Mesh mould

Robotically fabricated spatial meshes as reinforced concrete formwork
Digital architecture in the 1990s was predominantly concerned with new computer-aided design strategies and was often criticised for neglecting issues of materialisation and construction. The gap between what is digitally possible to design and what is physically feasible to build narrowed when throughout the early 2000s CNC machines became more commonly available and eventually enabled designers and architects to bring their designs back from the virtual medium into the physical world. These machines offered unprecedented freedoms for the fabrication of geometrical complex parts and intricate surfaces. However, they were largely limited to subtractive processes and prefabrication. With the introduction of industrial robots to architectural research, the scope of digitally controllable fabrication processes widened dramatically. Unlike with most specialised machines, such as CNC gantry mills, the scope of the industrial robot is not defined and limited by its kinematics and offers an opportunity not only to customise the machined parts, but beyond that to the entire fabrication process.

The generative, versatile and anthropomorphic nature of robots has inspired architects and researchers to equip these machines with almost every conceivable tool for gluing, melting, drilling, welding, cutting, painting. Even though, in the domain of architecture, robotic fabrication is still a new field of research, a remarkable amount of small yet sophisticated architectural structures have already been built and have impressively demonstrated the flexibility of such robots. Displaying a high degree of spatial and structural differentiation, these prototypical designs already hint at the potential for the application at a larger scale of load-bearing structures. However, until now applications in construction at the large scale have barely been investigated.

The Dilemma with Robots

If standard six-axis robots, applied in the manufacturing industry for years and a reliable and relatively cheap off-the-shelf technology, are to have applications in construction at the larger scale, a reconsideration of known material processes is required. The construction logistics and the material system have to be designed to accommodate the specific abilities and limitations of robots. For instance, on the one hand the small size of robots is a limitation; on the other, it holds a significant potential. Their payload limitations do not allow for the handling of materials in the sizes and weights they are commonly used in construction. However, their small dimensions and low mass do make them suitable for application directly on the building site. Mounted on a mobile platform and equipped with sensors, multiple robots can navigate the building site, react dynamically to the tolerances and changing conditions of this complex environment, and fabricate the structure directly in situ (see also Volker Helm's 'In-Situ Fabrication’ on pp 100-107 of this issue). This conceptual approach differs greatly from gantry machines, which either have to be scaled beyond the size of the building footprint, as in the case of the Japanese construction automation systems (see Thomas Bock and Sike Langenberg's ‘Changing Building Sites’ on pp 88-99 of this issue), or, alternatively, the building elements have to be scaled down to match the envelope of the machine. This in turn raises questions of segmentation, transport and assembly logistics on site.
Consideration of size, weight and payload has led to the conclusion that in order to be effective and competitive, an appropriate construction system for standard industrial robots needs to be lightweight, built from comparatively small elements, and allow parallelisation and collaboration with other robots, humans and conventional construction machines. However, most importantly, the application of robots is feasible only if it generates a value-adding effect. The centralised, fully automated Japanese construction systems failed to do so, as they merely tried to automate existing processes, placing the emphasis on the elimination of human labour from the building site. They did not manage to capitalise on the real potential of machine automation, they underestimated the complexity of the building process, and overlooked the fact that for many jobs humans are not only needed, but are also more efficient. Hence, different construction processes need to be developed to specifically address the strengths of robots in order that they can be applied where they actually outperform humans and conventional construction tools.

**Division of Mass and the Information**

At first glance, the requirements for a robotic fabrication system seem to be somewhat contradicting. Most common building materials for large-scale constructions are all but small and light. However, shifting the focus away from processing the entire mass of a building by robots, towards using them only for its geometric definition, solves the issue of limited payloads and simultaneously allows the benefits of their density to be maximised. In this respect, concrete, the most commonly used construction material, has the inherent properties to be separable into its heavy structural mass and light, shape-defining formwork. In other words, it permits the separation of mass and information.

In a future scenario collaboration between conventional tools, humans and robots, standard concrete pumps would transfer the actual structural mass, while the robot could unlock the inherent potential of concrete to take any desired shape by building complex formwork in high resolution. Due to the usually high costs of labour involved in the fabrication of custom formwork, this potential still too often remains inactive.

