# Slip-formed non-standard Sunshades for Green Building by Robotic Technology

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Robot arm technology has been increasingly considered a future solution for the building industry, which is keen to develop eco-friendly and labor-efficient processes. The automobile industry provides a powerful reference for such a revolution. However, in contrast to the automobile industry, which mostly uses standard industrial materials, such as metal, the building industry still relies on a variety of traditional materials, including concrete cement, brick, stone and glass which rely on intensive labor force to deal with. Although precast building components have been highly promoted, they present innate constraints, including limitations associated with transportation, storage, and installation capacity, which greatly impact the overall budget. In this article, research on a dynamic slip-form concrete extrusion method for sunshades based on the collaboration between human being and robot arm will be presented within the scope of laboratory experiments, on-site fabrication and a design-oriented installation that carefully considers energy efficiency.

Additional Key Words and Phrases: Slip-form, Dynamic Concrete Cast, free-form Sunshade, Automatic Robotic Manufacturing Pipeline, Computational Design, Green building

## 1 INTRODUCTION

The traditional technique for casting concrete is formwork in which a mold com-posed 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 off-shore platforms. Since the 20th century, slip-form has been developed as a cost-, labor- and time-efficient construction technique, but it is still a process that manual work is heavily involved. 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 [11], a V-shaped formwork, and dynamic form-works composed of rigid boxes with two metal plates[10]. 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 en-tire 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;
(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 system working nonstop by shifting between different working sessions.

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(5) A robot arm plays the key role in slip-forming task in which human being take the repetitive process of supplying the pipeline with prepared units for the dynamic slip-forming.

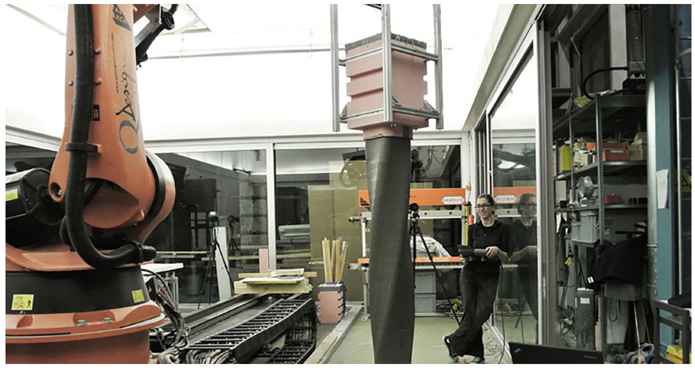

Fig. 1. Dynamic concrete slip-forming by multi-axis robot arm (ETH)

## 2 BACKGROUND

Since Contour Crafting first attempted to utilize a robotic arm for concrete fabrication[8], 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[7]. Recent examples of robotic concrete fabrication, such as the XtreeE [6] and 3DCP [2], also follow this path. However, our research focuses on a separate path based on a dynamic formwork method. In 1910, MacDonald published a paper entitled "Moving Forms for Reinforced Concrete Storage Bins," and it described the use of molds for moving forms composed of jacks and concrete, which formed a continuous structure without joints or seams. This paper described in detail the concept and procedure for creating slip-form concrete structures. On May 24, 1917, a patent was issued to James MacDonald of Chicago (James M, 1910) "for a device to move and elevate a concrete form in a vertical plane." Slip-forming enables continuous, non-interrupted, cast-in-place, "flawless" (i.e., no joints) concrete structures that present superior performance characteristics to price-wise construction using discrete form elements. The building of silos, a core building within a high-rise tower that presents a homogeneous cross-section from the bottom to the top, has adopted slip-forming casting as a very productive solution. This process is different from conventional static concrete formwork because it moves semi continuously with respect to the concrete surface being formed and form ties are not used[12]. Such technology could potentially reduce costs by up to 30-40 percent. In the process of slip-forming, the concrete is poured at a predetermined rate on top of a continuously moving form and then emerges in a quick sitting state with strength. Therefore, the concrete component is shaped by the section profile of the slip-form. The speed of slip-forming must meet the following two criteria.

• When the consolidated (by vibration) concrete emerges from the moving form, it should be strong enough to retain its shape, carry its own weight and carry the weight of the new concrete above it as well. Any drastic deformation will cause an unpredictable collapse.

The freshly set concrete should be flexible enough to permit the slip-form to move upward without too much friction in case the form and concrete stick together during the process, which would lead to failure of the whole piece.

