8010
or 005 316 50 480
(toll-free)

Visit our Online Customer Help available in 7 languages at www.wileycustomerhelp.com/ask