Pop-Up Concrete: Digital and Physical Materiality

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1. INTRODUCTION

Concrete has been used for a long time, and the interest in building concrete free-forms has gained relevance in the last decade, which has encouraged a large amount of robotic and non-robotic research in flexible formwork systems (Bak, Shepherd, and Richens 2012). It is clear that when building concrete free-forms, one crucial decision is the choice of formwork to guarantee its quality and financial feasibility (Verhaegh 2010). Despite the increased interest in free-form concrete and the vast amount of research on flexible formwork, most digital forms are still built using traditional formwork and methods. The problem lies in the fact that construction processes still rely on a unidirectional workflow from "digital design" to "physical production." This means that designs have to go through a lengthy rationalization process where friction between form, structure, and material occurs. An integrated design workflow is researched and presented in this paper that integrates design and building through the use of new material technologies and digital fabrication tools.

Technical devices and digital fabrication tools allow for new practices and are capable of opening new understandings of matter, new ways of organizing, and new complex and irregular relationships that expand material processes to create new non-linear workflows and can lead to a new language characteristic of the robotic era in architecture. Using a new material technology within a pop-up process, based on patterns that embed the shape into the material rather than prescribe it, requires an experimental approach, as the material exhibits probable but not *certain* behavior. Thus, a new path, based on feedback loops, is proposed toward the design of curved, thin, flexible structures in concrete without the need for complex formwork that would be otherwise required (Kotnik and Weinstock 2012). Our shaping system allows for complex curves to be created through a combination of the concrete sheet material and the embedded pattern.

2. PRECEDENT ANALYSIS

In the context of robotic fabrication of concrete, projects to date have been divided into four major areas of exploration, each with a unique set of limitations:

1. *Concrete 3D printing*: Over 10 years ago, researchers at the universities of Southern California

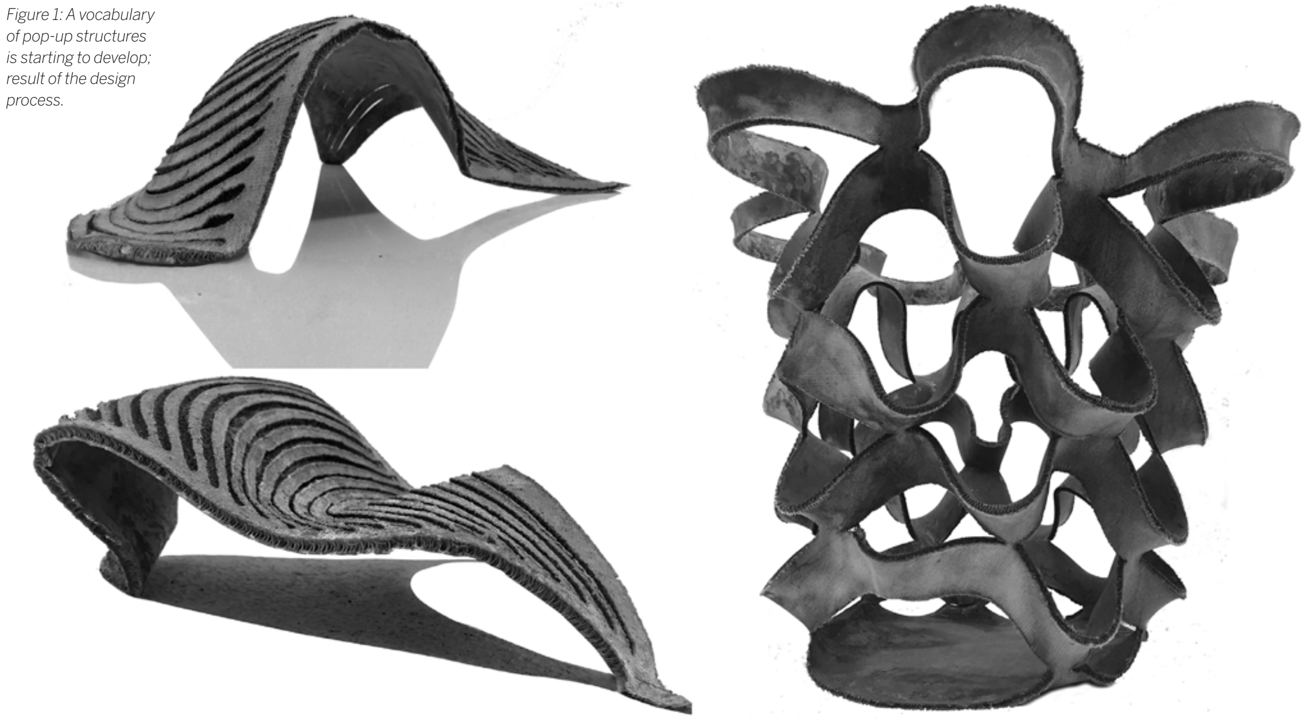


Figure 1: A vocabulary of pop-up structures is starting to develop; result of the design process.