## 3 MODIFICATION OF DYNAMIC ROBOTIC CASTING

Regarding the slip-form technique, the key challenge often lies in reducing the sit-ting 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. Chemical additives are incorporated into the new formula to reduce the sitting time so that each column can be fabricated within 30-50 minutes, 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 hours are required to cast a two-meter-tall column according to the ETH lab report. With above considerations, we set up a new type of the robotic slip-form system based on the precedence from ETH Zurich:

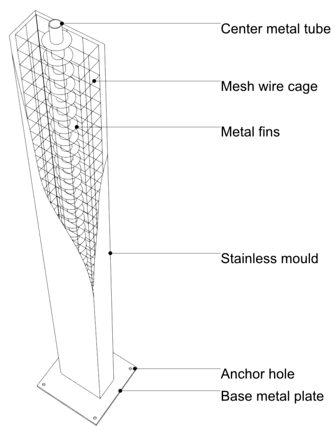


Fig. 2. Mould design

(1) To reduce the overall casting time, a larger mold is chosen to carry entire amount of mixed concrete;
(2) A steel tube is fixed in the center of the mold to ensure the strength and durability
(3) The fiber reinforced concrete is strategically stirred with proportional additives to avoid collapsing during the extruding process
(4) A continuous production pipeline is established to preserve a nonstop 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 the whole unit filled with the mixture and casting continuously overall 15 tons of concrete next to the construction site. A team of 4 person was working tightly with the robotic system to feed materials and install those columns specifically following the digital model, because none of them is identical.

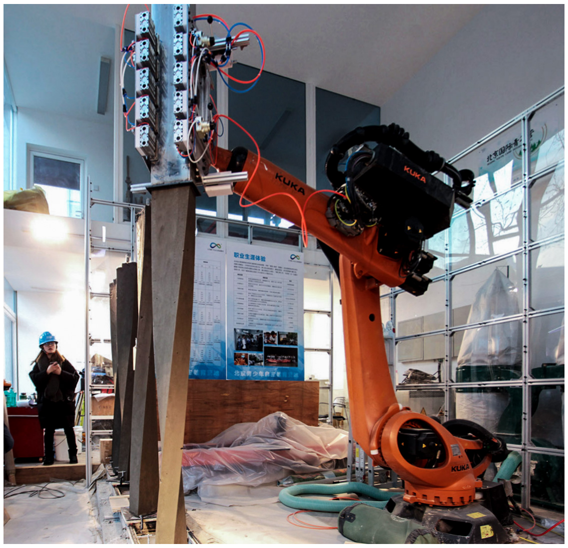


Fig. 3. Dynamic concrete casting process

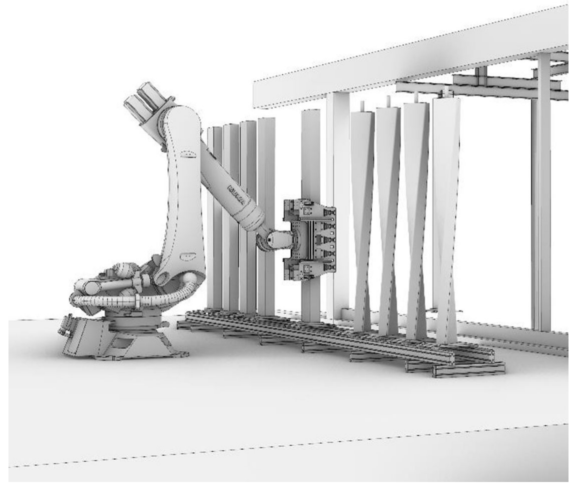

Fig. 4. Robotic slip-form pipeline

### 3.1 Fabrication Pipeline

A well-designated workflow was set up to meet the scheduled deadline, and it consists of two sections.

(1) Concrete mix and infill. In this section, most of the work is performed by human labor.
(2) Dynamic robotic slip-form. In this section, most of the work is performed by an industrial robot arm, which exhibits the power and flexibility of digital fabrication.

These two sections form a looping cycle that repeats as necessary (Fig.2,3).

Since each concrete column (200 mm*100 mm*2200 mm) plus the stainless-steel mold weigh over 100 kilograms, 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 6m 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 microns. 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 XY directions to firmly catch and release the 3mm thick stainless-steel mold. The air compressor was switched by robot I/O via two electronic compressor valves. 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 be-gins. The slip-forming time of each column is limited to 10 minutes 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.

