Chapter template for: '**Automating Cities: from Design, Construction to Operation of Buildings and Urban Operating Platforms'**

# From Factory to Site – Industrial Robots for On-Site Construction

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The emerging use of robots in manufacture sectors inextricably led to revolution in productivity, collaboration etc. Such development enhances industries' ability to handle complexity in a effective manner that not only reduce the cost and labor, but also increase the efficiency of material. On-site construction is known as a labor heavy and material consuming practice. Challenged by the increasing complexity and digitalization of architecture design, combining with social economic issues such as aging labor force and environmental concerns, both academic and industry community has raised increasing attention in applying the robots to construction industries.

What distinguishes contemporary industrial robots from their industrial predecessors and indeed from other contemporary computer-controlled devices—is their versatility(Willmann et al., 2018) Modern day industrial robots are open-end customizable platforms to perform a different variety of tasks. Specific application can be achieved with adaptation of industrial robots without the need to develop a robotic system from scratch. For architecture, industrial robots can be programmed and customized with graphical parametric interface that directly connects into the design workflow, making it not only a utilitarian mechanical tool, but also engaged in creative developments from design to construction.  It enables designers, engineers and contractors to develop novel automated fabrication method that deals with complexity, creativity and efficiency. It builds another relationship for exploring and manipulating of physicality of the build space.  In this chapter, we will discuss how robotic automation is applied in on-site construction from the aspect of how to move the fabrication process on sit, how to engage robotic during construction, and how such technology may impact the organization of building industry.

Our exploration of adopting industrial robots for on-site construction started with moving the robotic fabrication process of building component, which is typically conducted in a controlled centralized factory environment, to the construction site. Owning to the unique nature of construction, such adoption of industrial robots has several distinct advantages. For example, the logistic of fabricated components is greatly reduced, coordination between the fabrication with construction schedule are more effective, and significantly reduced the cost of using non-standard parts as replacement parts can be easily made on site with customized dimensions. However, moving a fabrication process to on-site faces challenges, which will be discussed in this chapter with a case study of our recently complete project of developing the on-site fabrication system for robotic slip-forming of eco-friendly façade(Yu et al., 2018).

Comparing to the mere adopting of the fabrication process onto the construction sites, perhaps using robots for the building jobs such as on-site assembly and masonry are where the most potentials lies, especially when the aging workforce is becoming a global issue. In Queensland Australia, the number of construction workers aged 55 and over increased from 8% of full-time workers in 1992 to 14.2% in 2014(2015), and the average of age of construction workers in Beijing China increase from 33.2 in 2007 to 43.1 in 2017(2017). The application of robotic for the physical demanding construction works would direct confront with the issue of aging work force by potentially transform the labor heavy traditional industry of construction into a technology driven and future oriented discipline that is attractive to the younger generation. Thus, the second part of this chapter dives into the discussion of how to develop automated systems based on industrial robot and what are the common challenges based on the our research project of constructing the garden of brick labyrinth conducted in Tsinghua University.

Though it is common for people to consider robots are future replacement of labor, the real impacts of application of robots are far more profound. It calls for deliberate collaborative engagement of different disciplines, ranging from design, civil to material science and mechanical design. The present moment is ripe for connecting robot technology with imagination and materialization, inspiring new fundamental discoveries and opening new scientific frontiers. In fact, we have within reach access to volumes of information and centuries of knowledge about how to design and realize the material world. Aided by global digital connectedness, open-source ideals and collective encounters, robotics rejuvenates traditional disciplinary wisdom with entirely new practices of scientific collaboration and knowledge transfer(Willmann et al., 2018). The cross-discipline nature of the applied robotic research not only impact on the academic and R&D of the technology itself but more importantly it influences on how the projects are carried out from design to construction. Comparing to the typical distinct design-bid-build process, the application of robotic for construction requires a more integrated process that break through the distinct phases. With the recent construction of Chronos Coffee & Book House project by ASW, we are able to explore in depth how the dissolving discipling boundary fundamentally transforms the culture, organization, and workflow of the traditional design-bid-build process, celebrating the full potential of robotic automation for construction

## Customized Fabrication on Site

The first step of using a robot on the construction site is simply transferring the fabrication process, which is typically conducted in a controlled factory environment, onto the construction site. Modern day industrial robots are widely applied in manufacture industries from automobile assembly line to co-working with human on electronic production. In building industries, owning to its versatility, industrial robots are increasingly involved in pre-fabricating customized parts such as formwork milling and fabrication of timber components. However, comparing with typical manufacture industry, building industry confronts a few challenges of its own, such as logistic of components and construction managements. Thus, moving the robot to directly fabricate on the construction site brings a number of benefits.

Comparing to other numerically controlled fabrication tools, industrial robots provides a programmable versatile platform that are not only in comparable to human arms in terms of degree of freedom but also capable of adapting to multiple functions by customized end effectors, making it possible to conduct a variety of fabrication techniques derived from traditional manual process. Also, robotic fabrication is a direct data driven process that does not require additional interpretation. In which case fabrication cost does not fluctuate according to complexity as long as the component falls within the same fabrication system, making it especially suitable for making parts of digitally designed buildings where components deviate from each other in a systematic manner.

Though industrial robots as well as other digital fabrication method has long been used in manufacture facilities for pre-fabricated components such as panels and joints. Comparing with other types of commercial products building parts are know to be a great challenge for logistic, storage and management. Bringing fabrication process onto the site and having it work alongside skilled workers is an effective way to reduce the cost in those. In turn making applying robotic for fabrication of larger components cost-effective.

However, different from prefabricating in a factory, bringing robots onto construction site face its own challenges. The limited site space and tight schedule requires the onsite fabrication process delivers with speed and intervals that matches the construction process, which can be integrated into the workflow. In this section, we use the example of developing on-site fabrication for a slip-formed eco-friendly façade system (figure 1) as an example to discuss the merits, constrains and process of designing the on-site fabrication system with industrial robots(Yu et al., 2018).

