Human Touch in Digital Fabrication

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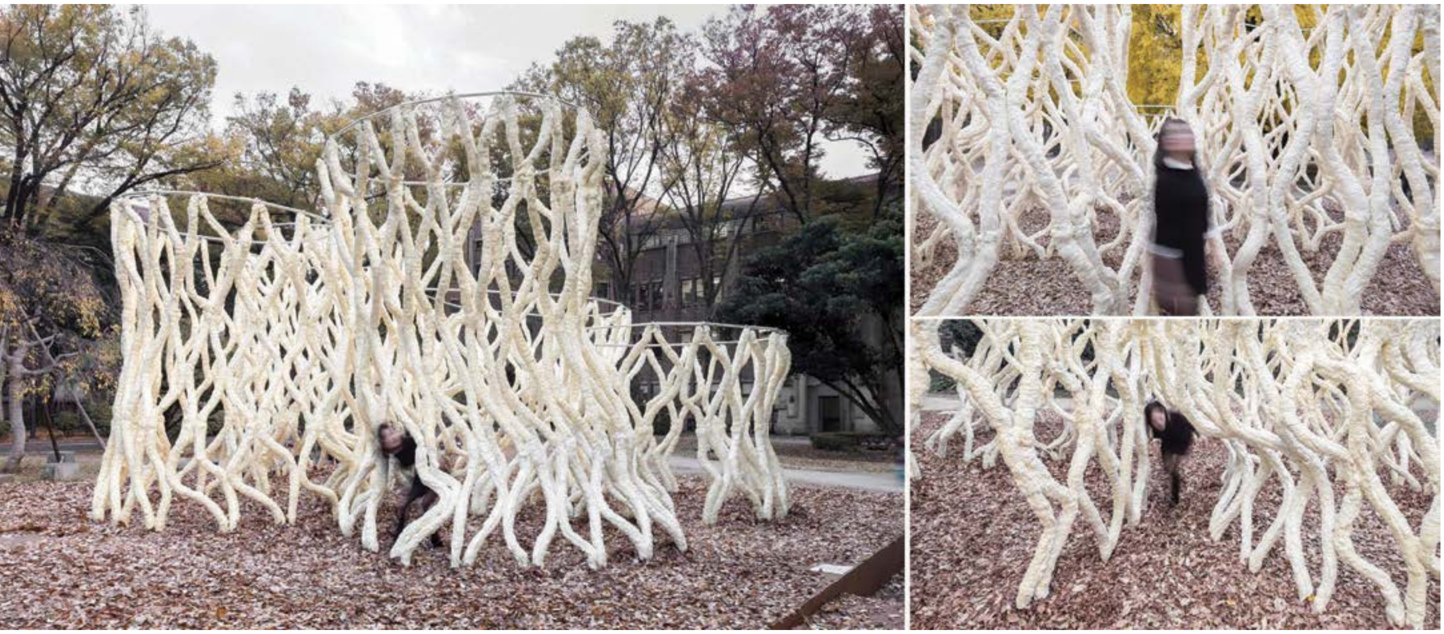

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1 The constructed pavilion as an outcome of the case study.

ABSTRACT

Human capabilities in architecture-scaled fabrication have the potential of being a driving force in both design and construction processes. However, while intuitive and flexible, humans are still often seen as being relatively slow, weak, and lacking the exacting precision necessary for structurally stable large-scale outputs—thus, hands-on involvement in on-site fabrication is typically kept at a minimum. Moreover, with increasingly advanced computational tools and robots in architectural contexts, the perfection and speed of production cannot be rivaled. Yet, these methods are generally non-engaging and do not necessarily require a skilled labor workforce, bringing to question the role of the craftsman in the digital age. This paper was developed with the focus of leveraging human adaptability and tendencies in the design and fabrication process, while using computational tools as a means of support. The presented setup consists of (i) a networked scanning and application of human movements and human on-site positioning, (ii) a lightweight and fast-drying extruded composite material, (iii) a handheld "smart" tool, and (iv) a structurally optimized generative form via an iterative feedback system. By redistributing the roles and interactions of humans and machines, the hybridized method makes use of the inherently intuitive yet imprecise qualities of humans, while maximizing the precision and optimization capabilities afforded by computational tools—thus incorporating what is traditionally seen as "human error" into a dynamically engaging and evolving design and fabrication process. The interdisciplinary approach was realized through the collaboration of structural engineering, architecture, and computer science laboratories.

INTRODUCTION

Where is the human?

The development and proliferation of digital tools in design have increased precision in performance and the fabrication process. Construction sites have become highly networked, necessitating an extreme degree of accuracy, and redefining the role of human involvement.

However, fluctuating environmental conditions often make construction sites unpredictable, requiring on-the-spot decisions—a characteristic that is inherently human. Could human improvisations, though inaccurate, be integrated into the design and construction process with the support of digital technologies?

Human capabilities have been the source of design and fabrication processes of different architectures at various scales; hence the production and assembly of form emerged as a hybrid of human capacity and a symbiotic relationship with materials, tools, and systems.

Currently, predetermined outcomes are secured by the use of standardized premade elements, formworks, and machinery, which also increase efficiency. Similarly, in-house fabrication can control production as a result of a controlled environment, further reducing the margin of error. Yet these methods are not necessarily novel, in that features of contemporary construction methods and techniques often have undetected precedents (Rudofsky 1964). Moreover, while errors can be reduced, the search for increasing precision generally entails breaking away from means of mitigating them (Hughes 2014), bypassing what Pye (1968) refers to as the workman's ability to approximate during an integrated design and fabrication process.

