Manufacturing the Bespoke

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R-O-B
Towards a Bespoke Building Process
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The term robot has its origins in the Slavonic word robota and is associated with notions of work and servitude. It was coined in 1920 by Karel Capek in his play RUR (Rossum's Universal Robots), which envisions a futuristic factory that assembles artificial people to carry out menial tasks. The subsequent association with repetitious, precise, nonspontaneous and nonvariant acts, became a defining image of automation in the 20th century. At the Institute for Technology in Architecture at the Faculty of Architecture at ETH Zurich, the work of architects and researchers Gramazio and Kohler dissolves this myth. There, programmable automation is approached as a composed digital score where the actions of commonly available robotic industrial arms are animated and choreographed to perform acts of sublime dexterity and meticulous craft.

Housed in a modified freight container, R-O-B is a robotic fabrication concept that enables the flexible production of architectural building elements. It combines the advantages of prefabrication – precision and consistent high quality – with the advantages of short transport routes and just-in-time production on the building site (Figure 1).

R-O-B also signifies a substantial shift for conventions of architectural design and architectural production. Although robots were conceived as highly flexible machines and have been around for half a century, they ordinarily perform precise repetitive tasks. This is especially true for industrial robots that are deployed to standardise and control complex production processes. However, by adopting robotic tooling as a means to facilitate nonstandard routines, this restriction is subverted and robotic assembly becomes a very different concept for the designer. Flexibility inherent in the machine is empowered through its programmability enabling the architect to manipulate and control the building process.

Moreover, R-O-B, and industrial robots in general, significantly expand the option for intervention in the fabrication process and thereby the scope of design. In contrast to common CNC machines specialised to perform a predefined task, R-O-B is a generic tool. It not only allows for the control of its movements, but also enables its user to define the material manipulation processes itself.

R-O-B allows the architect to control where to work, what material to apply and how to manipulate and assemble it. In consequence, the understanding of construction as an integral part of architectural design takes on greater significance. R-O-B thus continues and extends the tradition of constructivist thinking in architecture.

Fig 1: The mobile fabrication unit R-O-B working from a flatbed truck trailer.
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1. Robotics in Architecture and Construction
Automating on-site building processes has been a field of research over the last 30 years. To date, over 200 different prototypes of robotic solutions have been developed especially for the construction industry and tested on building sites. It is quite astonishing that despite this sustained effort, few of these developments have become established in the industry or passed prototypical stage. Perhaps one reason for this is how the introduction of robots was largely channelled through manufacturing industries in order to substitute manual craft, raise the pace of standardisation and manage profit. Robots were predominantly regarded as advanced manufacturing and construction tools rather than programmable design tools, and thus their flexible potential was not focused at designers. Today, accompanied by changing technical and economic conditions, and a different conceptual approach, there are signs of this being overturned.

Although the concept of automation dates back to ancient Greece, the term ‘robot’ was first coined in 1922 by the science fiction author Karel Capek. Later, in the 1940s, another author of science fiction, Isaac Asimov, laid out the field of robotics in his writing. His view of the robot as a benevolent machine, put into the world to serve humankind and ease man’s daily struggle, might be regarded as the inspiration for a scientific impetus for the field of robotics outside science fiction, for it became a popular goal to conceive of machines for specific tasks to replace in early robotic development manual labour, particularly labour that was hazardous, hard and exhausting.
Industrial robots are generally defined as automatically controlled, reprogrammable, multipurpose manipulators programmable in three or more axes. It was George Devol who handed in a patent for a programmable manipulator in 1954. His company, Unimation, developed the first industrial robot that went to work for General Motors in 1961, extracting and separating parts of a die-casting machine. Soon after, Ford Motor Company applied the Unimate to spot welding, which became a primary application for robots as these jobs were particularly exhausting and hazardous for workers.

In their limitation to perform only simple recurring operations, industrial robots of the 1950s and 1960s were nowhere near as sophisticated as the humanoid robots envisioned by Capek and Asimov. And, although future generations of industrial robots evolved their capability, mainly with regards to mechatronics, their assignments to perform repetitive recurring operations within industrial automation processes remained the same.

Following Victor Scheinman’s so-called ‘Stanford Arm’ in 1969, the robotic arm as we know it today was substantially developed by industry in the 1970s (Figure 2). ASEA presented the IRB-6, a robotic arm with six degrees of freedom controlled by a standard computer, in 1973. This was the first microcomputer-controlled all-electric industrial robot that allowed continuous path motion. KUKA followed with their FAMULUS model in the same year and by the mid-1980s such tools were a common industrial resource, flourishing under the economic boom of the Japanese automotive sector in the latter half of the decade.