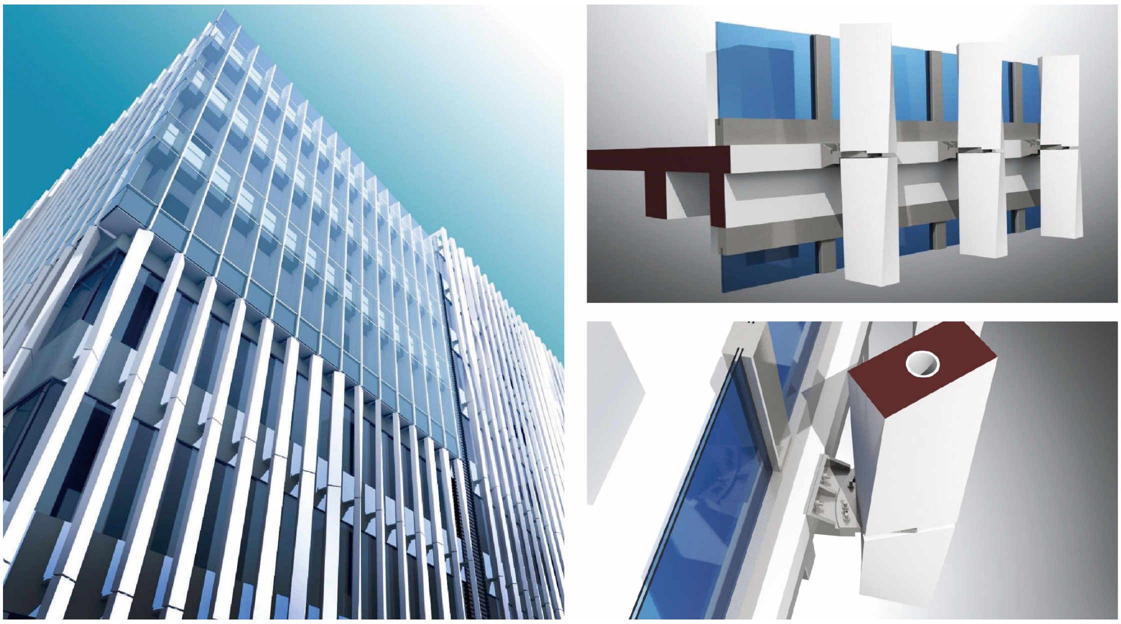

Figure 1 Design of Eco-friendly Building Facade Component

The curtain wall shading system represents a new element that excels in both aesthetic and functional aspects. It is designed with parametric tools(figure 2) that each linear component rotates in a certain angle according to the local solar exposure to mitigate heat gain and interior lighting. Also the programmable twist-formed concrete components could serve as an eco-friendly concrete façade structure for use in more-refined lighting planning for interior spaces and an expressive aesthetic element developed via the data-flow gradient and robotic fabrication pipeline. Although the concrete façade element has more self-weight than a typical curtain wall element, if strategically applied, it will only exceed the area weight of a typical glass curtain wall by 30%. Thus, the extra cost of reinforcement to the entire structure could be compensated by the reduced operational costs as an energy efficient building component. The benefit of SDC as a decorative façade element is enhanced by considering energy efficiency in a green building. In on-going research, we are investigating methods of lowering the impact of self-weight by redefining joints and connections.

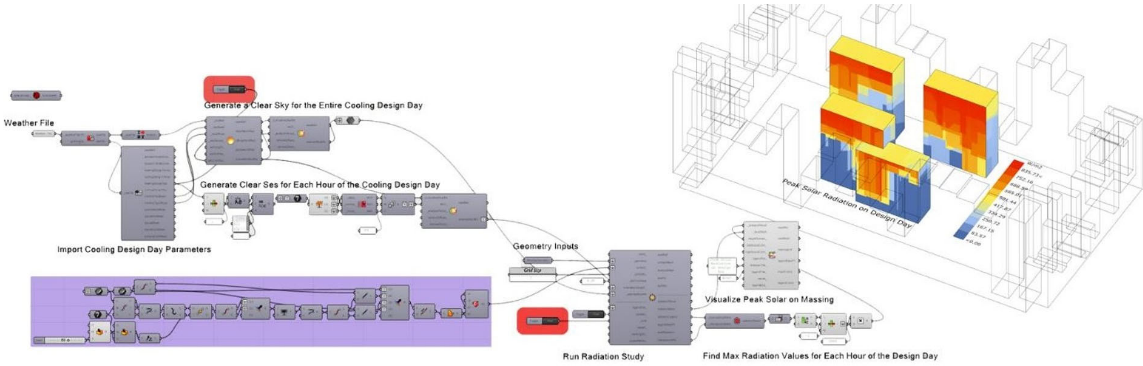


Figure 2 Façade designed in response to solar exposure and lighting condition

Though concrete as a common material for construction, the main challenge of our design is to fabricate the façade component in a cost-effective method. One challenge with concrete is that it requires form work for casting. Typically prefabricated concrete parts use standard modules and formwork that could be used repetitively to reduce the cost. However, each component in our scheme rotates in different angle that would requires different formwork for each one with traditional formwork. Also, none-standard curved surfaces would significantly increase the cost of formwork. Besides, concrete building component are heavy and space consuming. How to manage the labeling and transportation of the component from factory to site is also a major challenge for management. Considering the above issues of traditional form-casting method, we looked into potential alternate method of fabrication that is suitable for this specific project.

The traditional technique for casting concrete is formwork in which a mold composed of timber, plywood or metal sheet is installed to hold a well-mixed liquid concrete solution for a certain amount of curing time. After removing the mold, the solid concrete is released and used as structural or ornamental elements, such as columns, beams, slabs, and shading louvers. However, slip-form represents another casting method that has been widely used in the construction of roads, towers, and heavy offshore platforms. Since the 20th century, slip-form has been developed as a cost-, labor and time-efficient construction technique.