There is a recent growing interest in the relationship between human-driven methods, technological integration, and architectural output. Aesthetically, this could be due to a quality of craft that can be read in an object, something Marble (2010) attributes to the detection of human input, and which is achieved by a mediated relationship between humans and tools. Similarly, according to Hight (2008), these interests are due to an understanding of the human body as a hybrid site of mediation, and thus, the human can be considered in terms of all its capacities and lack thereof.

As interactions among human actors and technical networks are already supported (Carpo 2011), human limitations could otherwise be understood as unused potential, whereby constraints can serve as catalysts for design solutions as every design move creates additional constraints, thus triggering further contextual responses (Killian 2006).

In understanding what is inherent in machines and humans, Obuchi (2015) observes that while robots are highly precise, they are not particularly adaptive and do not integrate changes with ease, whereas humans, though highly adaptive, lack the precision of robots—raising the question of whether tools can be developed with traditional forms of human engagement in mind.

This research speculates that unskilled humans, embedded with some degree of intuition, have the capacity to engage in architectural fabrication via computational support. Three primary technical aspects were addressed and developed to explore this idea, each entailing their own sub-developments:

1) A catalog of human movements: this provided a library from which possible geometric combinations could be sourced. Research explored human movements that came instinctively and were replicable.

2) A material and tool: to materialize human movement, a combination of fast drying foam and porous steel mesh was used with a modified spray gun as a "smart" tool.

3) A feedback system to detect deviations in materialized human movements via a recursive correction process according to structural stability, therefore integrating human imprecision and decision-making.

Tested in the form of a pavilion (Figure 1), this research envisioned that with digital technology, such an approach could see a new form of craftsmanship and motivation reintroduced to on-site fabrication—incorporating the human touch as a design element and tool.

BACKGROUND

The multifaceted nature of the research prompted investigations into different fields of study—examining historical and contemporary methods of fabrication, as well as human-computer interaction, and feedback systems.

Production models based in vernacular tradition indicated that unique constraints result in the development of specific techniques; making use of inherent qualities in human physiology and intuition. At the architectural scale, human physical capabilities can be incorporated as a defining element in the construction process, as seen in the mud hut *tolek* structures produced by the Musgum people in Cameroon, where perceived patterns on the exterior façade are hand formed during construction. While ornamental, these patterns serve primarily as footholds for climbing the structure—resolving the need for conventional scaffolding (May 2010). In craftsmanship, basket weaving is performed as a sequence of repeated movements that are initially taught and guided through instruction, but can over time culminate into a skill—demonstrating the combination of using acquired knowledge and human intuition in smaller scaled production.

The above examples demonstrate how human involvement at physical and mental levels can be integrated into a generative production process. Yet current trends and the advancement of digital fabrication have seen the increasing disappearance of human production-based models in favor of automated computationally driven methods.

Still, many common everyday devices that are designed specifically to be used by humans have been subtly instilled with computation in accordance with human tendencies. For instance, predictive text and auto-correct functions in mobile phones allow users to type in an imprecise manner, but because the system recognizes the sequence of letters it can compute which word is most likely to come next while also correcting misspellings—allowing inaccuracy while maintaining a precise result. This example, though simple, suggests that computation could be used to absorb human imprecision. Could such an approach reposition the human as an integral part of the digital fabrication process?

In an effort to better understand how acquired knowledge can be supported through human-computer interactive processes, precedents in architectural and non-architectural fields were investigated. *Possessed Hands* introduces the acquirement of a skill (such as playing an instrument) through muscle memory by triggering muscle movements with electrical stimulus that are timed with computational precision (Tamaki et al. 2011). *Becoming Knowledge* proposes a new dance as a result of engaging with a "virtual dancer" programmed to grow and evolve in response to simulated mechanical (human) constraints and to a database of film material (Leach 2015). These studies helped provide an understanding of skill development through the engagement of bodily movements and improvisation.

In digital fabrication-based design, different research has been developed around integrating specific human tendencies. A real-time feedback system was developed in *Pteromys* for the design and fabrication of paper planes—allowing users to draw them free-hand, while also visualizing optimal solutions for aerodynamic performance through minor variations (Umetani et al. 2014). *FreeD* combined a handheld tool with a three-dimensional guidance system, permitting complex carving tasks to be executed by unskilled makers, which are tracked and controlled with reference to a virtual 3D model (Zoran et al. 2013). Motion tracking allowed a more bodily-driven design process, which was used in *Sketch Furniture* to materialize three-dimensional air-drawn furniture scale sketches into objects through rapid prototyping (Lagerkvist et al. 2005). At the tabletop scale, the *3Doodler* materialized three-dimensional drawings in real-time with a plastic extruding pen (Bogue et al. 2012). Most recently, *Making Gestures* imbued fabrication machines with behavior using artificial intelligence, creating a real-time relationship between body gestures and the control of machine movement (Pinochet et al. 2015).

Lastly, *STIK Pavilion* (Yoshida et al. 2014) was examined as an instance of human integration as part of architectural production. Used as mobile 3D printers, humans guided by a projection system used handheld tools to deposit material over target areas, using their physical capabilities as a substitute for an otherwise unfeasible large-scale onsite 3D printer. A scanning and feedback system was used to compare and match the built form as closely to the original target as possible—marking a distinction between human error-correcting (as used in the aforementioned research) and human error-integrating (as speculated in this research).

