Robotically fabricated spatial meshes as reinforced concrete formwork.
If robots are to be employed in the construction of high-rise structures, logistics and material systems have to be entirely rethought to cater for both their abilities and limitations: robots have limited loading capacity, but greater dexterity than other on-site, automated construction techniques. Here, Norman Hack of ETH Zurich and Willi Viktor Lauer of the Future Cities Laboratory (FCL) at the Singapore-ETH Centre for Global Environmental Sustainability (SEC) describe the research they have undertaken to develop ‘mesh-mould’ as an alternative to conventional 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 it 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 freedom for the fabrication of geometrically 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 the entire fabrication process.

The generic, versatile and anthropomorphic nature of robots has inspired architecture students and researchers to equip these machines with almost every conceivable tool for gluing, melting, drilling, winding, cutting, pouring or 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.

Fabricated structures are often a result of complex and intricate geometries designed by computer-aided design software and then fabricated using traditional techniques such as formwork and prefabrication. However, with the advent of new technologies such as additive manufacturing and robotics, there is a growing interest in using these technologies to create more complex and innovative architectural forms. This can be achieved by using robots to fabricate the formwork and reinforcement simultaneously, eliminating the need for traditional formwork and reducing the cost of construction. This approach, known as mesh-mould, was developed by researchers at ETH Zurich and the Future Cities Laboratory at the Singapore-ETH Centre for Global Environmental Sustainability. The method involves using robots to fabricate 3D mesh structures in an additive, waste-free manner, providing increased geometric complexity without raising the costs.
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 limitation does 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 situ4 (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 return raises questions of segmentation, transport and assembly logistics on site.

Conventional Construction Versus Robotic Fabrication
Embedded within the broad scope of investigations at the Future Cities Laboratory at the Singapore-ETH Centre for Global Environmental Sustainability (SEC), the Mesh-Mould research3 focuses specifically on the mechanisms and the constructive processes of mass-produced architecture in Asia. In Singapore, over 80 per cent of the building stock consists of high rises, with the biggest share erected as prefabricated large panel system constructions. This dominant technique, driven by an economy of scale, becomes efficient only if the same elements are repeated over and over again. In a structural sense this practice results in an unsustainable over-dimensioning of a large number of structural members that have to be designed for the worst load case. In the bigger picture, the inherent limitations of such systems to incorporate variation do not allow programmatic or spatial differentiation, which ultimately results in an equally unsustainable oversimplified, mono-functional and monotonous urban fabric.

A shift away from this outdated ‘one size fits all’ ideology towards a new fabrication paradigm based on flexible, robotic in-situ fabrication could promote an alternative tectonic that encourages variation and differentiation instead of being bound to geometric simplification, standardisation and repetition. The feasibility of non-standard fabrication, as demonstrated numerously at the small scale, leaves little doubt over its potential at the construction scale, yet the leap into bigger dimensions carries various challenges and raises new questions of its ability to scale.

Housing and Development Board, Housing complex, Singapore, 2013

Due to the high fabrication costs of formwork, most conventional prefabricated concrete structures are based on the repetition of a few geometrically simplified elements. This ‘one size fits all’ approach does not only dramatically limit the freedom of design, but is equally unsustainable since far more material is used than is structurally needed. The robotic in-situ extrusion of formwork and reinforcement, in contrast, allows for locally differentiating the structure, using material only where it is needed, and thus liberating construction from the restraints of repetition.
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 comparably 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 machinic 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 Information**

At first glance, the requirements for a robotic fabrication system seem to be somehow 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 dexterity 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 all too often remains inactivated.

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, have 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.

The corrugated plastic panels are clipped together on site, holding in place the vertical and horizontal steel reinforcement. A fairly fluid concrete is tuned to entirely flow around the steel reinforcement and the plastic panels, but still needs to be sufficiently viscous to not completely leak out of the perforations. Since the operator can see through the perforated plastic panels during the concrete pouring process, he can subsequently densify the cavities; hence there is usually no need to vibrate the concrete.

Danny Hill/Forma-Tech, Leaking Formwork, Victoria, Australia, 2010
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 freeform 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 connect, which consequently downgrades 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 System for Concrete**

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 ‘leaking 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 protrudes 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 freely 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 in 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 ‘knitting’ of structures freely in space.

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*Fabio Gramazio and Matthias Kohler, Mesh-Mould, close-up of extrusion process, Architecture and Digital Fabrication, ETH Zurich, 2013*

This second generation of extruders is based on a combination of custom-machined parts, off-the-shelf 3D printer components and an additional air-cooling system. Pressurised air is directed at the extruder tip, so that the material can harden the moment it is extruded. Air-cooling, feed rate, extrusion rate and designated motion stops need to be carefully calibrated in order to facilitate a spatial extrusion and to minimise material-dependent tolerances.
A few large acrylonitrile butadiene styrene (ABS) samples with sizes of approximately 80 x 60 x 8 centimetres (31 x 24 x 3 inches) were fabricated to test the robustness of the process. A complex geometry displaying a variety of curvatures helped to better understand critical positions in which errors are more likely to occur. Within 10 hours, a mesh with a diameter of 1.5 millimetres (0.06 inches) extrusion thickness and a total volume fraction of 2.5 per cent was fabricated. Concepts for the development of faster multi-nozzle print heads, inspired by inkjet printers, are currently under development.
This conceptual change, from layer-based material deposition to spatial extrusion, has several noteworthy implications. Whereas the former remains generic, mostly for the reproduction or representation of form, the controlled spatial extrusion becomes specific to the construction process. Firstly, the fabrication time is significantly reduced and becomes feasible for application in construction at the large scale. Furthermore, the mesh densities are generated according to the various forces that act on the structure. This applies for the static case after the concrete has cured, but also for dynamic loading during the concrete pouring process itself. Most interestingly, the alignment of the extrusion in accordance with the forces has the potential for co-extruding a strong filament such as carbon, glass, bamboo or basalt. This addition enables the structural activation of the mesh, making it accountable for high-tensile forces and ultimately replacing the entire conventional steel reinforcement. The robotic fabrication of freeform meshes not only allows for local adaptation towards various parameters like stresses and curvatures, but additionally enables the integration of cavities for lighter porous structures. Internal branch-like ducts for an enhanced concrete flow can be integrated directly in the algorithmic generation of the meshes and guarantee an optimal distribution of concrete within the structure.

Beyond these functional advantages, varying densities of the meshes can be used to generate advanced material effects, for example by keeping the concrete from reaching all the parts of the mesh, or inversely by making some parts of the meshes too large to hold back the concrete. Such material effects are specific to this system and could not be achieved by means of conventional mould-based formwork.

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, Mould-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 geometrically unconstrained method of fabricating complex non-standard concrete constructions.
As a prototypical setup for a process that is based on collaborative multi-agent in-situ fabrication, large-scale experiments are carried out on an ABB robot mounted on a mobile platform. The sample was extruded to a height of 1.8 metres (5 feet 11 inches) and, apart from slight instabilities caused by the slenderness of the sample, has not displayed any major inaccuracies. Fabricated in 30 hours with an extrusion thickness of 2.5 millimetres (0.1 inches), the final sample weighs about 3 kilograms (7 pounds).