(Khoshnevis n.d.) and Loughborough (Lim et al. 2011) started to investigate the potential of extruding concrete for printing buildings. Both attempts used an extrusion head mounted on a gantry crane to deposit horizontal layers of concrete. However, limitations exist regarding the scalability of the gantry, the hydration process, the loading capacity, the adhesion of the different layers, and the integration of reinforcement.

2. *Dynamic formwork*: "Smart Dynamic Casting" (Lloret et al. 2014) focuses on the vertical extrusion of concrete columns, using sensors and a feedback loop to monitor and control the hydrating of the concrete. This information is then used to determine the slip velocity, tackling the problems of previous 3D printing methods. The careful calibration of sensor feedback with the spatial movement allows for a high level of control over the formation process.
3. *Mould-based formwork, flexible and rigid*: Tailor-Crete developed a digitally controlled, recyclable, flexible wax mould system that is produced off-site, then brought on-site and inserted into standard formwork systems to produce complex concrete structures (Oesterle, Vansteenkiste, and Mirjan 2010). Conversely, the "UNIKAbeton" prototype showed the possibilities for complex concrete construction using digitally fabricated rigid EPS blocks (Sondergaard and Dombernowsky 2011).
4. *Leave-in formwork*: The Mediated Matter Group at MIT (Oxman, StevenKeating, and Klein n.d.) and the project "Mesh Mould" at the ETH (Hack et al. 2014) explore techniques where the robot 3D prints permanent formwork, which doubles in function as thermal insulation in the former and as reinforcement in the latter.

3. METHODOLOGY

Pop-up is a technique that transforms planar materials into 3D forms. Research in pop-up as a construction system in architecture and other fields remains relatively unexplored. Researchers in nanomaterials have only recently started to look at the potential of pop-up as a manufacturing technique and as a simpler route to achieve 3D frameworks by buckling planar structures, allowing them to create complex shapes using a variety of materials, such as silicon and semiconductors (Xu et al. 2014). There is also ongoing research using a pop-up system on modified crystals for implantable devices that can be triggered to morph once inside the body (Verduzco 2015). The formation of pop-up structures is not random—it is caused by set boundary conditions of the embedded cut and joint pattern and follows precise physical principles.

These concrete geometries rely on a system based on 2D cutting patterns performed in "Concrete Canvas," described below, that transforms into a 3D shape by buckling on-site using inflation to create a surface. The Concrete Canvas cures with the addition of water to become structurally rigid after an initial period of three hours and becomes fully set after 24 hours. Concrete shaping is possible as long as the concrete is in its wet state; this curing period or "transition" phase of the concrete opens possibilities for new shaping strategies where the form of the three-dimensional object is transformed. Digitally, 3D shapes can be collapsed into 2D cutting patterns to be popped back up into 3D surfaces. The design is not finalized until the material hardens, giving various opportunities for interaction between the architect and the material, and thus making fabrication an interactive process of creation.

4. PHYSICAL FABRICATION

4.1 Concrete Canvas

New materials provide an opportunity for designers to create new typologies (Thompson 2007). Material developments and higher-strength concrete have been used to explore 3D complex concrete shapes that pop up from flat 2D patterns. Concrete is not traditionally a flat sheet material. However, fabric impregnated concrete, a new hybrid material technology, combines the compressive strength of concrete and the tensile strength of fabric. This seemingly contradictory characteristic allows for a more intuitive design workflow that can lead to a flexible and adaptive design process. Through prototype testing, it became clear that a feedback step is needed within the process to address the possibilities and uncertainties presented by the material when used in novel ways.

Concrete Canvas (www.concretecanvas.com) allows easy deployment and rapid construction of thin concrete shells, as it only requires air and water for construction. Shelter structures up to 50 square meters have been built using this material. It consists of two flexible membranes on each exterior surface, with a 3D fibre matrix impregnated with cement. The top layer is a fibrous surface that can be hydrated, while the back membrane is made of waterproof fire-resistant PVC. The cement-based composite fabric uses inflation to create its surfaces that are optimized for compressive loading. When hydrated after 24 hours, the membranes harden, forming a thin, robust, and lightweight concrete structure. Concrete Canvas comes in different thicknesses (5, 8, and 13 mm). The experiments described in this paper use the 5 mm variety.