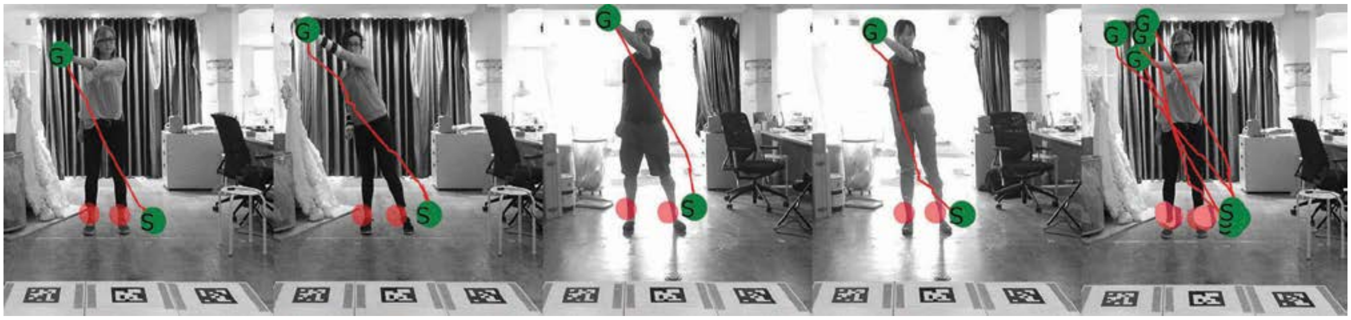
The above models demonstrate the potentials and shortcomings in human-machine hybridized fabrication. By incorporating the different parts mentioned (feedback system, handheld tool, guidance, and human movements) into an entire coherent system, the present research seeks to evolve the dialogue between human patterns, machine learning, and communication in on-site three-dimensional fabrication.

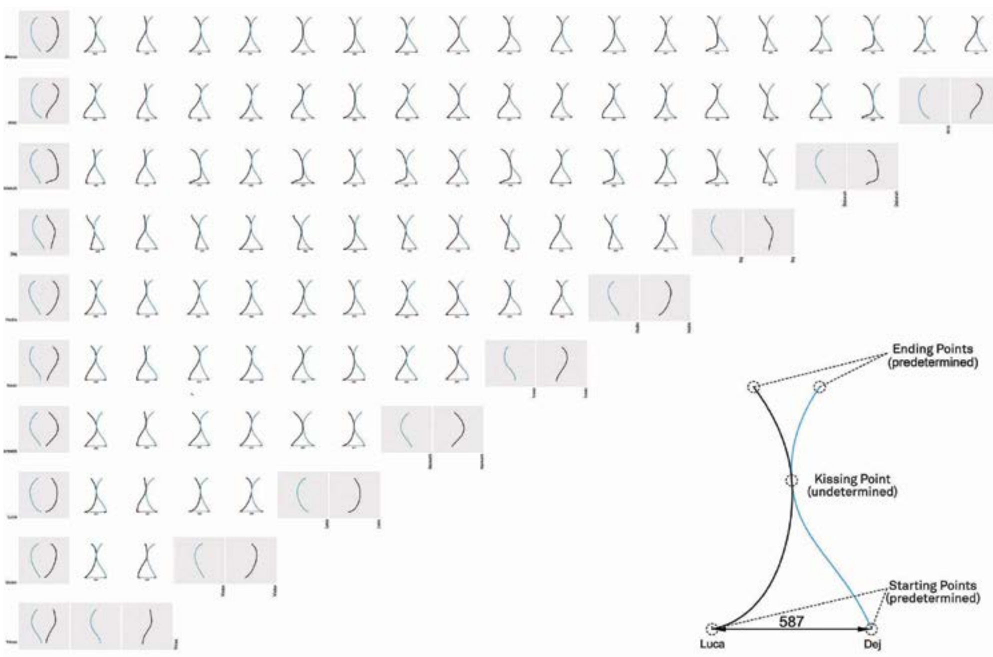
METHODS

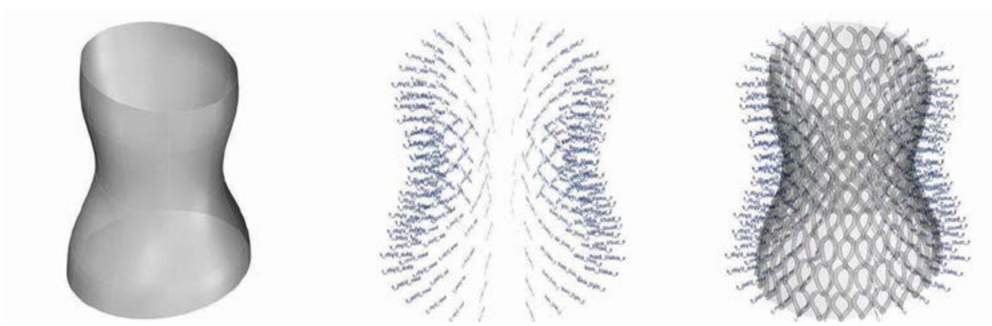
To examine how human capabilities and computational precision might be combined in an on-site fabrication process, the devised system sought to integrate: 1) human movement, based on inherent human tendencies, 2) an appropriate material able to materialize those tendencies, 3) a tool that would ergonomically deploy the material, and 4) a feedback system that could embrace the difference between target form and actual form.