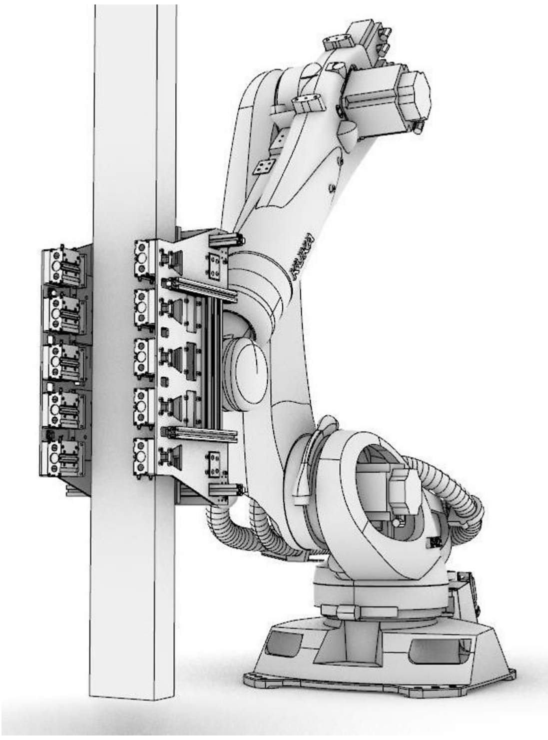

Figure 3 Design of the End-Effector

Since Contour Crafting first attempted to utilize a robotic arm for concrete fabrication(Khoshnevis, 2004), robotic fabrication of concrete has been progressing at a rapid speed. However, most research studies are focused on additive manufacturing methods based on 3D printing, which includes the layering of materials (Hwang and Khoshnevis, 2004) . Recent examples of robotic concrete fabrication, such as the XtreeE(Gosselin et al., 2016) and 3DCP (Bos et al., 2016), also follow this path. However, our research focuses on a separate path based on a dynamic formwork method.

The core of our project lies in the flexible formwork, which is based on Smart Dynamic Casting (SDC). Several different SDC solutions have been based on recent developments by researchers at ETH Zurich and designed to achieve sectional transition during the extrusion process, and they include the earlier prototype of a four actuator driven formwork(Lloret et al., 2014), a V-shaped formwork, and dynamic formworks composed of rigid boxes with two metal plates(Fritschi et al., 2017). A different technical solution to achieving such sectional flexibility has been designed with a specific goal and resulted in sets of extruded dynamic columns with recognizable features. Based on laboratory research work conducted at ETH Zurich, we have taken one step further towards applying dynamic slip-form casting to a real project and created a flex-wall installation of 115 pieces, which has the potential to serve as an angle dependent smart shading device for a building façade. The fabrication process is technically developed and refined for rapid manufacturing, thus serving a practical requirement based on the specific project and design. The research developments mainly encompass the following aspects:

1. To reduce the overall casting time, a larger slip-form mold is used to carry the entire amount of mixed concrete;

2. A central steel core is fixed at the center of the mold to ensure strength, and it resembles the reinforcement system of conventional load-bearing concrete (figure 3);

3. The fiber-reinforced concrete is strategically stirred with a mixture of additives to avoid collapsing during the extrusion process, and a considerably reduced sitting time is observed;

4. A continuous production pipeline is established to preserve a steady workflow that maintains the robot arm working nonstop by shifting between different sessions,

including pouring concrete, vibrating the concrete, locating on a railing for concrete curing, slip-forming, and concrete sitting for hydration.

a) Management of Fabrication Time

One crucial aspect of adopting robotic for onsite fabrication is the management of fabrication time for each piece. Unlike factories that occupies a large area of space, construction sites are often crowded with different works going on. Also, fabricating on site means that there is very limited leading time for the preparation of material and fabrication before the component is ready for assemble. On site, components are fabricated in a similar speed parallel to the assembly process so that the workers on the job has access to fabricated components all the time without the need for waiting for fabrication, which means the typical casting of prefab concrete panel that requires several days of curing and finishing would be a challenge for on-site construction.

Regarding the slip-form technique, the key challenge often lies in reducing the sitting time to match the speed of slipping. Conventionally molded concrete requires at least 2–3 days of sitting time before the formwork is removed, another a week to reach a full solid state, and a month or so to reach complete structural strength under the desired moisturized condition. To reduce the overall casting time, a larger mold is chosen to carry entire amount of mixed concrete. Also, chemical additives are incorporated into the new formula to reduce the sitting time so that each column can be fabricated within 30–50 min, which is associated with the requirement of the extruding speed and to ensure that the concrete can be self-supported after lifting the slip-form mold. Although the additives accelerate the hardening speed, the overall casting time is still not short enough for production. Approximately 2 or 3 h are required to cast a two-meter-tall column according to the ETH lab report.

b) Developing a Robotic Fabrication Method from Common Material and Technique.

Another core of our research is the structural quality of the robotic cast concrete component. Although fiber-reinforced concrete has better physical properties than traditional concrete, bonding with rebar should be performed to ensure the structural performance under pressure and tensile force. In this case, not only we seek innovation with the material, we also looked into common reinforcing methods for concrete components. A steel core is inserted as well with mesh bracing for reinforcement. Those additional reinforcement also reduced the requirement of concrete quality, thus making the use of off-shelf material possible and significantly reduced the fabrication cost.

During slip-forming, an accurate time-control process for hydration is critical. If the concrete mixture is too soft after slipping from the mold, it will be deformed by gravity, instantly lose its retaining ability, and severely collapse as a consequence. However, if the concrete mixture is too hard, then the twist force from the robot arm will crack the concrete columns, resulting in an undesirable surface quality. Compared with that of the conventional concrete framework, the time window for dynamic slip-forming is very narrow. The experimentally developed basic mixture formula is as follows: one batch of material contains 32.3 kg Portland cement, 30.5 kg fine sand, 11.5 kg of water, 80 g Nylon fibers at 30 mm, 80 g Nylon fibers at 20 mm, 40 g Nylon fibers at 8 mm, 105 g

Superplasticizer #5, and 82 g Accelerator. The mixture is rapidly stirred for 5 min, well vibrated and allowed to sit for 50 min before it is ready for extrusion.

