Abstract Despite a growing interest in robotic fabrication in academic research, its impact on the design of large-scale architectural typologies has not yet been explored. At the Future Cities Laboratory in Singapore robotic fabrication was integrated in a design research studio to produce 1:50 scale models of mixed-use high-rise typologies. Its methodology aimed for the reconsideration of the traditional architectural model by directly linking the digital design process with physical manufacturing processes and tools. As such, it established a strong correlation between computational tools, material systems and robotic fabrication strategies. Since high-rises are strongly rooted in the industrialization of building, with repetitive elements stacked along the vertical axis, they represent an interesting architectural typology to be challenged by a new fabrication paradigm (Gramazio and Kohler 2008: Digital materiality in architecture. Lars Müller Publishers, Baden). This chapter presents customized robotic fabrication processes and tools that were developed in the 2 year long design research studio.

Keywords Robotic fabrication • High-rise • Architectural model • Design studio • Computation • Singapore
High-rises dominate large parts of the urban landscapes in fast growing regions throughout Asia. In cities like Singapore a majority of the population lives in residential high-rises. The construction of this typology is strongly rooted in an industrial paradigm (Cousineau and Miura 1998). It is mainly driven by efficiency and economic criteria, with repetitive elements being stacked along a vertical axis. The questions arise, how contemporary computer aided architectural design with the integration of robotic fabrication could contribute to a more differentiated articulation and leverage more variety in the formal expression and functional capabilities of this widespread typology (Willmann et al. 2014). The design methodology itself comes into the focal point of investigations, which is tested in the context of a design studio.

The design research studio for master students is set up at the Future Cities Laboratory (FCL) in Singapore in order to put significant research into this question. Through the robotic fabrication of 1:50 scale models of mixed-use residential high rises the experimental research studio investigates potential impacts of these technologies on the design and construction of novel high-rise typologies (Fig. 1). The studio is in constant exchange with PhD researchers in the robotic laboratory, which thus serves as an experimental test bed for both digital design and fabrication research (Hack et al. 2013). PhD research on computational design processes and the development of software environments to control robots plays a crucial role in the studio, and it offers in return test cases (Lim et al. 2013).

Within the design research studio teams of two to four students develop their architectural concepts based on the integration of computational design strategies and customized robotic fabrication processes (Fig. 2). The physical and the digital models are in constant negotiation with one another (Sheil 2005). Therefore constraints of the actually built model, e.g. in terms of material properties or manageable element dimensions, directly influence the computational design setup in a continuous feedback loop. The model scale of 1:50 requires a careful selection and abstraction of investigated aspects, but also demands a rigorous consideration of its tectonic logic (Budig et al. 2014). Up to four meter high models create their own construction reality. They oblige students to tackle problems of structural stability and the construction process from the very beginning on. This chapter discusses (a) the customized robotic system, (b) the embedded mechanical tools, like the development of end-effectors, and (c) it explains the research through case studies by illustrating how they conceived physical processes for the construction of the 1:50 models.

1 In Singapore more than 80 % of the population lives in high-rise and high-density flats built by the Housing Development Board (HDB).

2 The Future Cities Laboratory is run at the Singapore-ETH Centre for Global Environmental Sustainability (SEC), co-funded by the Singapore National Research Foundation (NRF) and the ETH Zurich. The design studio was run over two consecutive years, with a one-year program in each in 2012 and 2013. Participating students were from the Swiss Federal Institute of Technology Zurich (ETH) and National University of Singapore (NUS).
Fig. 1  Studio filled with series of tower models that were built in several iterations (Gramazio and Kohler, FCL Singapore, 2012, image by Callaghan Walsh)

Fig. 2  Image of robotic facilities with the final generation of tower models (Gramazio and Kohler, FCL Singapore, 2013, image by Callaghan Walsh)
1 Robotic System

Students and researchers share three customized robotic units. Each one consists of a small Universal Robots UR5 robot arm with six degrees of freedom that is mounted to an automatically driven Guedel axis configuration (Fig. 3). This robotic system enlarges the working space of the robot arm from a range of 85 cm to an envelope of 4 m height, 1.7 m diameter and 2.7 m depth; due to its small operating diameter the robot arm can still reach very intricate locations. The setup is planned for the digitally controlled assembly of complex physical models within this working envelope (Brayer 2013).