### 3.2 Material and Formula Composition

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, 30.5kg fine sand, 11.5 kg of water, 80g Nylon fibers at 30 mm, 80g Nylon fibers at 20mm, 40g Nylon fibers at 8mm, 105g Super plasticizer 5, and 82g Accelerator. The mixture is rapidly stirred for 5 minutes, well vibrated and

Fig. 5. Dynamic concrete slip-forming by multi-axis robot arm (ETH)

## 4 DESIGN PROCESS DRIVEN BY DATA FLOW

### 4.1 Computational and Interactive Design

In this design, 115 slip-formed columns are situated at every half meter on a 60 m long lineal flat steel base (Fig.4). 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.

### 4.2 Data Flow from Design to Fabrication

A parametric 3D model created in Rhinoceros was used to connect 115 sets of da-ta 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 [3], 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.

## 5 SCENARIO OF ECO-FRIENDLY BUILDING DESIGN AND FABRICATION

The design and form of a building façade has a significant impact on the heating, cooling, and lighting loads as well as the thermal and visual comfort in the perimeter zones of a commercial building [5]. With the effective distribution of solar energy via passive façade elements, energy consumption can be significantly reduced [13]. Additionally, the lighting quality can be improved to address the need for different programs and spatial comforts[1]. Beyond serving as a mere installation for a soft division of urban space, the design of such units and the associated techniques have a greater objective of potentially become a passive smart shading device to adjust solar gains and interior reactions based on the nuanced relationship between the building and the sun.

### 5.1 Smart Sunshade Component

Motivated by the dynamic concrete slip-form technique, the curtain wall shading system represents a new element that excels in both aesthetic and functional aspects. This digital fabrication technique could change the role of concrete, a traditional building material, and allow it to perform on a new level in the near future. Com-pared with GRC (Glass Fiber-Reinforced Concrete) technology, which still uses static formwork to produce a surface curvature, robotic slip-forming provides an effective solution to the challenge of free-forming concrete construction. Overall, this new technique has considerable potential for use. Based on the outlined smart fabricating solution, the twist-formed concrete components could serve as a green-building 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.