Human Movements

As the human body can be understood as being composed of fixed and rotational joints, a person drawing a line from the ground up with their arm fully extended tends to result in arc-like motions. These movements were analyzed through two parameters that are contingent on the person producing the movement: 1) the arc's radius and length, which is derived from arm length, and 2) the type of movement, which was determined by each person's starting and ending points relative to their body's disposition. Five different and intuitively replicable movements, which created five different arcs, were tested by four people, scanned three-dimensionally using ARToolKit (Kato 1999) visual markers, and transferred to Rhinoceros. It was observed that the same person repeating the same movement resulted in







2 Scanned movements ("S" indicates start, and "G" indicates goal). Different people producing the same movement; diagonal left-to-right.

3 Catalog of movements of the ten people scanned and paired (left). Detail of paired movements, showing starting points, ending points, and kissing points (right).

4 Original target geometry (left). Division and distribution of paired human movements in relation to target geometry (middle). Paired human movements best matched to target geometry (right).

minor but noticeable deviations. Furthermore, the same movement produced by different people demonstrated a variation in tendencies, similar to differences in writing. For instance, asked to repeat a diagonal movement from left to right, some demonstrated a dipping tendency, while others demonstrated a bulging tendency (Figure 2).

Catalog of Movements

Two kinds of movements, 1) a right-bending arc and 2) a left-bending arc, were selected for application in the research. Ten people were scanned producing the two movements, and the resulting arcs were then paired to produce the catalog (Figure 3). The two paired arcs met somewhere tangentially between the two people—this point came to be referred to as the *kissing point*.

Using Rhinoceros and Grasshopper, the archived curves are used to pair one person's left arc with another person's right arc. The target geometry is divided into the number of paired movements that best completes it, whereafter the paired movements are then selected according to those that most closely match it (Figure 4).

Material

To materialize these human movements, a light and fast drying material is required. The selected material for research was a combination of 1) a common spray polyurethane foam (SPF) composed of equal parts polyol blend and polymeric methylene diphenyl diisocyanate, and 2) a flexible and porous woven stainless steel mesh tube 70 mm in diameter with 2 mm spacing, and 0.1 mm thickness. The steel mesh served as reinforcement and physical guide for the foam. The foam's quasi-unpredictable expansion maintained the concept and the practice of human imprecision (Figure 5, 6, 7).

To determine the most appropriate SPF for use, the material was compared structurally against soy-based SPF and water-based SPF in controlled conditions, revealing that the tack-free time of all three foams was 30 seconds, the time to completely solidify was 3 minutes, and the expansion ratio once the foam completely dried was 300%. Compression and bending tests suggested that common SPF was the most suitable for construction because of its superior structural capacity. However, the material is commonly used as insulation for buildings and is significantly weaker than traditional architectural materials, having a Young's modulus of 1.9 MPa (19.40 kgf/cm², equivalent to a 1.16 cm square section of cedar).

In order to find the most suitable reinforcement option, three aspects of several materials were evaluated: foam adhesion, structural strength, and ease of manipulation. Mesh fabrics of various materials and porosities were tested on two, three, and four sides of sprayed foam (Figure 8).

The results of these tests, however, were deemed structurally ineffective, while they also limited possible angles in movement as foam tended to droop and fall from the open edges. Ultimately, a custom-ordered woven stainless steel mesh in tube form performed the best, increasing the Young's modulus to 12.8 MPa (131 kgf/cm²) (Figure 9) and allowing unrestricted movement. To secure structural stability and facilitate calculations, the radius of each element was fixed at 8.5 cm.

Once foam components are sprayed, they require a method of being connected and assembled. In this research, horizontal components were connected at the aforementioned *kissing point* and at vertical connections with H-shaped joints consisting of two 300 mm U-shaped aluminum profiles. A base jig and a tripod jig were used to hold the joints in place at the starting and

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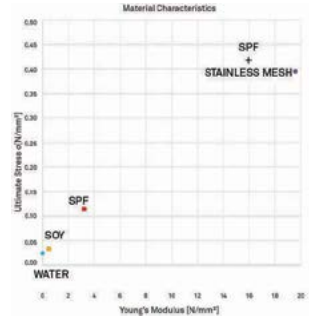

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5 Common SPF foam.

6 Woven metal mesh.

7 Sprayed component with combined materials.

8 Material tests. A stress test and bending test indicated SPF is much stronger than water-based and soy-based foam.

9 The material's Young's modulus increased significantly when sprayed inside a stainless steel mesh.

10 Tripod jig.

11 "H" joint.

12 Base jig.

13 Early kissing point test.

ending points of each component (Figure 10, 11, 12) (explained further in Handheld smart tool).

The jigs were also used as part of the overall construction method of the project case study; once a completed layer of components had been sprayed in a ring formation, each layer could be lifted and held in place with the tripods. After locating the new base jig positions, workers could then spray the next connecting layer. This process eliminated the need for scaffolding and allowed workers to perform all tasks at ground level.

Handheld Smart Tool

To deploy the material as an extrusion made from human movement (Figure 13, 14), a handheld “smart” tool was developed around five key design criteria: 1) augmentation of standard spray gun, 2) secured injection of SPF inside of mesh tube for guided expansion, 3) minimal size and weight to facilitate use by pairs of humans, 4) controlled amount of foam sprayed, and 5) guided movement speed to achieve consistent radii in sprayed elements (Figure 15).

Once the trigger is pulled, the foam begins filling the stainless steel mesh. The speed of human movement is guided with a beeping device connected to a rotary encoder and an Arduino, which sounded only when the movement was in excess of the ideal 7 cm/s. The advantage of using an audible device is that workers can remain visually engaged while intuitively adjusting their speed (Figure 16).