This period also marks the beginning of primary developments on robotics and automation in the building industry where research and development was also led by Japanese companies and universities. Here, focus was mainly directed on the development of new robotic systems as well as the automation of existing machinery. Robots were conceived to perform specialised tasks such as spraying, smoothing concrete, distributing materials, fitting equipment to ceilings, assembling formwork, installing facades, painting and many more. In 1990, the Shimizu Construction Company prototyped and launched an automated high-rise construction site, in effect an automated on-site factory capable of building one floor after another in a vertical ascension. Kajima and Maeda among others followed and developed systems known as SMART, ABCs and AMURAD, largely concentrating on the automated assembly of premanufactured building elements.

By inheriting many of its concepts on robotics and automation from manufacturing, the construction industry ignored its own unique structure and initially developed specialised machines engineered to fulfil one specific task or to automate the building process as a whole. Contrary to the industrial production of a high-performance mass-produced object such as the automobile, the construction industry is a project-based venture where every building is one of a kind, designed for a special purpose on a particular site, with a unique team who are charged with meeting a client’s special demands. In addition, the construction industry, as it has evolved over many centuries, is mainly comprised of small to medium enterprises (SMEs) rather than large capital investment firms.

Thus, applying robotics in construction largely concentrated on efficiency and focused on monetary gains through the use of machines to save labour, reduce costs and obtain a quality control in production. In addition, the introduction of highly specialised robotic systems was also limited by their unaffordability for many SMEs. Their inherent flexibility to adapt to different design situations or challenge designers was a capability beyond the scope of the industry to exploit.

In addition, as Gasselt and Maas argue, research and development on early construction industry robotics was primarily executed and led by process engineers. Architects and professional builders were not included at the development stage yet process engineers did not possess the specialist building knowledge required in construction and its direct relation to the architectural design process. Architecture is a highly complex practice and a good understanding of the work processes is essential for the successful construction of buildings. The implicit knowledge required by the architect and the builder on the sequence, assembly and connection of elements is a vital ingredient.

It is a paradox that as robots were initially conceived to replace human labour and in particular the dexterity of the human arm – with its inherent flexibility and usefulness to control a multitude of different tools – such potent machines were constrained to perform repetitive single tasks. Sadly, one reason might be that extensive deskilling of the labour force had already been in place by the time of their arrival, where mainly unskilled workers performed only a limited number of simple tasks. Hence, the skill set demanded of the robot was limited to the same operations and the flexibility and potential of both machine and the worker, who in the past would have been more variously skilled, was neglected.

2. Conceptual Turn

For robots to successfully prevail in the building industry and thus become relevant to architectural design, a new conceptual approach is urgently required that differs from the endeavours of the past and unleashes systematic flexibility. In this approach, the robot is no longer merely a mechanical subworker, aiming to make construction faster and cheaper, but an agent that opens completely new potential within architectural design, realising structures and building elements that would not be possible to conceive otherwise.

In contrast to the use of robotics in construction during the 1990s, this conceptual approach is framed by changing surrounding circumstances. Firstly, performance-to-cost ratio of computer components has improved drastically, and robot manufacturers...
today integrate off-the-shelf personal computer technology in their controllers as well as in programming and control software. Information technology has also entered the everyday domain of architects, where practice in computer-aided architectural design and computer-aided manufacturing have become mainstream skills, and thus allow for a seamless connection between design data and fabrication data. This enables the direct control of the production machines, allowing for differentiated designs in an automated process. Furthermore, as worldwide installation of industrial robots has doubled and prices have decreased by more than half, the SMEs that constitute the majority of the building industry can now afford to invest. In other words, industrial robots and the means to control them are on the verge of becoming a public domain.

Potential for architectural design offered by such technology is determined by two main factors. On the one hand, control software plays a crucial role. As with other computer numerically controlled (CNC) machines, robots enable the manufacture of objects directly from their digital description, and therefore allow the designer an in-depth engagement with the manufacturing process and a high differentiation or nonstandard project-specific fabrication can easily be realised. Due to the enormous computational power available to us today, these objects can be permeated with information. Material is combined with data, creating a richness of detail, which in its logic expresses the possibilities of the computer. This digital materiality is a direct consequence of the changing production conditions of architecture.

On the other hand, in addition to digital control, industrial robots substantially expand the option for a physical intervention in the fabrication process and thereby the scope of design. Unlike common CNC machines that are specialised on a single manufacturing operation (for example, milling, laser cutting), the action and actual processing of material performed by an industrial robot is not predefined. In essence, it offers a generic arm that can reach any position in space in accordance to its kinematic range. The arm can be combined with any given end effector, which defines the physical material manipulation. The definition of these end effectors can be highly specific and unique for a particular project and thereby become part of the overall design process.

Due to this flexibility in programming, and in defining the actual fabrication process, specific constructive systems can be realised, applying a multitude of different materials. The integration of material processes and digital control techniques revives and extends the tradition of constructive thinking in architecture and gives evidence to a new culture of craft that combines the physical and the digital. Thereby, architectural design evolves into the interplay between conceptual intentions and the engineering of a fabrication process with its possibilities as well as its constraints.