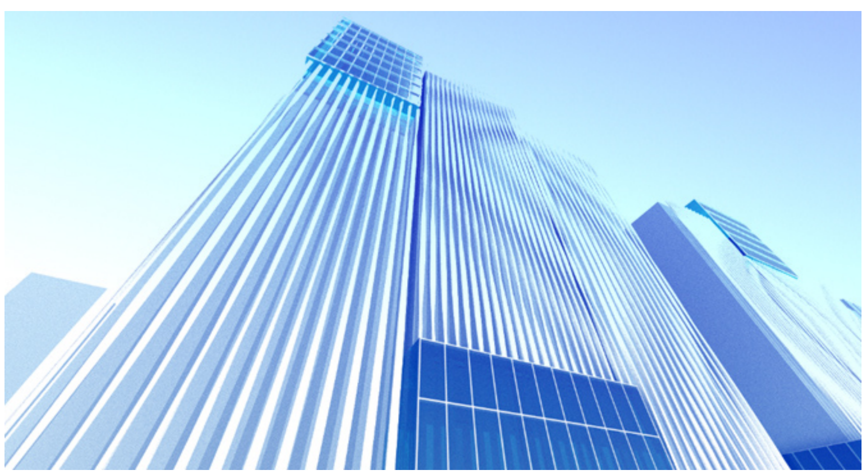

Fig. 6. Building elevation scenario with concrete components

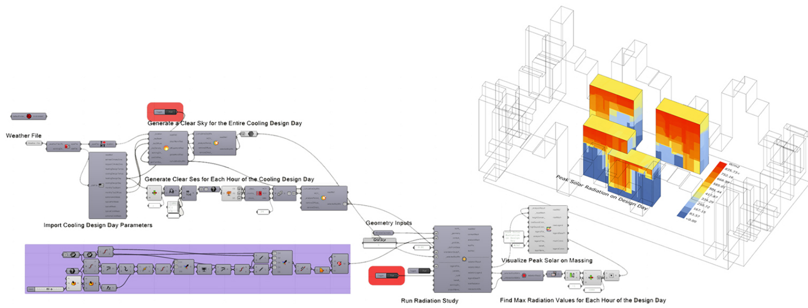


Fig. 7. Solar analysis from Ladybug in Grasshopper

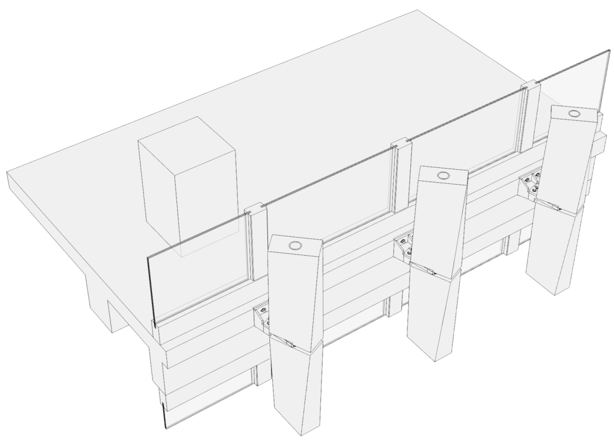

Fig. 8. Scenario of Sunshade installation

### 5.2 5.2 Eco-Friendly Concrete Sunshade

As a further development of the previously described "Flex-wall", we propose a mixed-use building scheme that implements this robotic technique together with green-building design strategies. Initially, four basic requests are registered.

(1) The concrete component should be able to hide the facilities and equipment attached to the exterior of the building, such as AC workstations, water shafts, etc.
(2) This concrete installation should provide a comfortable shading solution based on the statistics of the local climate and environment.
(3) The shading solution should also meet the goal of improving the interior lighting conditions.