The robotic towers are modularized to enable reconfiguration within the research laboratory. A high degree of modularity accommodates quick modifications of the robotic system, e.g. their height and thus the operating space can be adjusted without the need of any special tools. Four adjustable base points allow the robotic tower to be leveled and transfer its 1.2 t to the floor. This configuration has two advantages: First, it causes little vibration, so no additional floor enforcement is needed. Second, it ensures an equal distribution of dynamic and static loads, which is crucial on floor constructions without specifications for machine installation. Hence the robots can be taken out of the typical industrial environment and implemented in a design studio environment (Fig. 4).

2 Physical Tools and End-Effectors

For the development of a robotic fabrication process in the design studio the robotic end-effectors become the most crucial physical components. Available mechanical grippers are mostly not flexible enough to grasp pieces of various sizes and geometries, and can hardly be adapted to different assembly concepts (Kripper et al. 1989). To overcome any limitation a modular gripper system was developed to enable multiple options of mechanical and vacuum suction gripping. Students can produce these grippers easily and develop their own configurations, in order to figure out the solutions for the model building process (Fig. 5). While the initial focus was put on the gripper geometries for the control of picking and placing behavior, special concepts were eventually designed with more functional integration, such as sensor equipment and high-resolution control valves for optimized vacuum suction grippers (Monkman et al. 2007).

Since the previously developed grippers with suction cups restricted the building components’ geometries, a second generation of vacuum grippers emerged from the idea to design a surface with hundreds of small apertures. The gripper is built out of three layers. The first layer is the perforated surface, with the air-feeding layer below and the third layer covering the feeding cavity from the

---

3 Universal Robots UR5 robot arms are integrated in Guedel 2-Axes Linear Modules Type ZP-3.
backside. With this configuration grippers could easily be produced with a laser cutter and optimized for the elements’ geometries. Due to the thin buildup of the grippers of 3–5 mm, they were better suited for dense assemblies at 1:50 model scale (Figs. 6 and 7).

Unlike their industrial counterparts the lightweight Universal Robots do not need to be sheltered in a safety environment. The UR5 robot arm is equipped with built-in safety systems that allow its use without any further safety measurements. This opens the possibility for direct human–robot interaction, which became one of the primary advantages of the robotic facilities for a continuous refinement and adaption of robotic end-effectors. Only when the whole system, including the horizontal and vertical Guedel axes, are in full operation, a higher-level security

Fig. 3 Elevation of one of the robotic fabrication units; a Universal Robot UR5 robotic arm is mounted to a Guedel axis system in order to increase the building envelope (Gramazio and Kohler, FCL Singapore, 2012)
installation comes becomes a requirement. This is met with a laser scanner system, which registers any changes or approaches within a defined safety envelope. Users can still approach the facilities while the UR is in motion, but the Guedel axes will decrease their speed first and stop instantaneously on closer proximity. As such, the operating paradigm of the robotic towers is to combine the highest possible level of accessibility, human intervention and safety in the laboratory environment.

Fig. 4 A simple pulley is used for installation and height adjustments; the vertical axis is modularized into five segments (Gramazio and Kohler, FCL Singapore, 2012)
3 Software Tools

In a similar vein to the customizable hardware components, a custom robot programming library called YOUR and a corresponding toolkit of Grasshopper components were developed that are open to end-user modification. These software tools aim to make robot control accessible to students without prior specific knowledge or programming skills. Students use the toolkit either from
Grasshopper visual programming environment or from the script editor in the Rhinoceros 3D modeler; the former is geared towards those without any programming experience while the latter suits experienced programmers. In either case, students are able to control the robot directly from their computational design environment.