In previous prototypes (Figure 17), a stepping motor was used to deploy the mesh, which controlled the human’s speed. However, in the interest of pursuing adaptation to human inaccuracy, a system that distinguishes itself by guiding, rather than controlling, was preferred.

Feedback Loop

To integrate human imprecision as a part of the design process, a feedback loop was developed between five intercommunicative aspects: 1) target, 2) guidance, 3) scanning, 4) structural re-calibration, and 5) structural validation (Figure 18). The loop connected humans on site, material, and construction. The creation of the feedback loop was facilitated by collaboration between three fields of study; structure, architecture, and computer science (described further in the following section).

Target Geometry

A target geometry is defined as a model for production. Due to the effects of wind on such a light material, the target geometry is modified using Kangaroo simulation software in order to reduce the maximum amount of deformation, thereby reducing


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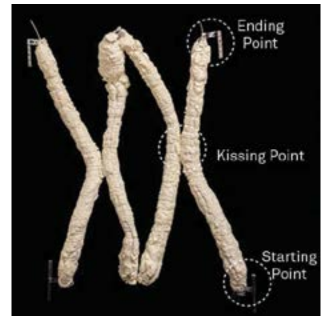

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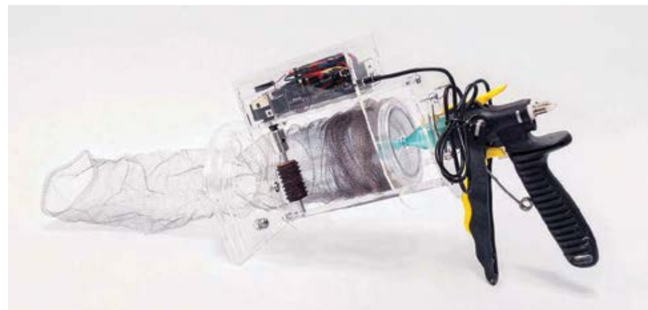
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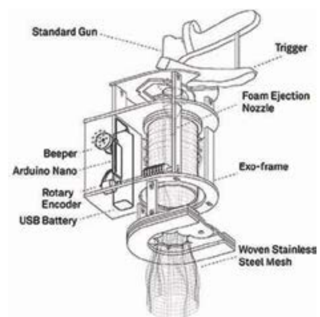

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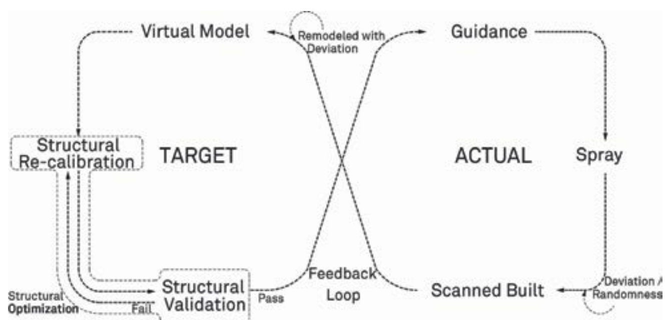

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14 Two components sprayed and joined at kissing points and starting and ending point joints (right).

15 Handheld smart tool: Final prototype.

16 Handheld smart tool diagram.

17 Smart tool prototype evolution: different sized exo-frames, two-sided and three-sided mesh, passive and automated mesh deployment.

18 Feedback loop diagram.

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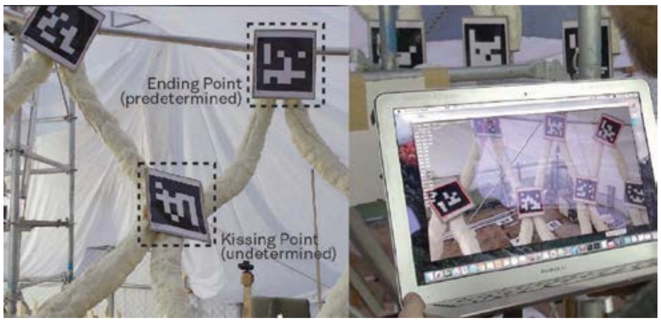

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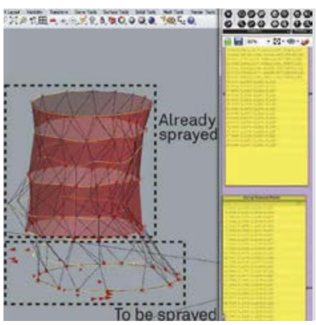

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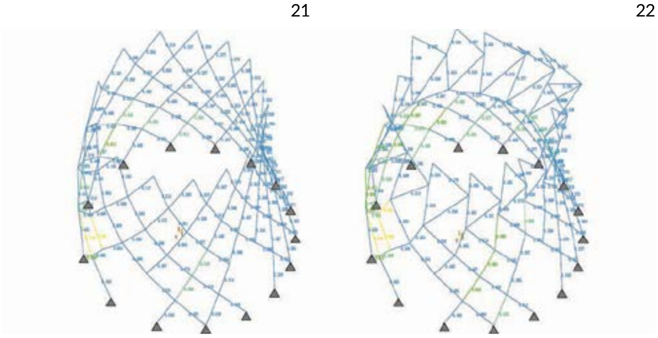

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19 (Left) Guidance system setup: base jig location (top right), and tripod jig location (bottom right). (Right) Display setup and view on screen.