4.2 Robotic Tooling

A set of key variables was identified for the design of the robot tool, such as: the turning radius of the cuts; the depth of the sandwiched material; and the robot's cutting speed. A laser cutter was used initially, but the additional installation requirements made it unsuitable for on-site applications. Circular diamond saws were also tested, but the speed at which they needed to rotate caused concrete powder to eject and weakened the overall structure. A solution using a 45 mm-diameter, sharp circular blade was selected because it allowed efficient cutting, smaller turning radii, and lower rotational speeds. Enough depth is needed at the entry points so that it cuts all the way through the material using a single pass.

4.3 Surface Definition and Tool Path Generation

The process starts with the definition of a base surface. A control pattern of cuts and joints that will define the surface form is then applied. Four main criteria that define the final popped-up geometry are identified and parametrically controlled (Vazquez et al. 2010):

1. The cutting pattern defines the relationship between the 2D pattern and the 3D volume. The cuts on a flat material need to be offset to achieve a concave geometry. The spacing between the cuts needs to consider the material behaviour and avoid extreme clustering that will result in long, thin elements that can buckle, given a very small distance from the edges. If the cuts are too far apart, the pop-up will be too shallow. A minimum section of 30 mm has been established for the 1.0 x 1.0 m prototypes.
2. The joints between cuts affect the stability of the overall structure. The joints are the areas where there is no cut, and they are crucial for the popping of the unit. When joints are staggered, a more rigid structural system is achieved. Our experiments show that joints of 40–50 mm create rigid

Figure 2: (Left) 2D pattern laser cut in Concrete Canvas. (Right) Popped-up Concrete Canvas shell prototype.

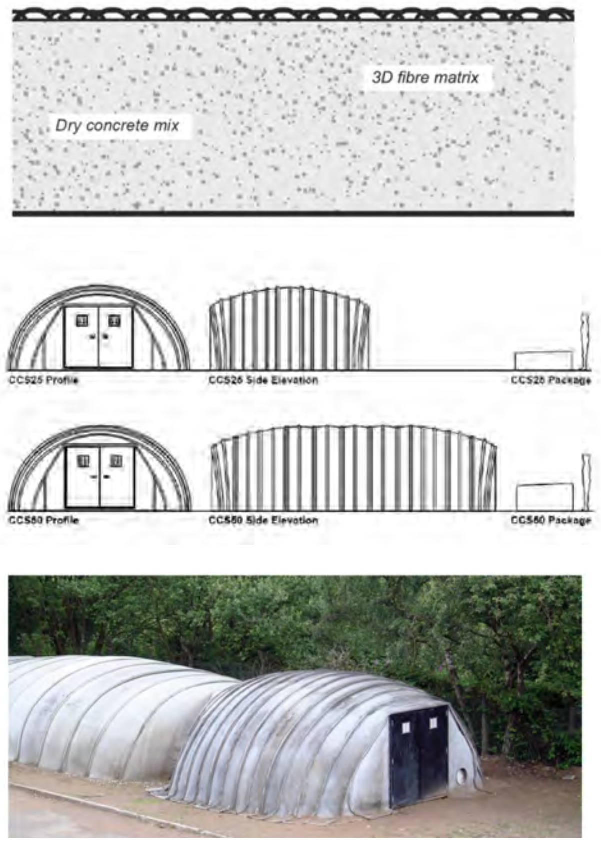


Figure 3: (Top) Concrete Canvas section. (Middle) Typical deployment sequence. (Bottom) Shelter structure. - images courtesy Concrete Canvas

conditions. Joints smaller than that create flexible and semi-flexible conditions.

3. Relaxation, form manipulation, and inflation determine the final position and shape of the surface.
4. Pre-hydration and drying times affect both the structural rigidity of the surface and its elasticity. In our experiments, we tested different sequences of hydration and cutting to maintain the integrity of the final form and minimize concrete loss.

Once a pattern of cuts and joints is determined based on aesthetic and structural constraints, the curves need to be rationalized to maximize continuity. This ensures path continuity and decreases the possibility of singularities and out-of-reach positions for the robot. The end points of each curve are offset on the Z-axis for the robot to move vertically after each cut and allow for the joint areas.