By directly assembling components from the Grasshopper toolkit, students were able to set up and control their robotic fabrication sequences. This visual programming approach facilitated students in quickly prototyping processes, as they only needed to learn how a few essential components worked and could connect them in different ways. Since the text-based code defining these components is accessible, students become able to modify them once they acquire more experience in programming and knowledge in robotics. This allows them to introduce more complex assembly logics and more intricate robot motion patterns for material manipulation.4

4 Case Studies: Robotic Fabrication Processes

4.1 Picking and Placing

The first aim of the design research studio is to build models as high as possible to gauge the limits of the robotic facilities. Initial towers are stacked configurations that are fabricated in a simple pick and place fabrication process, for which the

---

4 See Lim et al. (2013) for more details on the software environments.
students develop different vacuum gripper systems to glue and place cardboard elements. Hence in the beginning developments focus on the use of multi-functional grippers. They incorporate the gripping of pieces from different directions and have to consider material thicknesses, drying times, and height deviations caused by the applied layers of glue. The major challenge is to master the negotiation of a computer generated 3D model in a physical reality.

After this initial phase further strategies to utilize the robots’ inherent manufacturing potential emerge and the concepts that become guiding principles for their tower designs. One concept in the studio investigates in an increased resolution of their towers by building with small components. This development culminates in the incorporation of a material feeder and a gluing device into a multi-functional end effector. Using spray glue, this system can hold several hundred pieces at a time and consequently speeds up the construction process by minimizing the distance the robotic arm had to travel for placing each piece. One of the resulting towers consists out of more than 15,000 pieces based on two different types. The focus shifts on structural systems that can cantilever outwards from the main vertical structural system (Fig. 8).

Another fabrication concept focuses on the smooth integration of the laser cutter, which allows students to produce elements with different sizes and geometries in an efficient workflow. Since the picking point varies for each piece, a corresponding feeder system and Grasshopper setup are developed. The cardboard containing the prefabricated elements gets constrained to fit into the robot’s workspace. The data for the laser cutter is automatically generated in the digital model. The individual sheets are then placed directly on the feeder that contains a gluing station. Since the laser cut sheets are generated by code, the geometric data is used to coordinate the picking, gluing and placing movements of the robot. Although the process needs high precision, it enables fabrication processes with individual components and hence becomes a very generic and geometrically widely applicable process (Fig. 9).

### 4.2 Material Deformation Processes

Beyond picking and placing strategies the integration of a material deformation process explores the potential of the robot in its unique capacity to produce bespoke parts by just deforming identical elements. Taking the cardboard elements from previous studies a setup is developed that enables the bending of identical sheets at various angles. In a further iteration aluminum elements can be bent more precisely to defined angles. This leads to the production of large numbers of uniquely folded configurations out of the same generic element. By bending each piece in two opposite directions each wall stabilizes itself. Afterwards these walls are arranged in a way that they intersect with a wall on the story beneath to ensure continuous vertical load transfers.
For the controlled bending process two pneumatically powered actuators are integrated in the robotic system. One mechanical gripper is holding the piece in place, while the other mechanical gripper is mounted on the robot arm. Through rotating this gripper around the stationary one, identical basic components are folded into unique parts (Fig. 10).
It proves to be a promising strategy to exploit the robot’s unrestricted potential of spatial movements and by directly informing the material. Working with identical basic elements can eliminate logistic problems that are for example inherent in using the laser cutter in combination with the robot. In contrast to simple picking and placing, the robot plays an active role in the form-giving process. The deformation leads to the implementation of new sets of parameters related to material properties, for example a translation of a heating process of acrylic elements into the geometric data set of the modeling program (Grasshopper is primarily used for the robot control).

Two case studies integrate a heat gun in their robotic setups to deform plastic material, which allows students to locally heat material and then bend it by using the robotic arm. One concept builds up on the experiences with a high number of building elements (see project in Fig. 8) and in this further development involves bending acrylic stripes at multiple points to create a tower’s primary structural system. After the thermal deformation, the pieces are cooled in order to avoid retraction and increase assembly speed (Fig. 11). A similar process is used in another case study for twisting acrylic sheets and producing a façade louver system. To expand the previously developed picking and placing process with the material deformation (compare with the process illustrated in Fig. 9), a combined mechanical and vacuum suction gripper was used (Fig. 12).
An entirely different approach to deform material is showcased by another case study with robotically stapled paper strips. This process requires the development of a gripper that can pinch two stripes of paper and then staple them together to fixate their positions. By sliding the two paper stripes with different intervals and stapling them again it is possible to produce geometries with undulating outlines (Fig. 13). The resulting geometries are used to produce layers of exterior enclosing. Instead of pre-computing the shape of the outline, the material’s intrinsic properties are used to produce complex geometric shapes. The formal result thus resembles the material’s capacity and requires a feedback loop between material and structural tests in physical space in the physical model, and a translation into both reliable and controllable parameters in the digital model.