20 (Left) AR markers placed on joint/vertex locations. (Right) Red outlines on screen around AR markers indicate successful detection.

21 Actually sprayed layers (indicated in red) are used to update the target model by replacing the previously modeled vertices with newly scanned ones, while the bottom layer is ready to be re-calibrated.

22 Genetic algorithm for structural re-calibration. Blue labels on the points indicate materialized and scanned layers. Unlabeled points indicate newly calculated points of proceeding layers.

23 Structural validation comparison between original target geometry.

risks of structural failure and avoiding the need for additional foreign supports.

Guidance

To indicate on site where each person's movement must be performed in order to achieve the target lattice geometry, an augmented reality (AR) guidance system shows the starting and ending points of each movement. Initially, it was tested by displaying the exact arc to be produced in its entirety. However, providing only the minimum amount of information required—starting and ending points—allows the workers to move freely between those two points.

ARToolKit was selected as the guidance system because of its user-friendliness and minimal setup of AR codes, web cam, and monitor. The AR codes are placed in a grid on the ground, and the camera must detect a minimum of three for accurate positioning. This facilitates visualization on the monitor of 1) starting point, indicated by the rectangular footprint of the base jig, and 2) ending point, indicated by three circles defining the tripod's legs (Figure 19). The flexibility in the minimal guidance method allowed for in-situ fabrication decisions, facilitating the intuitive aspect and making deviation from the target geometry expected.

Scanning

Upon completing a layer, a scanning system is used to compare the target model with the actual sprayed geometry. Scanning was done at the two types of vertices: (i) controlled vertices, which are the starting and ending points of the movements, and (ii) uncontrolled vertices, which are the varying middle (kissing) points where two different humans' movements meet. Using ground markers as reference points, the vertices of newly sprayed members can be digitally located in three-dimensional space, and used to update the original model (Figure 20, 21).

Structural Re-calibration

Once the sprayed geometry is scanned, a newly optimized target geometry that absorbs materialized deviations is calculated via Karamba and Galapagos (plug-ins for Grasshopper) with a genetic algorithm (GA), minimizing the maximum deformation of the whole structure (Figure 22). The GA works by moving the vertices of the layer to be built horizontally along a circular path contained in the target geometry—negotiating the tolerance of human imprecision with respect to structural integrity.

Structural Validation

A structural analysis (Figure 23) of the optimized model is performed in Hogan (Sato 1993), which uses load, cross-section, and boundary conditions as input parameters, in addition to calculating Young's modulus and yield point as material properties. If the newly optimized model does not pass the structural validation, it returns to the re-calibration stage, where a new solution is generated and tested again. This step is repeated until the validation is passed.

The feedback loop described in this section is repeated throughout the entire construction, producing a different possible outcome with each added layer and optimization (Figure 24).

CASE STUDY

To validate the hypothesis of an adaptable, hybridized human-machine on-site fabrication system, a pavilion was designed and constructed using the methods described in Section 3.

Design Overview

Five towers were bundled together to create the overall geometry. Each tower varied from 2.3 to 3.0 m in diameter and ranged in height from 2.4 to 4.2 m. The towers were translated into a lattice and divided vertically into 1.2 m layers, each with 15 horizontal divisions—the dimensions of which were decided in relation to human spraying heights and spacing, as well as structural integrity.

Site and Construction Prep

The use of AR codes as the guidance method necessitated a perfectly flat surface, so a platform was constructed. 121 AR codes were placed in a grid of 11 by 11 with 950 mm spacing.

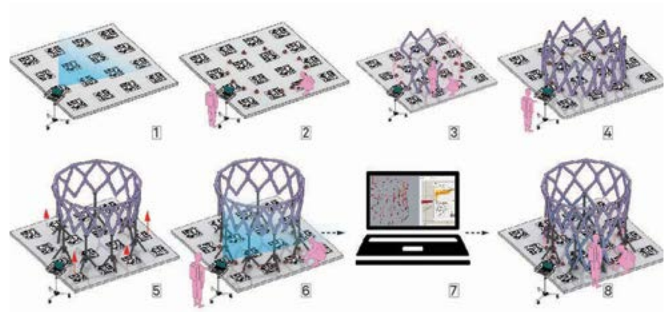
A laptop PC with Intel 1.86 GHz core 2 Duo CPU and 2 GB memory for the computer monitor and a Logicool HD Pro Webcam C920r were mounted on a small trolley to facilitate on-site relocation of the scanning and guidance system.

On-site Construction Flow

Five people were needed on site for production: two sprayers, responsible for spraying components; one person responsible for ensuring a successful “kiss”; and two supporters, to maintain a smooth process.

The two sprayers, at their respective starting points and aware of their ending points, inferred a general area where the kissing would take place. Sprayers counted down from 3 together and created their arcs, communicating and adjusting as necessary. The two supporters aided the process in the event of a malfunction, and the fifth person ensured the appropriate amount of contact area at kissing points by applying pressure to both sides until the foam elements sufficiently bonded together (Figure 25).