In addition to the basic formula, adjustments will have to be made for different batches of material orders. The water amount, for example, should represent the most critical parameter related to the concrete sitting time. However, the moisture inside the sand should also be accounted for in the total. As a result, to guarantee desirable slip conditions, hand-testing must be performed first to ensure that the proper curing time is in an acceptable range.

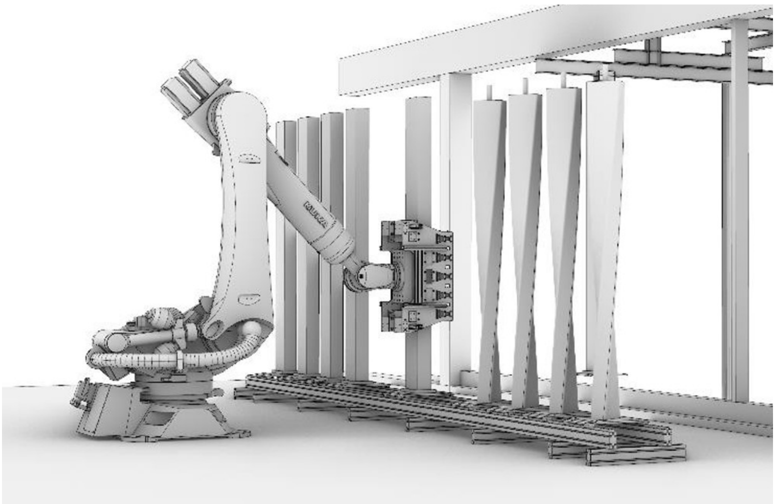

Figure 4 A pipeline of work flow

c) Pipeline Fabrication Alongside Construction Workflow

Another crucial issue that must be optimized is the human labor factor. To fully exploit the multi-axis industrial robot arm, the fabrication process should be automated to an extent that minimizes the involvement of labor. The automobile industry is a good example in which human involvement is minimized. In the case of this project, the robot arm not only works on the slip-forming task but also the delivery of the mixed concrete, which needs to be performed between every session and is extremely labor intensive due to the weight of the concrete. Thus, a highly efficient continuous production activity similar to an automatic assembly line is formed, and the robot arm plays a key role. A continuous production pipeline is established to preserve a nonstop workflow(figure 4).

Since each concrete column (200 mm * 100 mm * 2200 mm) plus the stainless steel mold weigh over 100 kgs, a ceiling rail was installed between the concrete pouring workstation and the robot slip-form workstation. After the mold was fully filled with concrete and evenly vibrated to eliminate air bubbles, it was delivered to the robot working range via the rail.

Another 6 m long ground rail was installed in front of the robot arm. Six carts were slid on top of the high-quality lineal rail with a tolerance of 10 l. The robot end effector was a heavy-duty clamp driven by compressed air above 0.8 MPa. The clamp was designed to open and close in the X&Y directions to firmly catch and release the 3 mm thick stainless-steel mold. The air compressor was switched by robot I/O via two electronic compressor valves (Figure 5).

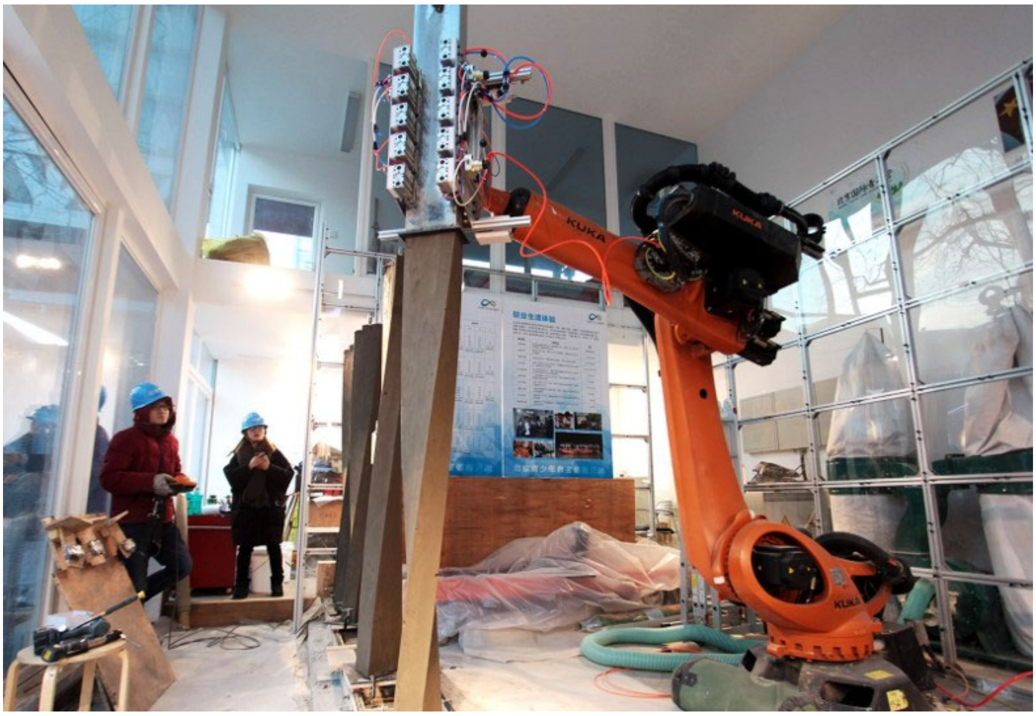

Figure 5 Dynamic concrete casting and slip-forming process

As long as the fully loaded mold was in the correct location, the program for fabricating a specific column would be launched to perform a series of operations.

1. The robot clamp will catch and carry the load to a cart on the rail, and the position of the column in the queue is determined by the sitting time. Each column is on record starting at the first infill of concrete. Every key point of the timeline is strictly monitored.

2. When one of the molds is ready for slip-forming, the robot will carry it to a designated place, usually on the left side from the center axis, where a simulation is run to ensure that it is free of singularities.

3. After the mold is released from the base plate, the dynamic slip-form process begins. The slip-forming time of each column is limited to 10 min each.