5. DIGITAL COMPUTATION AND SOFTWARE WORKFLOW

The digital process is set with the aim to foresee materialization and control it during its forming. It requires the customization and integration of different software platforms for material computing, physics solvers simulation, and structural analysis. To achieve the initial goal of merging modelling, analysis, and fabrication into a single process, the form-found geometries need to be brought back into the digital world, and a direct link needs to be created between the digital and the physical models.

After the initial surface with the joints and cut patterns is defined and modified, it is exported to form-finding software based on particle spring systems. In this case, Grasshopper and Maya Nucleus solver were used to approximate the shape digitally. The Autodesk Maya N-cloth delivers sufficiently accurate results in replicating the material performance and pop-up behaviour observed in the physical tests, as it allows embedding and calibrating different physical constraints, such as damping, strength, stiffness, and density. Each pattern was established as a boundary condition and relaxed to find its resultant pop-up geometry within the pattern. Once the pop-ups are generated and evaluated, the pattern is turned into toolpaths using a custom-made robot communication platform for cutting and physical testing. Further research is being conducted to develop a workflow that integrates the robotic and physics simulation into a single platform, to enable a continuous workflow from design to realization of non-standard, material-driven fabrication processes.

5.1 Feedback Loops

Utilizing a commercially available 3D scanning application, a strategy was evaluated in this research project for its potential in establishing the following iterative feedback loop: material deployment; automated inflation process; measurement of deformations in the physical geometry; calibration of the digital mesh; structural and aesthetic analysis of both; live manipulation of the inflated concrete structure; and point-cloud 3D re-scanning.

In the implemented approach using Autodesk 123D Catch, the scanned information consists of a point cloud and a mesh that can be imported to the digital environment. This is then used to calibrate different parameters, such as damping, strength, spring stiffness, and density to approximate the digital and material behavior. This allows the designer to quickly understand and evaluate the many factors that influence the process and to "mould" the material. Feedback loops enrich the process, as this information is taken to the following cut pattern. Enhancements or modifications to the cut pattern of the flexible sheet material are related to the whole process, as the cut and joint strategy gives unique identifiable characteristics to the final rigid material. The iterative process allows us to integrate computational and material logic into the design with which we can predict and orchestrate sequential material behavior. It negates the unidirectional flow from "digital input" to "physical output" that pervades current processes of digital fabrication.