When a full ring of lattice components was completed, the layer was lifted to a 1.2 m height (requiring eight people), and held in



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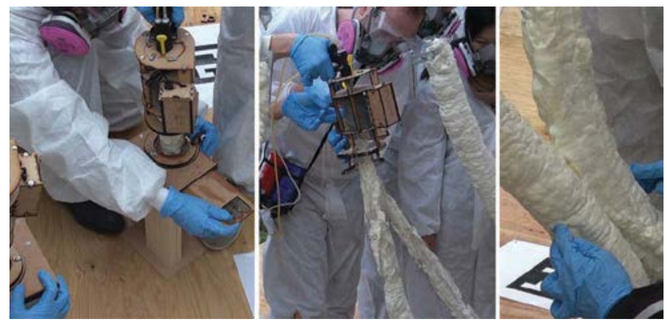

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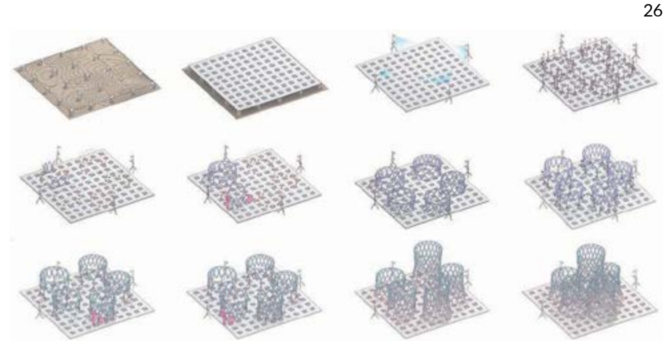

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24 Feedback loop workflow: 1) scanning of AR codes on the ground, 2) guided placement of jigs, 3) spraying of members, 4) completion of layer, 5) lifting of layer, 6) scanning of layer, 7) GA structural re-calibration and structural validation of subsequent layer, 8) the process is repeated for all layers.

25 On-site paired spraying (from left to right): respective starting points, meeting in the middle, parting to ending points, ensuring kissing point.

26 Lifting of sprayed layers of two towers (background), and completed single layer (foreground).

27 Construction overview diagram.

place with tripod-jigs. The initial starting points of the first layer became the ending points of the subsequent layer (Figure 26).

Next, the geometry was scanned, revealing deviations between the target and the actual sprayed geometry. After updating the virtual model by replacing the original vertices with the newly scanned ones, the GA then created a new target, which was tested for structural validity. After passing structural validation, the base and tripod jigs (start and end points) were positioned on site according to the newly generated model, followed by the spraying process—this was repeated for each new layer until all the towers were formed (Figure 27) When all five towers were complete, the AR system was used to determine each of their originally intended final locations. Each tower was manually lifted, relocated to its target position, and screwed to the platform at the base joints.

Three different possible final geometries had been generated from the start of the construction to its completion (Figure 28).

RESULTS AND DISCUSSION

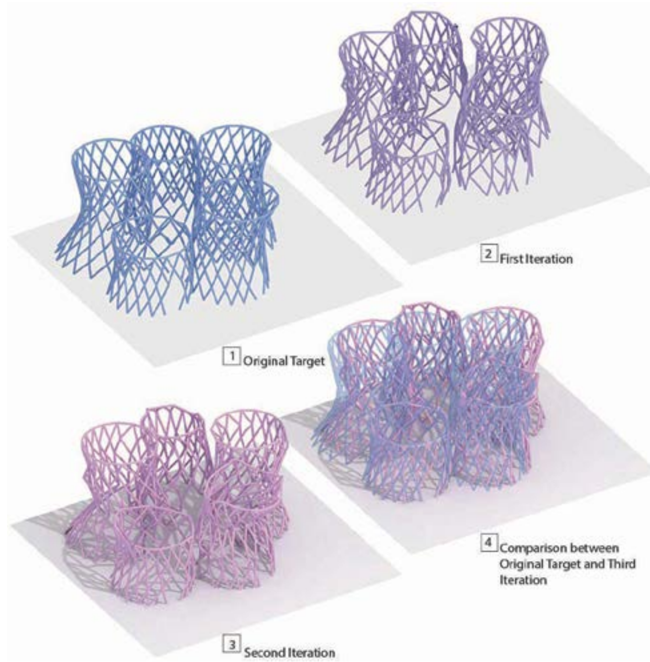
The proposed hypothesis made two assumptions—the first was that human intuition and tendencies could become a generative part of architectural fabrication, and the second was that the integration of humans in an on-site fabrication process would inevitably produce “errors,” which with the support of computational tools, could become essential parts of the design and fabrication process.

Evolving Outcomes

A comparison of the original target geometry and the final built geometry shows there is a difference between a precisely computed geometry and a human made one, but structurally speaking, they are both viable (Figure 29). This demonstrated that flexible, human-based production could embrace unpredictability, and improvisation could become a part of the global design agenda.

A Glitch in Tower 2

The first layer sprayed was that of Tower 2. An error in the AR code caused a significant deviation from where the ending points were intended to be and where the guidance system was actually indicating them to be. This was only discovered once the layer had been sprayed, scanned, and compared against the original target. However, because the overall system was designed around the intention of incorporating and resolving similar types of error throughout the entire process, the layer was preserved and used as part of the final outcome (Figure 30).