4. After the slip-form is completed, the concrete column, which is still soft and wet, is pushed to the other side of the rail to continue curing.

5. The empty mold is sent back on the ceiling rail and cleaned by a water jet for the next session.

6. By the next day, the concrete column will be hard enough for the final curing phase,

which is at least one-week long.

d) A Data-Driven Automated Workflow

To validate the proposal and techniques, a real project was commissioned, designed, fabricated and installed within 2 months. The task was to create a landscape screen wall (2 m tall and 60 m long) composed of 115 concrete columns cast and formed by a robot arm. This linear queue of deformed up-rising columns with half meter spacing defines an obscure borderline between a main pedestrian entrance and a parking area. A KUKA KR150 R3100 Prime robotic arm was used and equipped with a custom-made air-pressure-control clamp, and it was capable of carrying and casting over 15 tons of concrete.

In this design, 115 slip-formed columns are situated at every half meter on a 60 m long lineal flat steel base (Figure 6). Each column has a certain vertical twist angle and is algorithmically related to its neighbors. This layout formats column rows into an undulating panorama, although they stand in a straight line.

A parametric 3D model created in Rhinoceros was used to connect 115 sets of data packages for the columns (in Cartesian coordinates) with the design parameters. This reaction is automatically transferred to the robot arm simultaneously from the Grasshopper environment. KUKAprc, a plugin in Grasshopper, is the application used to generate the.src file, which is the file format of the KUKA robotic system. This digital design-fabrication solution attains at least three advantages compared with the conventional method.

1. The path from design to fabrication is highly interrelated via the data flow. If the form is adjusted by changing the parameter for design evaluation, then the fabrication data are automatically updated. For example, if the distance between two columns is weaked with different numbers, the entire set of fabrication data will be updated accordingly.

2. The data sets, including the 3D model and robotic G-code, will be documented after construction in case any column needs to be replaced for maintenance. Simply by sending the data package to the robot, a brand-new column could be produced.

3. Data flow runs seamlessly between the schematic design and the fabrication machine, thus representing a brand-new process in which conventional human involvement is a supplement.


Figure 6 Demo project of Flex-wall installation

**Developing Robotic System for On-site Assembly and Construction**

Though moving the fabrication process onto the construction site has its merits, the robots manifests its full potential in construction by directly engaging with the construction process itself. Currently though special heavy-duty equipment is used on construction site, it is considered a manual process as most of the core procedures requires the manual operation by skilled workers. Comparing with the contained factory environment and the standard operation for pre-fabricated components, on-site construction not only encounters unconstrained environmental challenges, but also requires the flexibility, agility, and judgement of the worker to improvise at work, adapting to the condition of the site and precedent works. The unconstrained environmental challenges and need for instant adaptation raised a different type of challenges that beyond the normal strength of industrial robots which are designed to perform similar tasks repetitively in a controlled factory environment. Thus, applying an industrial robot on construction site requires adaptation to be made for the system to accommodate the special requirement of on-site construction. In this section, we will use the development of robotic system for the construction of brick garden in rural China as an example of adapting an established robotic system developed in the lab environment for on-site construction in a harsh vernacular environment. This exemplary project is first published in paper Automatic Brick Masonry System and Its Application in On-Site Construction on the 2019 annual conference of Association for Computer-Aided Architectural Design Research in Asia(Xu et al., 2019) where part of this section is adopted from.

As a self-contained subdomain of construction(Bonwetsch, 2015) , the process of brickwork assembly holds many positive features that are especially suitable for robotic automatic assembly. For example, the brick, as a basic component, is widely accessible around the world. The size and weight of a brick make it suitable for manipulation by robotic arms but labor intensive for workers. The assembly process of bricks is largely repetitive and thus easy to program into robots. Additionally, as a component-based assembly, architects with parametric tools can quickly iterate a range of dynamic forms. Owing to these positive features of brickwork, many pioneer researchers have established workflows and experimental projects with on-site robotic automation.

Utilizing robot automation for brick construction can be dated back to the late 1980s(Anliker, 1988) . Since then, decades of research have been conducted on the construction of straight walls, with a focus on unit labor and productivity in construction (Felipe and Kumar, 2014). With the progress in digital design and parametric form generation in architecture, discussion on the robotic assembly process of brickwork has shifted to its potential as an accurate digital fabrication method and its adaptivity for complex nonstandard brickworks. The Gramazio Kohler research group is the leading research team on this topic. Ever since 2008, their research lab has carried out numerous studies on the assembly system of nonstandard brickwork(Dörfler et al., 2016) ,  which has a great influence on the set up of our system. However, as technologically advanced as their robotic system is, because it was developed in an ideal laboratory environment in Switzerland, there are several typical issues restricting its direct application in on-site construction, especially an underdeveloped rural site.

Figure 7 Brick Labyrinth, Zhangjiako China, 2018 .

The brick garden(Figure 7) is located in Wujiazhuang Village (Dingfangshui, Xiahuayuan, Zhangjiako), a village featuring brick buildings specially designed for the 2022 Winter Olympics. The village owns the only brick factory in the neighboring area, so red bricks have been used widely in the renovations as construction materials and decoration in recent years, making the village famous in Zhangjiakou. The garden is located in a triangle site near the entrance of the village. After its completion, the garden became a place for villagers to gather and relax. As a typical site in rural China, much of the challenges we faced when developing the robotic system for this project are common issues for on-site construction. The development of solutions serves as reference for typical on-site construction with robots.

a) Low quality materials and its consequences

Different from factories where the supply of materials is stable with quality control, owning to the logistic and social economical reason, it is common that the quality of construction material varies project by project. In our case, it is required by the client to use a low quality non-facing brick manufactured in local village. In the work of the Gramazio Kohler research group, high standard facing bricks were selected as the construction material. Each brick was very consistent in size and quality. The obligation to use the local non-facing bricks is the cause of redeveloping the end effectors as well as many other problems. Beside the mere appearance of the low quality non-facing brick, the inconsistent size, uneven dented surface quality, and porous material created the challenge for typical pneumatic gripper to pick-and-place as well as selection of mortar. An end effecter that uses vacuum suction is developed replacing the gripper to pick-and-place bricks was developed to accommodate the uneven and inconsistent brick dimensions at different approaching angles. Also, the porous brick is filled with dusts and residues from the manufacture process, in which case the vacuum gripper requires readjustment by adding a filtering plate to prevent the intense dusts from the low-quality brick from blocking the vacuum suction system.