5 Case Studies: Integration in Architectural Concepts

5.1 Connecting Algorithmic Design and Robotic Fabrication

A second generation of test cases takes over previously designed fabrication concepts and re-evaluates these processes in correlation with algorithmic design strategies. A predefined programming and robotic control setup in Grasshopper was combined with the physical toolset of the integrated gripper and feeder system.
for prefabricated laser cut sheets. The initial setup enables students to work with an unlimited number of different parts from the beginning on. This shifts the focus away from fabrication experiments, and allows them to identify specific typological elements that could be directly translated into parametric design models and utilized to produce differentiated high-rise assemblies.

The students develop computational design engines that are connected to the robotic fabrication process and can start to build multiple iterations of tower models. These models are analyzed for structural performance, material behavior and architectural performance. They are used as the starting point for the next generation of models, thus forming a feedback loop between computational design and robotic fabrication. The resulting designs incorporate several iterations of structural modifications in accordance with a suitable material system. Structural optimization becomes part of the development (Reiser and Umemoto 2006), although this was not the main focus. The following examples show, how different fabrication concepts generate elements that define spaces and express different formal languages.

### 5.2 Assembly of Folded Elements

This typological concept inverts the traditional approach of conceiving high rises as envelopes and then slicing them into floors by starting the tower design from its interior spaces. Interior spaces are defined by a set of simple rules. The number of shear walls gets increased while their distances decrease. Walls are framing functions rather then rooms, and spaces were defined by cut outs in a sequence of walls instead of being defined by enclosure.

The design code distributes these opening sequences in the walls, which correlate with different apartment and mixed-residential types. In a second step the force flow is calculated from top to bottom around these apertures. Each shear wall adjusts its opening’s geometry, negotiating between the calculated force flow and the necessary cut out for the flats.

![Fig. 13 Tower made out of paper stripes and stapling process, which uses paper’s intrinsic properties in the material deformation process (Gramazio and Kohler, FCL Singapore, 2012, student project by Ernst S, Rickhoff S and Strohbach S)](image)
The final tower consists of 5,200 paper elements, which are robotically cut, folded and assembled to a 3 m high tower. The robotic setup contains a mechanical gripper that is able to pick thin paper stripes, a gluing station and a custom designed vacuum clamp for folding. The robot picks a paper stripe and places it into a vacuum clamp at a specific angle, which is computed by the design engine. The students then cut the piece manually with a knife. After that the robot folds the cut piece, applies glue and places the wall onto the model (Fig. 14).

Since the wall elements can be fabricated with cuts in different angles and with individual dimensions, the system is capable of producing a highly differentiated assembly with a single system: on the local scale this leads to different sized spaces and room sequences. In the global system a coherent structural system is achieved while the undulating slab typologies can adjust to contextual parameters. The thin paper adds intriguing light qualities to the model through the large range of variation and the gradual transitions from one element to the next.

Fig. 14 The tower is made out of paper elements that are manually cut and then robotically folded, glued and placed on the model (Gramazio and Kohler, FCL Singapore, 2013, student project by Jenny D and Stadelmann JM)
5.3 Sensor Integrated Assembly

Sensor assisted picking and placing in combination with robotically controlled thermal bending of acrylic façade elements is used to fabricate this concept for a bundled tower. All data required for the robotic process is generated in the same software environment as the design. The fabrication part itself is not fully automated, since elements are ‘handed’ over to the robot’s gripper. With the integrated sensors the placing of the robotic assembly process allows for tolerances in the material feeding process. Only the centerline of the element must be aligned with the gripper, the sensor measures the vertical distance when placing the element and pushes it just enough to ensure a sufficient contact before the glue hardens (Fig. 15).