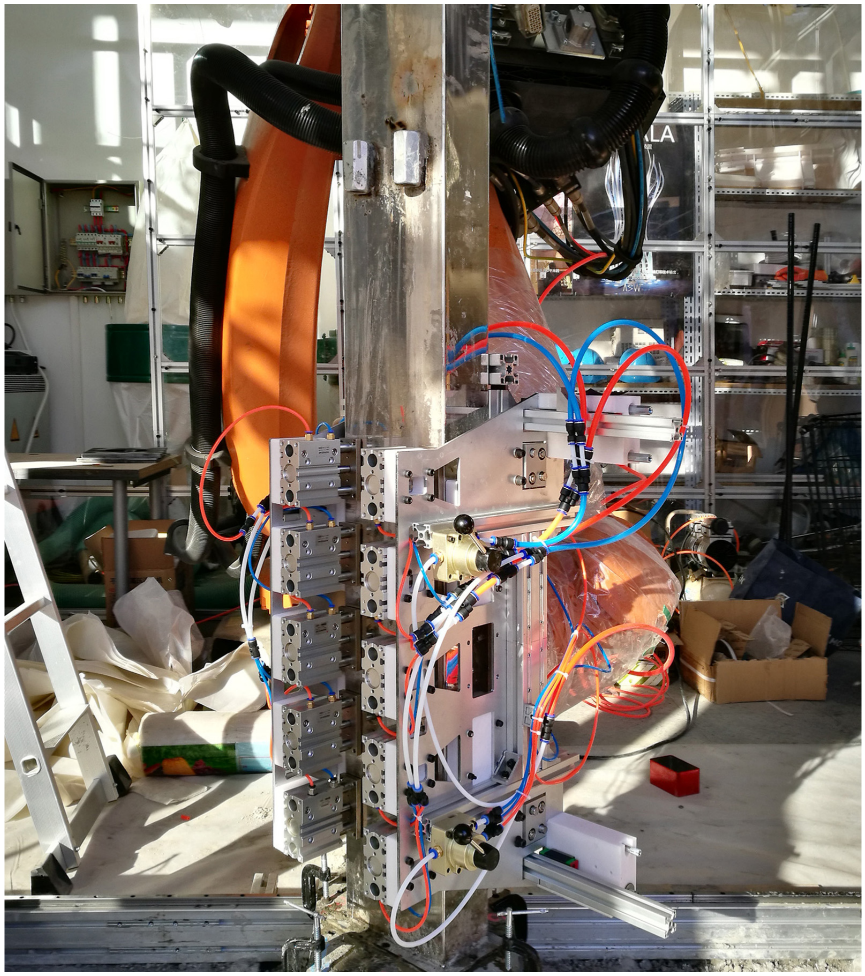

Fig. 9. Robotic slip-forming system

## 6 HUMAN ROBOT COLLABORATION

In this chain of productivity, the robot arm is employed as a partner who is able to precisely give response to G-code.[4] This slip-forming task is mandated to be seamlessly continuous to ensure the perfect cosmetic surface quality and the geometric consistency regarding to a smoothly transitional sequence. Any nuance of deviation will result a visual-broken. Therefore, the slip-forming is the most critical session among the whole process, which is usually ranked as an experienced craftsmanship in the traditional point of view. Even if this task is taken by a skilled master to work on these slip-forming series, this person cannot guarantee a high percentage of success as robot arm does in any case. In terms of human robot collaboration[9] for this research and experimental practise, robotic equipment takes the position to profoundly carry design data-flow down to the next stage. Meanwhile, the rest tasks, which are mostly repetitive and low-skill, could be handled by people who are not required to be superior like a master, such as concrete mixing, pouring and vibrating, mould carrying onto and unloading from production rail etc. It leads to an inspiring point that digital crafts-ship can potentially be a new working mode for a teamwork of robot and human-being with extraordinary efficiency and flexibility. This is benefited from the digital fabrication technology that robot system and CNC machine could be fitted in highly skill-demanded positions, while human being will handle the tasks demanded in low skills and with less experience instead. Obviously, this reciprocal collaboration will encourage an upgrade of productivity, in which licensed robotic technician manages how to coordinate human beings and automatic robots who have multi-capacity to accomplish specific assignments to link upper and lower workflow.

## 7 CONCLUSION

This paper presented a joint thesis between research and practice based on dynamic robotic concrete casting, a method of digital fabrication developed via the NCCR at ETH Zurich, and an extending discussion between digital fabrication and computational design of ecological architecture. This ambitious endeavor is an attempt to move from a laboratory setting towards the building industry, which requires practical cases to breach the boundary. Therefore, the "Flex-wall" is selected both as a research exercise and proof that a robot arm, as a captain of the neo-product pipe-line, offer considerable flexibility and efficiency for linking a chain of different disciplines, and it will eventually be driven by data flow from the early design phase all the way to fabrication. This thesis also aim to make a scenario of the companionship between robots and human beings in the future building industry. The task distribution in this new work mode will be commensurate with the criteria of how to maximized the productivity, how far to reduce the waste of natural resource and how to build the trust in between.

## REFERENCES


[1] İbrahim Atmaca, Ömer Kaynaklı, Abdulvahap Yiğit, et al. 2007. Effects of radiant temperature on thermal comfort. (2007).

[2] Freek Bos, Rob Wolfs, Zeeshan Ahmed, and Theo Salet. 2016. Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. *Virtual and physical prototyping* 11, 3 (2016), 209–225.

[3] Johannes Braumann and Sigrid Brell-Cokcan. 2011. Parametric robot control: integrated CAD/CAM for architectural design. (2011).

[4] Sigrid Brell-Cokcan and Johannes Braumann. 2010. A new parametric design tool for robot milling. (2010).

[5] Ying-Chieh Chan and Athanasios Tzempelikos. 2012. A Simulation and Experimental Study of the Impact of Passive and Active Façade Systems on the Energy performance of Building Perimeter Zones. *ASHRAE Transactions* 118, 2 (2012).

[6] Clément Gosselin, Romain Duballet, Ph Roux, Nadja Gaudillière, Justin Dirrenberger, and Ph Morel. 2016. Large-scale 3D printing of ultra-high performance concrete–a new processing route for architects and builders. *Materials & Design* 100 (2016), 102–109.

[7] Dooil Hwang and Behrokh Khoshnevis. 2004. Concrete wall fabrication by contour crafting. In *21st International Symposium on Automation and Robotics in Construction (ISARC 2004), Jeju, South Korea*. Citeseer, 301–307.

[8] Behrokh Khoshnevis. 2004. Automated construction by contour crafting—related robotics and information technologies. *Automation in construction* 13, 1 (2004), 5–19.

[9] Yanan Li, Keng Peng Tee, Shuzhi Sam Ge, and Haizhou Li. 2013. Building companionship through human-robot collaboration. In *International Conference on Social Robotics*. Springer, 1–7.

[10] Ena Lloret Fritschi, Lex Reiter, Timothy Wangler, Fabio Gramazio, Matthias Kohler, and Robert J Flatt. 2017. Smart dynamic casting: slipforming with flexible formwork-inline measurement and control. *HPC/CIC Tromsø 2017* (2017), Paper–no.

[11] Ena Lloret Kristensen, Fabio Gramazio, Matthias Kohler, and Silke Langenberg. 2013. Complex Concrete Constructions–Merging existing casting techniques with digital fabrication. (2013).

[12] B Risser, TY PICAL FO, and RA ISING RAT. 1995. Advances in vertical slip-form construction. *Aberdeen's Concrete Construction* 40, 10 (1995), 40–45.

[13] Athanassios Tzempelikos and Andreas K Athienitis. 2007. The impact of shading design and control on building cooling and lighting demand. *Solar energy* 81, 3 (2007), 369–382.