Figure 8 Lab Testing of the Planned Path and the Automatic Brick Assembly System.

A second problem we encountered as the result of using the low-quality brick is the change of mortar which in turn forced the incorporation of concrete printing system with the end effector. In the earlier references, thin mortar bed was used in most robotic brick construction projects because the application of a normal mortar system is a complicated process that includes placing surplus mortars and scraping out the overflows. Thus, using a thick, adhesive-based mortar instead of a typical cement-based mortar would largely reduce the time and effort required in this workflow. However, in practice, there is another key function of the thick mortar system. That is, the thick mortar system levels the uneven surface of the bricks. This is not a problem the lab experiments because high quality bricks were used. However, with the low-quality brick we were using, a think mortar system became problematic, as the deviation in the bricks quickly accumulated as the layers increased, and very soon, the top surface of the wall became so uneven that new bricks would not level and would slip down frequently. Thus, we had to return to the typical thick layer solution and develop a system to include accurate in-place robotic printing or mortars combined with advance sensory perception. Owning to budget constraints, we used to modify off-shelf mortar for the brick construction (Figure 8).

To achieve accurate placement of the thick cement-based mortar, the end versatile effector was redesigned to integrate bricklaying with 3D mortar printing in one (Figure 9), thus achieving a pipeline for brick construction including uninterrupted brick placing and mortar printing. The automatic masonry system changed the typical clamps used for picking up bricks in robotic brick assembly to a vacuum, which could tolerate the slight variation in the sizes of the low-quality, non-facing bricks and could lay bricks in variegated walls without collision. Meanwhile, with the same effector, the mortar could be printed in a more accurate manner to avoid excessive superflux that would require scrapping off later.

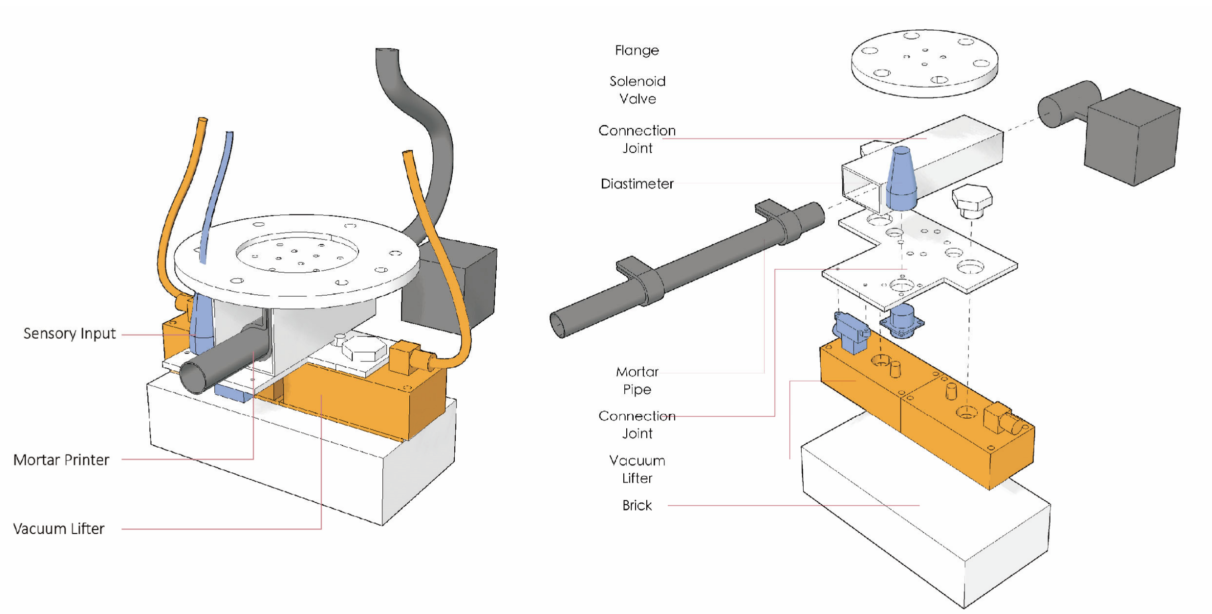


Figure 9 End-effector Design.

A vacuum lifter was used instead of the typical clamps for grabbing the bricks. As the touching region of the vacuum lifter was smaller than the surfaces of the brick, it required no buffer space around the brick, which clamps typically need, thus allowing the bricks to be laid in variegated walls with different tiling methods with our collision. The filter was also added to the vacuum lifter to filter the dust from the low-quality bricks.

b) Control System and Calibration

To coordinate such a complicated mechanical system and plan for its use in the construction process, there are three systems in the integrated system that run parallel and are controlled by a central controller; which coordinates the inputs from the control and sensor, processes commands and sends out signals to the three mechanical systems. The first system controls the robotic arm, and the control of the movement comes from the motion planning in Grasshopper based on the geometry of the wall. The second signal controls the mortar-printing system, which includes the control of the external mortar pump that pumps the mixture and the motor head that starts and stops the printing. The last system is the brick-lifting system, which mainly consists of an air pump, an air tube and a brick lifter. The brick-lifting head is controlled by the air pump receiving an on/off signal from the central control (Figure 10).