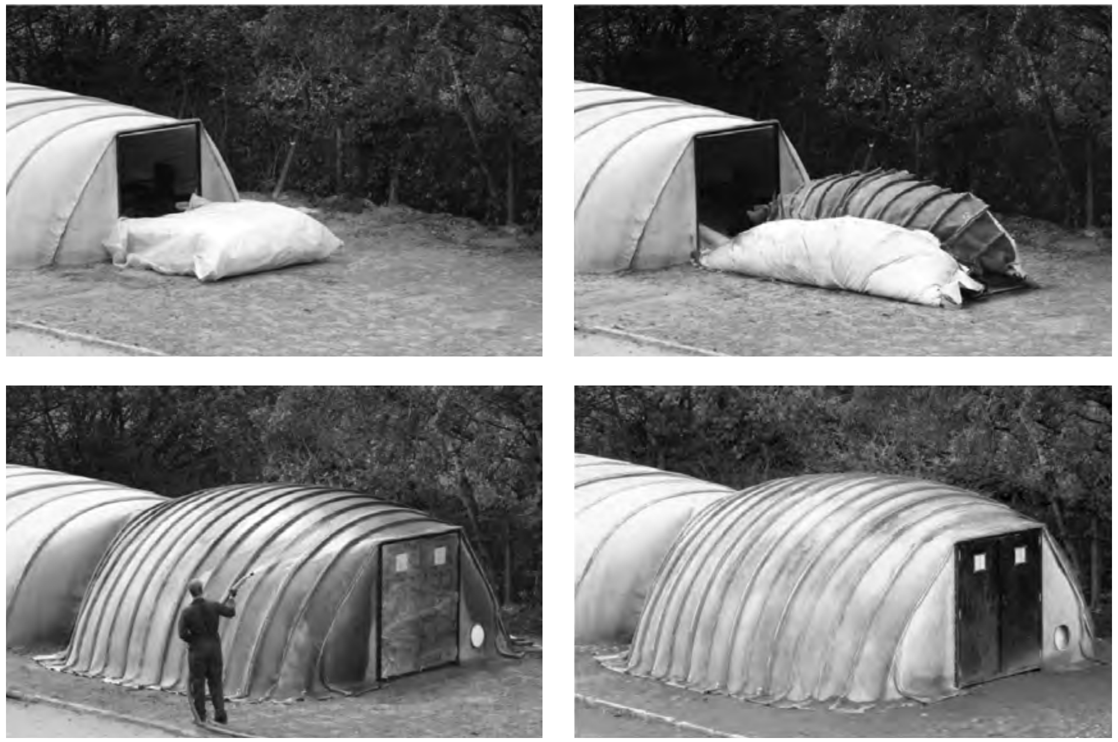


Figure 4: Detailed traditional deployment of Concrete Canvas. (Top Left) Delivery. (Top Right) Inflation. (Bottom Left) Hydration. (Bottom Right) Setting. - photos courtesy Concrete Canvas

5.2 Analysis

The uncertainties regarding the behavior of the Concrete Canvas with the applied "cuts and joints" pattern, intertwined with the fact that the pattern can allow for material extension beyond its safe limits, requires continuous analysis. Scale models were built and popped up. Through scanning, the response of the model to the pattern was measured, and its structural behavior analyzed and calibrated with the digital model. Modifying the control cut pattern gives different properties to the material. What was expected to be a homogeneous shell became flexible, semi-flexible, and rigid. Rhinoceros Scan&Solve was used to check the shapes qualitatively. This allowed a clearer image of the structural and material response to the cutting pattern.

5.3 Simulation

Iterative digital physics-based simulations were used to gain a deeper understanding of the relationship between the cut patterns and the final 3D form. The production of low-resolution meshes using particle-spring systems is an established practice for physics simulations. They provide the designer with an intuitive and qualitative knowledge during early design stages that can be augmented with structural and fabrication constraints through a feedback loop (Vazquez et al. 2014). Calibrating a digital low-resolution mesh with the high-resolution material input from the scanning process allows the designer to work interactively with the geometry while enclosing all the important technical details, such as singularity points, boundary and topological conditions, holes, clearances, etc. (Bhooshan and Sayed 2011). It also allows for an iterative quick evaluation of a range of options by adjusting key parameters that affect each realization (Williams et al. 2011).

5.4 Flexibility

The ability of the designer to intervene at any stage during the process is very important. During the inflation process through the feedback loop, the designer has the flexibility to interrupt and change the flow of information. The resultant geometry can then be analyzed for its structural and aesthetic characteristics, while changing the parameters, and consequently the geometry itself, before hydration and curing.

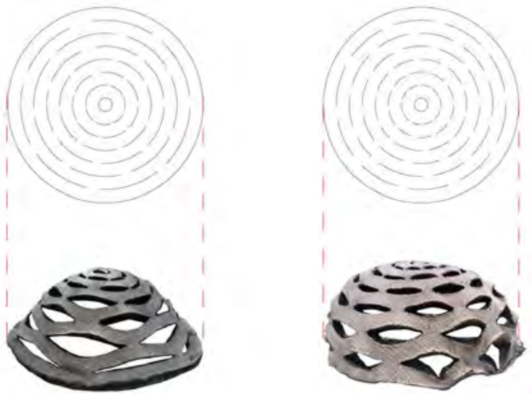


Figure 5: Changes to the cut and joint pattern; boundary conditions and relaxation constant.

Figure 6: Comparison of geometric differences in the 3D pop-up surfaces; product of changes in boundary conditions and cutting patterns.

6. SCALABILITY

Unlike other material experiments, due to its native use for infrastructure, fabric impregnated concrete can scale up as it is normally used in large-scale infrastructure projects. Physical models have traditionally been the basis for the design of fabric formwork as there is a relatively direct relation between scaled and full-scale models (Manelius 2012). Professor Mark West, with 20 years worth of experience on the design and construction of fabric formwork, argues that "anything you can build in a scaled model, you can build at full scale" (West 2011). Anne-Mette Manelius at the KADK, Denmark, after several workshops working with students, confirms this relationship of causality (Manelius 2012).

Experiments so far have been limited in size by the maximum width of the fabric of 1,030 mm. To move into larger structures, Concrete Canvas geometries will have to be constructed assembling segments to complete the form before inflation and hydration. The fabric-like properties of the material enable the possibility of sewing various pieces together following a pattern as with traditional fabric formwork. This means that geometries that can be unrolled and cut out of fabric can be done using this technique. Concrete Canvas trademark shelters are built using this approach. To succeed at 1:1 scale using concrete impregnated fabric, adjustments to the sequencing and construction planning are being explored, while the fundamental concept remains feasible.