3. R-O-B
The mobile fabrication unit R-O-B builds on this conceptual approach. It respects the uniqueness of the building industry, while still benefiting from the advantages of automation that were driving forces and already present in earlier robotic developments for construction.

The generic set-up of R-O-B allows it to be applied to building processes at an architectural scale using various materials. In addition to the freedom given by its programmability and the freedom in choosing a specific fabrication process, R-O-B is liberated from a fixed production location. The unit consists of a customary industrial robot mounted on a linear axis and housed in a specially adapted freight container of standard size. As such R-O-B can cover a workspace big enough for architectural elements and can easily be transported directly on to the building site, where it can prefabricate highly precise elements on site or build directly in situ (Figures 3, 4, 5). This brings about both economic and ecological plus factors. Instead of complete building elements, only the raw material has to be brought on site, hence drastically reducing transport needs.
Consequently, accommodating the regional nature of the building industry, local materials may be applied. Also, fabrication processes can be planned, implemented and tested off site and then be distributed on compatible robot units worldwide that produce with the same accuracy and quality. The production of building parts is synchronised to the progress of the building. Design and fabrication can therefore easily be adapted to unforeseen changes in the course of the construction process. Probably the most significant aspect of applying R-O-B is the ability to exploit the flexibility of the industrial robot in making use of its programmability. For once, there is a way for designers and builders to react to strategic changes while the fabrication process is already running, or even go as far as to change materials that may differ in dimensions and tolerances.

Furthermore, as the digital control of the machine allows the architect direct engagement with the fabrication process, automation is combined with an architectural culture in which design and construction are intrinsically tied to one another. Conceptual design and practical realisation are no longer sequential phases, as the data set that describes a formal shape is identical to the code of its making. The inherent knowledge of the architect to assemble and join discrete elements and material in order to accomplish a specific design intention is transformed into explicit commands for the robot. Programming the construction steps for an architectural element, design is now the explicit description of its making (Figure 6). Due to the ability of computers to manage and process a large volume of data, a ‘digital description’ can be highly specific and consist of a myriad different instructions that the robot can transform into precise physical actions. Additionally, by digitally formulating the description, the designer has the possibility to intervene in and possibly alter and tweak the fabrication process at each operational step.

Thereby, existing traditional construction methods can be converted into digital processes. In making them explicit and combining them with the computational power available to us today, as well as applying a robot that can perform an arbitrary number of highly precise movements and material manipulations, these processes can be
transformed and reimagined. Manual operations are not simply imitated and automated, but are enhanced by the logic and the specific characteristics of the machine. Explicitly controlling the construction process, functional aspects can be synthetically integrated into a building element, while at the same time the boundaries between structural order and ornamental expression are blurred (see Figure 7). Contrary to former engineering solutions for robotics in construction, the concept of R-O-B does not limit but expands the architectural possibilities. Its artefacts are the creative amalgam of robotic processes, material manipulation and control software.

4. Conclusion

R-O-B demonstrates a radically different approach to robotics than that applied in industrial manufacturing. By using the robot not only as a means for automation but also as a design tool, the goal is to engineer not a perfect and widely applicable fabrication process but a unique one. The process of making remains a combination of several factors each specific in itself: a chosen material, the tool manipulating it and the design data controlling the tool and thus the process as a whole. Their combination is unique to a specific project and even more to the author of the process defining each factor. In the synthesis of these factors, an architectural design solution emerges which embraces architectural diversity. Thus buildings may remain singularities, prototypes designed for a specific context, each having a specific site, client and programme. There is a great diversity of architectural solutions and crafts involved, where robotic solutions may enable adaptive building processes and enrich the spectrum of constructive and architectural solutions (Figure 8). Thus it can be said that through flexible and adaptive robotics, construction processes and material manipulation not geometry, are the drivers of design. In this manner, innovative architecture may be developed as an interplay of the custom engineering and controlling of fabrication processes and, more importantly, specific design intentions.

Notes

1 This number includes various mechatronic devices from completely autonomously working machines to teleoperated apparatus. Also, not all perform tasks that are stringent necessary for construction, as for instance painting (Bock 2008; Howe 2000).


14 From the beginning, the human arm with a weight-to-load ratio of 1:1 was considered the ultimate benchmark in a primary research target to reduce the mass and inertia of robot structures. This goal was set in 2006 with the lightweight robot from the company KUKA (Hagele, Nilsson et al 2008).

15 Applying robots for nonstandard manufacturing remains surprisingly unusual, even in industries outside construction. But for the building industry, with its unique structure as outlined above, this is a necessity in order to be able to establish robotic processes at all.


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