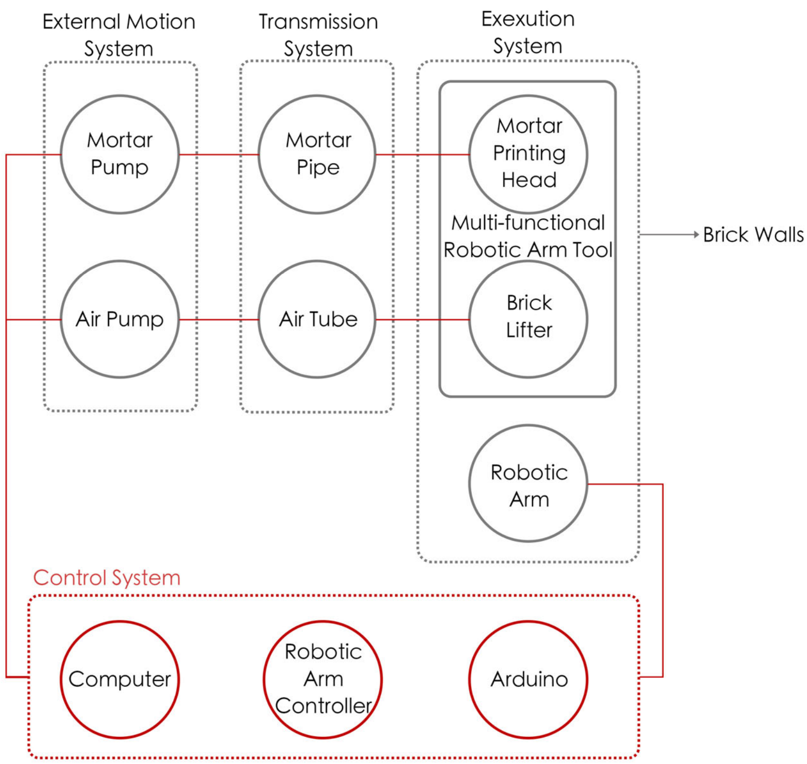


Figure 10 System Design and Workflow.

Additionally, to accommodate the large deviations between each piece, a distance sensor was added to scan the top layer of the piled bricks to calibrate the print path of the following layer. Thus, before printing the mortar of each layer, the extruder moved along the expected path on the top and measured the distance along the top. The measurements were accumulated and evened out for the most appropriate height of the mortar printer.

One more challenge that greatly influenced the design and setup of the system was the construction environment. The construction site was located in a rural village near the 2022 Winter Olympics site, where the temperature easily drops below 0 degrees in winter and varies greatly on a day-to-day basis with strong wind. The onsite construction lasted from October 2017 to April 2018. Because the construction was constantly halted due to the extreme weather, an effective system was developed to facilitate the positioning and orientation of the robotic arms on site. Two type of mortar mixture are developed to cop with temperatures dropping below threshold.

d) Dimension and Mobility

The core aspect of finalizing design scheme is to refine the dimension of the scheme with the consideration of maneuver of industrial robots during construction. As this was a real project requiring on-site construction of multiple industrial robots, there were many more aspects to consider beyond typical design brief —for example, how to case the foundation to support not only the wall but also the robotic arm. Additionally, the placement of the robotic arm during construction was carefully studied because it could not be placed on the area that was designed to for plantation and could thus not cast a concrete foundation. What was the construction sequence so that the robotic arm would not be “trapped in” and build a wall around itself? What was the limitation on the vertical cantilever and curvature of the wall that the structure allowed based on the properties of the customized mortar? As the foundation casting, paving, and landscaping were carried out by local low-skilled workers, thus human errors are inevitable, how can we coordinate between the accurate robotic automation and the inaccurate handiwork of local workers and where were we to insert tolerance? The design and construction sequence progressed together, and the final outcome was an interplay of design intention, site restriction and the pragmatic requirements of the robotic automated construction process.

The base of the garden is a circle with a diameter of 13 m with irregular carved areas. Three winding brick walls laying on the circle form continuous drapes in the plan and adopt a curved form in the vertical direction as well. With more changes in the bricks’ position and angles, these walls form a labyrinth both visually and spatially. Bamboo and grass are planted in the outer area of the curved walls, while the inner space is designed for the villagers’ activities, which presents the relationship of Chinese Yin and Yang in relative complexity. With the models of robotic arms confirmed, the form of the brick garden is once more optimized while path planning for the robots, ensuring clearance for the folk lifter to move the arm and limiting the among of positioning required for the robots.

Figure 11 On-site Construction.

There were two robotic arms working together in the construction process: the KUKA KR210 with an arm length of 2.7 m and the KUKA KR120 with an arm length of 3.9 m (figure 11). The positions for construction and their procedures were designed to maximize the efficiency of this automatic system and avoid any collisions between the robots and the walls or between the robots themselves. The two robotic arms were moved 7 times to complete the entire process, and each course was simulated in the PRC program. The result of such simulations also gave feedback on the initial form-finding process to increase construction efficiency.

After the digital model of the brick walls was generated, the design team designed the robotic arm's path of movement in combination with the construction method and used KUKA|PRC to export it as program codes recognizable to the robotic arm. The process included picking up bricks by vacuum lifters, releasing bricks in designated positions, flipping the tool to print the mortar and printing the mortar according to the designed path. The codes also integrated commands for external devices such as air pumps that were issued by the robotic arms' IO module and passed the obstacle avoidance test in simulation. After simulation in the program, the PRC exported the program for the robotic arm execution so that we could achieve accurate conversion from the digital model to the actual building. To meet the schedule of the project, multiple robots participated in the construction to meet the deadline. The paths and locations of the robots were meticulously planned and synchronized to avoid collisions and interference with the working path.

Figure 12 Designed Plan vs Constructed

The construction process includes measuring, foundation construction, wall masonry, landscape construction, and ground paving. After we used the total station to measure the site, we used the robotic arm to cut 30 cm-thick foam blocks to make molds for the outer curved green area and poured reinforced concrete inside the forms to make a slab for brick walls and activity areas. The masonry process with the smart construction system required at least two workers. One of them operated the system, and the other moved mortar and bricks. A forklift was used to move the robotic arm to the designated positions. To ensure construction precision, robotic arm positioning calibration was conducted after each movement. After the completion of the walls, we removed the surrounding foam and refilled the soil; we plan to plant grass and bamboo in the future. Concurrently, inside the wall, hollow bricks were used to pave the garden.