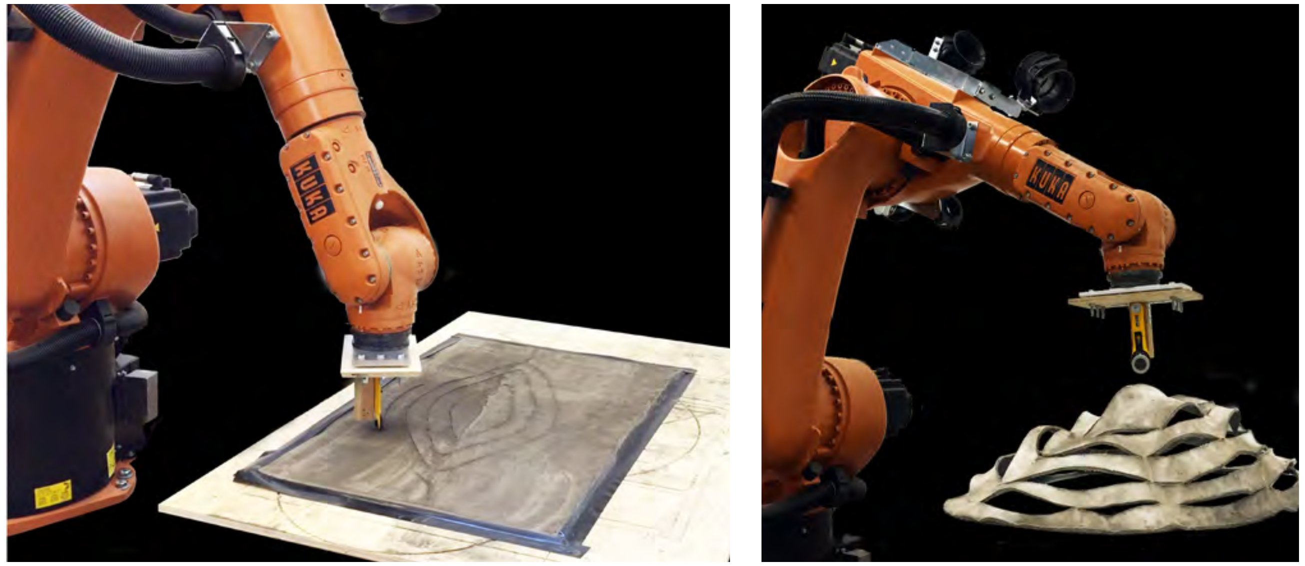
7. HYBRID TECTONICS

Additive, subtractive, and formative processes are the three main accepted fabrication categories (Chua, Leong, and Lim, 2010). Embedding patterns in the concrete fabric is mainly a subtractive process in a homogeneous material. The distribution of cuts and joints gives areas of varying rigidity within the final form. This is the first step in introducing heterogeneous properties to the material. Based on the analysis of the 2D patterns and their 3D pop-up resultant geometry, further research is being done on ways to add material to reinforce specific areas during and after pop-up. A 3D printing step before popping up can be an option to reinforce zones where more structural resistance is needed and that can be weak after pop-up. Introducing the possibility of adding material to the process gives the ability to tailor structural and material properties of an otherwise homogeneous material to improve efficiency and functionality in the final 3D geometry.

8. CONCLUSIONS

The implementations of pop-up structures that generate 3D surfaces out of 2D patterns clearly yielded

Figure 7: (Left) Robot cutting pattern in concrete. (Right) 1.0 x 0.7 x 0.7 m popped-up prototype.