For the more intricate, single- and double-bent façade elements a similar deformation process is used as previously described (compare with Fig. 10). For the precise location of these elements, the robot guides the correct picking location by referencing it on the model. Although this fabrication process becomes in large part manual, the assembly is quicker and more robust than the heavily engineered and fully automated process with the feeder for laser cut sheets (compare with Fig. 9). This aspect creates a very interesting dichotomy into fully automated
processes that demand high precision and high amount of debugging, and a mixed manual and robotic processes that benefits from the human interaction for immediate supervision and correction.

5.4 Spatial Wire Cutting

This tower concept consists of a porous mesh with slender tower strands. Several towers merge and separate as they grow in height, structurally supporting each other. Individual residential units are generated on top of each other and oriented away from their immediate neighbors to provide privacy. These units are based on wall elements with complex geometries. Each of them has different geometries, optimised to transfer the loads through the walls and shaped to accommodate various functions on the inside.

Fig. 16 The robot picks extruded Styrofoam cubes and moves them through the hotwire along a computed path, thus utilizing the robot’s potential for performing spatially unrestricted tasks (Gramazio and Kohler, FCL Singapore, 2013, student project by Aejmelaeus-Lindstroem P, Chiang PH and Lee PF)
As a matter of course the cardboard material becomes limiting for the intended geometries as it proves to be too rigid to be spatially deformed. After several evolutions of gradually more complex articulated wall systems extruded Styrofoam is considered as the solution with most potential to produce the volumetric characteristics. For the final tower, pre-produced cubes are placed on a custom designed feeder. The robot picks the cubes and moves them through a hot wire along a computationally generated path to fabricate the complex wall elements (Fig. 16). As such this process in particular takes advantage of the robot’s capability to accurately move and orient in space. The resulting tower consists out of six strands, in each of them up to fifty units with four individually cut Styrofoam pieces. About 2 weeks is the fabrication time for the final tower model for a group of three students.

6 Conclusion

In total twenty-seven 1:50 models were produced in the studios 2012 and 2013. The unique experimental setup gives the architectural model a new meaning and re-values its importance in the combination with digital design tools. The systematic developments of the designs in correlation with the physical artifact obliges students to deeply and creatively engage with the fabrication logic, which becomes a crucial part of the design (Gramazio and Kohler 2008). The construction of iterations of tower models involves continuous feedbacks between physical result and digital design concept. Beyond that models reach a complexity, which could not be manually achieved. The robot thus enables new design explorations in architectural models and it is accounting for the basic condition to avoid a conventional design sequencing, where the data in the end gets handed over to a completely separated fabrication process.

The diversity of the produced towers exemplifies how, after acquiring the skills, computation and digital fabrication can be productively integrated in the design process. The consistent interaction with the robotic process leads to a direct and sensual understanding of the tectonic qualities in the model (Willmann et al. 2012). This exposure to the process of making also requires a profound understanding of the tools and their effects on material and geometric shapes. The role of the architect is challenged here, where design opportunities become sustained in physical space through the adaption and even invention of suitable toolsets. The tested methodology proves to be a valuable experiment on the way to further implementation of robotic fabrication in the design process of large-scale architectural typologies.
Acknowledgments  This work is part of a larger research project at FCL and demanded support from Prof Fabio Gramazio and Prof Matthias Kohler, senior researchers Jan Willmann, Silke Langenberg, and co-researchers Norman Hack and Selen Ercan. It was established at the Singapore-ETH Centre for Global Environmental Sustainability (SEC), co-funded by the Singapore National Research Foundation (NRF) and ETH Zurich.

We would like to thank our students for their great efforts, whose projects are illustrated here: Petrus Aejmelaeus-Lindstroem, Pun Hon Chiang, Sebastian Ernst, Kai Qui Foong, Yuhang He, Pascal Genhart, David Jenny, Patrick Goldener, Lijing Kan, Sylvius Kramer, Ping Fuan Lee, Sven Rickhoff, Jean-Marc Stadelmann, Silvan Strohbach, Michael Stünzi, Martin Tessarz, Florence Thonney, Alvaro Valcarce, Fabienne Waldburger, Andre Wong and Tobias Wullschleger. The studio 2013 was conducted under both the ETH Zurich and the National University of Singapore (NUS) curricula. Special thanks go to our academic partners at NUS, Chye Kiang Heng, Yunn Chii Wong, Shinya Okuda and Patrick Janssen.

References