**Design + Build, the Alternate Process**

Though concepts of efficiency and productivity are often associated with robotic construction, the consequence of robotic engagement on construction sites expands far beyond simply increasing the efficiency by saving in labor, material time etc. Historically speaking, the revolution of material and construction techniques not only increased the productivity of construction industry, but each revolution also transformed people's idea of the typology and tectonique of building that resonates with distinct feature of the technology itself and how the industry work. For example, though concrete was initially used as a more efficient replacement for stone and brick in constructions, with the modernism movement it quickly discovered its own feature in design, hence impacted character of the building, raising design challenges of its own. Similarly, robots on construction site are not mere replacement of labor with more efficient method of conducting existing work, it expands the potential of how building materials aggregates to become buildings, thus in turn translate our understanding of building tectonic and the structure of building industry.

Deployment of robots changes how the information from the design translate into buildings. Though parts of building components can be pre-fabricated with numerically controlled fabrication technologies that directly translate design data into physical forms, the onsite fabrication and assembly process still heavily relies on the skills of the construction workers, while limited by such skill set at the same time. Digital data in this process are translated with human maneuvers. During which process the complexity and accuracy of digital data are dissected and simplifies into instructions that skilled labor can operate on. However, with robots operating on construction sites, digital data are driving the building process directly without additional processing, maintaining the fidelity and complexity of the original data, including information on flexible spatial positioning, material handling, joint condition. etc.

One significant impact of this fidelity of information flow from digital to physical space is that the increase in complexity does not necessarily means increase in cost and procedures. Similar to how people use standard modules during design to manage the efficiency of construction process, with robotic on construction site, instead of designing with standard modules, it is crucial for the designer to engage early on for the scheme to be compatible with the robotic system on-site.

Figure 13 Design of the End-Effectors

The recent construction of Chronos Coffee & Book House project by Archi-Solution Workshop project is a prime example of such incorporations. The design strategy and the robotic system for construction co-evolve during the design process. In this case the main architecture itself composed of undulating sweeping sections based on the contour of traditional house. Contours meet the ground at a gradient of different angles. Consequently, all building component joints with different angles but in a similar system. Traditionally comparing with regular structures, the undulating angels would require scaffolds to facilitate the spatial positioning of the building components, which is the major cause of the difficult and extra cost.

To accommodate the design, a robotic system is developed in parallel for the construction process. Pneumatic clamps are customized for placing of the building components during construction. Unlike the typical clamps for pick and place (Figure 13), the customized clamps composed of two connected clamps that could pick two components and hold them in place at any giving angle in relation with each other within range. The dimension and payload of the system are calibrated for the building components such as metal structure and glass facade pieces. As the system is directly driven by the digital input, the assembly process fully reflects the complexity of the design data. With such system, the none-standard angle and dimensions in design can be achieved with no additional cost comparing to a typical rectilinear design.

Also, an external rail is incorporated early on and become both a feature of design and a necessary utility for the construction. During the construction, it is the rail ensuring the mobility of the industrial robot by expanding the working zone of the robot. After completion, the rail will be used for the movable furniture and coffee bar. The design of the building is one continuous elongated space where the sectional dimension is designed to fit into the working zone of the Kuka robot while the rail would expand the working zone to cover the entire span of the linear space. The non-standard dimensions and angles in the construction are simply dataflows driven the robots performing procedures which can be achieved with high level of accuracy with no additional effort. It is in the construction of such system that follows the strength and constrain of the robots in construction where the advantage of adopting such technology really manifests, surpassing the traditional method of construction

Figure 14 Industrial Robots for On-site assembly of Steel Structure

This project showcased that comparing to the typical design-bid-build process, how an alternative workflow that brings design and construction together in an early stage of a project can fully benefit from on-site robotic construction. By being aware of the constrains and advantage of the robotic arm for the construction, the designers incorporated such parameters into the design process which further impacted on the dimension of space as well as building components. The special equipment such as the end effectors and the rail are developed simultaneously with the design proposals where not only the rail maintained as part of the final design, the construction system is also customized for the most effective execution of the design.

**Conclusion**

Though the idea of an omnificent robot that serves as a replacement of human labor remnants with general public. In reality, robots in construction site, as well as automation in other industries often emerges to facilitate the work alongside human. There is certain aspect that the industrial robots excel in, such as spatial positioning, pay load, and accuracy in numerically controlled movement. In all the robotic construction projects we delivered in Tsinghua University and ASW, beside operating the robot, skill workers worked in collaboration with the robots, typically handling light duty agile works requiring spontaneous analyses and judgements, such as welding, fixing the angled joint, sealing and polish the thick mortar between the brick layers. In practice, instead of replacement, robots stand out as our prosthetics or a collaborator that enhance our abilities in areas such as complex spatial positioning or holding components in non-standard angle for workers to operate on.

In this chapter, the examples encompass a comprehensive selection of using industrial robots for concrete casting, brick assembly, and building of steel structure for on-site construction. However, currently most of the application are still based on pre-scripted working path and sensor feedback. Modern industrial robot platform made it possible for people without robotic background to learn to program it with a short training, which is sufficient for most of industrial use where robots are performing repetitive task in a controlled environment with little deviation. On site construction on the other hand, is essentially a creative process that require intelligence and judgement to adapt to different design, site condition, material quality, and co-working interaction with fellow human. Recent development in computer vision and artificial intelligence strongly enhanced the machine's ability to understand the environment and self-calibrate in an intelligent manner. Those abilities are already expanding the application of industrial robots to more complicated industrial use, such as sorting and loading for logistic. Also, our recent research in using robotic, AI and machine vision to engage in a creative process of understanding material properties and finding alternative fabrication method led to positive out put as well as a novel 3D printing method(Luo et al.). Though much of the experimental application are still conducted in the R&D labs, the nature of the research has clear visions in industrial application and future proofing the traditional labor heavy construction industry into an emerging discipline that builds itself on the comprehensive development of multiple disciplines, that call for the humans' aspiration to exercise creativity and professional expertise.

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