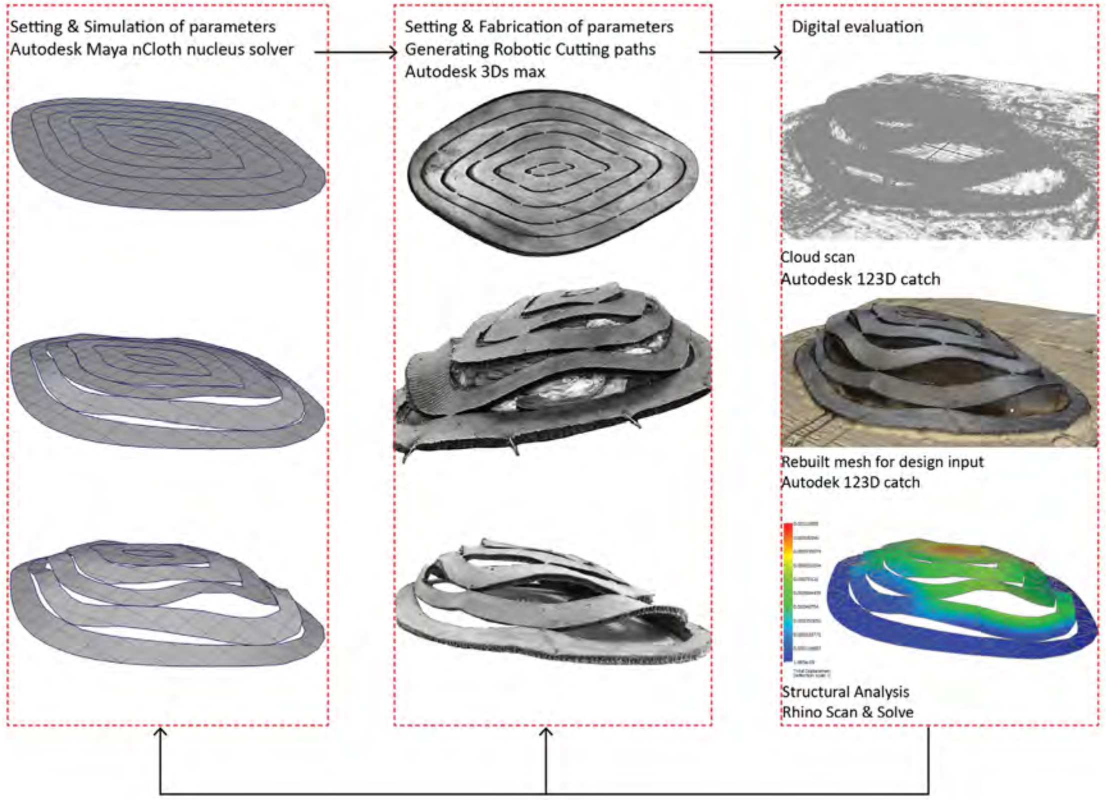


Figure 8: Diagram showing the workflow setout and digital–material feedback loop.

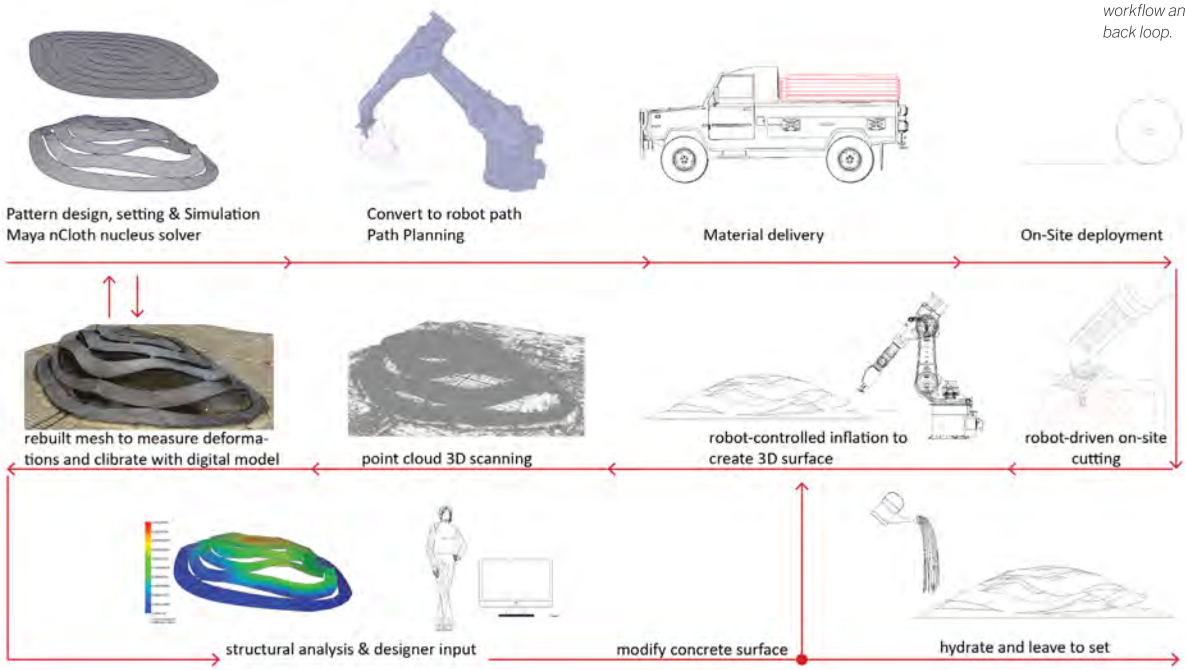


Figure 9: Path planning workflow and feedback loop.