The desire to fully explore the malleable potential of concrete has a long-standing tradition, beginning in the 20th century. Le Corbusier and, most notably, Pier Luigi Nervi, built complex curved concrete structures using manually assembled formwork. More recently, the increased geometric complexity enabled through digital design tools on one hand, and the technical possibility to mill Styrofoam inlays directly from design data on the other, has led to the emergence of a technique that combines custom inlays with standard formwork, which is state of the art and economically viable for a limited range of building typologies and budgets.

However, in the past decade, academia and industry have made large efforts to eliminate the need of formwork entirely. Even though there are some differences, these approaches are best being generalised as layer-based 3D printing of cementitious, or concrete-like, materials. And though these developments offer hope regarding the potential to build formless surfaces entirely waste-free, there are certain limitations and difficulties of such systems. For example, the hydration process of cementitious materials is difficult to control, and has a profound impact on the bonding behaviour among the layers. In the case of wrong timing, these do not sufficiently cohere, which consequently degrades an otherwise isotropic material to an anisotropic one, and thus limits the constructive capacities of the material. Furthermore, layer height, surface resolution and printing time are closely correlated parameters in order to achieve a smooth surface, the layer height needs to be sufficiently small, which through every layer bisection cubically increases fabrication time. These issues have so far not been convincingly resolved and are reasons why recent research has shifted away from printing the actual concrete structure itself.

**Mesh-Mould Combined Formwork and Reinforcement**

Based on these findings, for the Mesh-Mould research project the decision was taken to concentrate on the fabrication of the formwork using an interesting technology known as 'linking formwork'. Here, concrete is poured into a corrugated formwork that is built up from perforated flat plastic panels and enables the erection of straight and single curved walls. The concrete then passes through the perforations and covers the formwork. In a subsequent step the surfaces are manually trowelled, leaving behind a smooth concrete surface.

Against this backdrop, polymers were firstly extruded in 3D space, precisely controlled by the robot, in order to create the required meshes and liberate the formwork from geometric constraints. The use of thermoplastic polymers, such as used on conventional 3D printers, permits precise control over the material’s hardening behaviour. Pinpoint cooling during the extrusion process, for example, gives such a high level of control that free spatial extrusions become possible and, consequently, the 'casting' of structures freely in space.

_Danny Hill; Foma Tech, Loadilng Formwork, Victoria, Australia, 2010_

_Fabio Gramazio and Matthias Kohler, Mesh-Mould; close-up of extrusion process; Architecture and Digital Fabrication, ETH Zurich, 2013_

The corrugated plastic panels are clipped together on site, holding in place the vertical and horizontal steel reinforcement. A semi-fluid concrete is funnelled in through slots around the outer reinforcement and the plastic panels, but still needs to be sufficiently viscous to not entirely run out of the perforations. Once the operator can see through the perforated plastic panels during the extrusion process, he can substantially adjust the flow, hence there is usually no need to vibrate the concrete.
A few large, corrugated stainless-steel domes (6.5 m in diameter and 2.4 m high) were fabricated to test the robustness of the process. A complete prototype displaying a series of corrugated stainless-steel domes is being developed for a project in Ireland. The domes are made of a material that is currently under development.

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Potential for Design, Planning and Construction

The collaborative, distributed manner in which the mesh-fabricating mobile robots work together on the building site is scalable to various project sizes by parallelisation. By simply adjusting the number of collaborating agents, Mesh-Mesh stays flexible and versatile, both in terms of design freedom and required infrastructural investment.

A typical concrete process involves a long and sequential chain of tasks from the prefabrication of formwork, transportation, site logistics, bending and placing of reinforcement bars, installation of formwork, concreting, disassembly and cleaning of formwork, and finally surface finishing. As the robots directly extrude the reinforcing formwork in-situ, several of these crafts and professions involved can be folded into one, allowing a higher product complexity while simplifying the process itself.

Under the consideration of Asia’s incessant building activity and the sheer amount of buildings to be constructed in the near future, it is becoming increasingly important to develop sustainable construction systems that are cost sensitive, material efficient, and that provide for substantial architectural variation and programmatic differentiation. The unification of the two conventionally separate requirements of concrete—the reinforcement and the formwork—into one single robotic fabrication process can produce an additive and waste-free, material-efficient and geometically unconstrained method of fabricating complex non-standard concrete constructions.

References
3. Mesh-Mesh is a PhD-research project co-founded by specialty chemical company 2014 Alt Switzerland, and conducted by Romain Hardi.
5. See http://www. formadecentral.ch/en/ content/logistics/