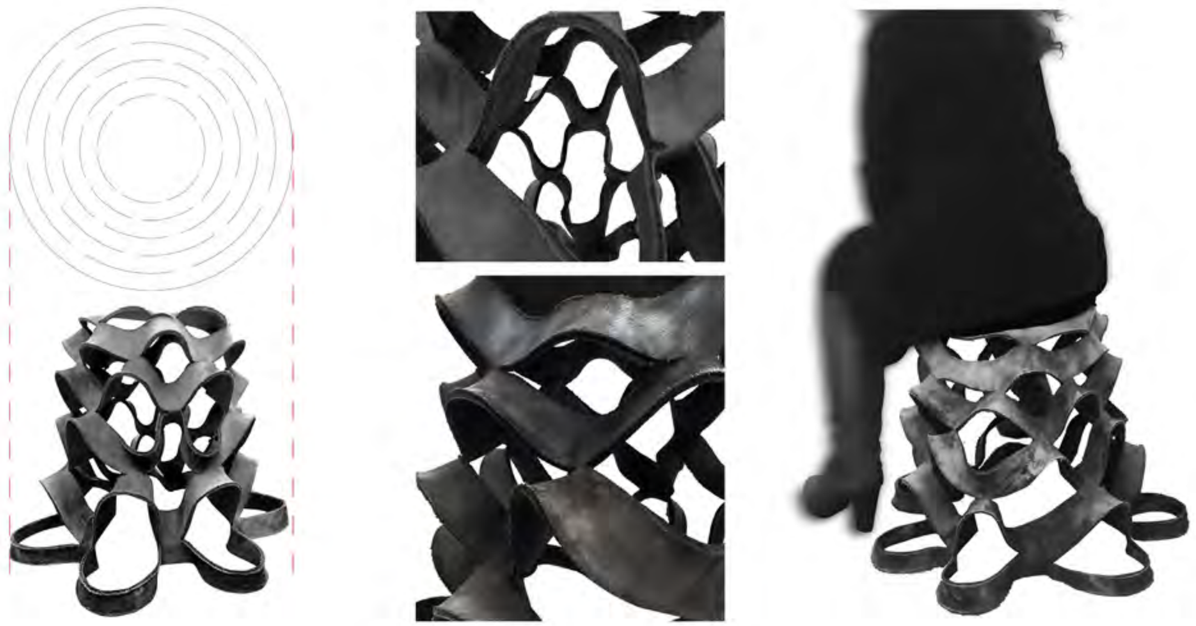


Figure 10: (Left) Pattern and resultant pop-up geometry. (Middle) Concrete details. (Right) Live load testing to calibrate with structural assumptions.

an expanded domain for design exploration that can generate a new language for architecture in the robotic era. The generation of pop-up structures is not random but caused by set boundary conditions of the embedded cut and joint pattern and follows precise physical principles during its pop-up. Through the feedback loop, and with defined boundary conditions, the results can indirectly be controlled and emergent shapes created by stopping the process at any point in time during the "pop-up" phase of the concrete. 3D pop-up geometries can achieve a space-enclosing surface faster than 3D printed ones. A main challenge of this technique is that while the desired end 3D shape is known, the pattern to produce it is not, an inverse situation to that of traditional construction methods (Ye and Tsukruk, 2015). Future work will be conducted to develop 2D patterns that pop up into the desired 3D structure.

Initial experiments were concentrating on the development of pop-up strategies for industrially prefabricated products like Concrete Canvas. However this product is mainly used for infrastructure, and its structure and finish often don't allow the desired forming. For the next test scenarios, the authors want to include the design of the composite material itself, as it promises a huge impact on the formal results caused by the formation strategy.

At a design level, the aim is to establish more intricate and larger patterns where two or more sheets are sewn together and their initial configuration responds to more complex geometries. The scanning of the physical geometry after being streamed to the digital simulation for analysis will be used to automate the control of the popping up, in order to investigate viable inflating and interaction sequences that allow for closer relationships between designer, robot, and material before implementing them in real time for a full-scale prototype. Through this exploration, we anticipate the realization of complex concrete geometries responsive to embedded performance criteria.

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