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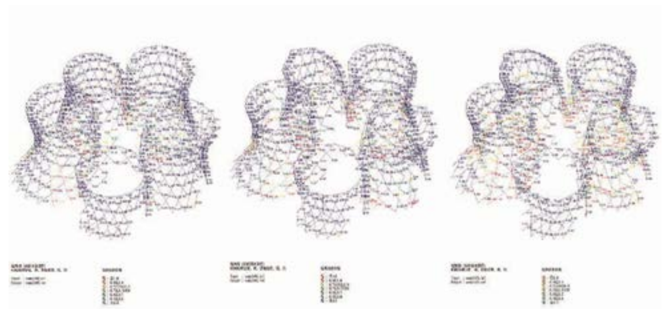

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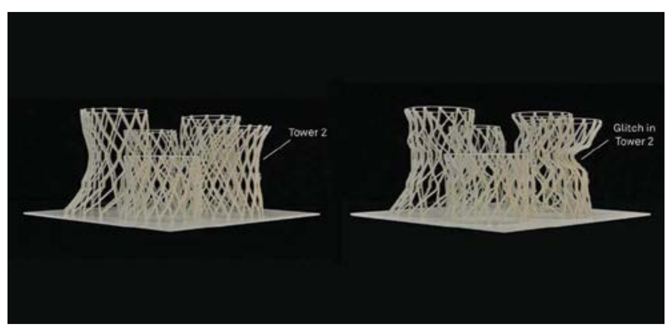

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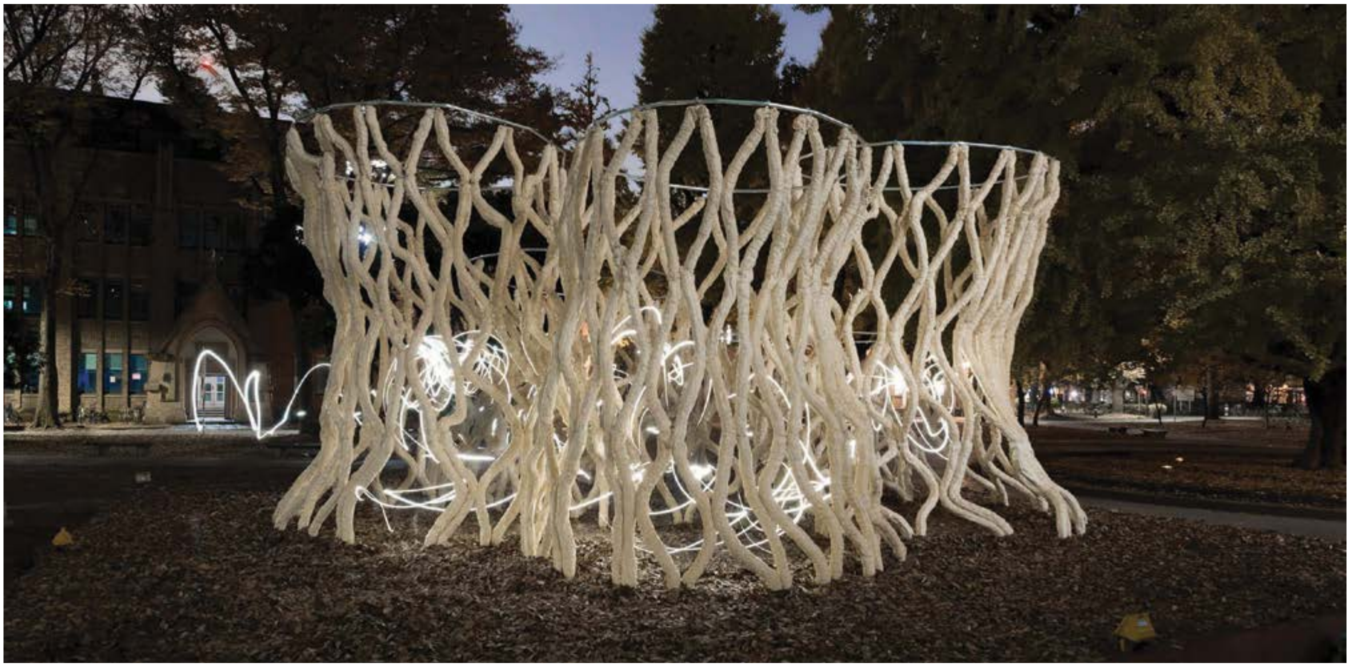
28 Evolution from original target geometry to actual sprayed.

29 Structural comparison (from left to right) original target, first iteration, third iteration. A color range from purple (stable) to red (unstable) indicates safety level.

30 3D printed models of original target geometry (left) and sprayed geometry (right).

31 Final pavilion.



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Catalog of Movements, Material Constraints and System Support

Although originally the catalog of movements was created to design the initial target geometry and to organize workers on site, the system's ability to register and incorporate variation proved effective, rendering the catalog obsolete for the specific pairing of sprayers at specific locations on site.

This was furthered by the material's drying time, which was not fast enough to instantaneously materialize an individual person's movements and tendencies, creating an inevitable difference between the movements performed during the spraying process and the actual solidified component.

Ultimately, this constraint highlighted the flexibility in the system, allowing any two people available on site to spray within the designated starting and ending points, which were provided and supported by the system.

CONCLUSION

The case study required a target final form prior to construction, however, future research could seek to forgo this step in favor of a more streamlined bottom-up process, using the GA and real-time feedback to produce solutions based on more local rules. Additionally, with a faster drying material, the catalog of movements (which was a closed and static source) could be substituted with a dynamic movement/pattern tracking and recognition algorithm, which could allow for emergent combinations and outcomes. Holistically, the implementation of 1) real-time movement scanning, 2) machine learning, and 3) real-time feedback and guidance, would further the potential for an intuitive and non-deterministic approach to design and fabrication in an adaptive hybridized system—creating a multi-directional flow of information via a human-machine dialogue.

Moreover, many on-the-spot decisions were made during construction as a result of unforeseeable circumstances, demonstrating the accomplishments of the system. This was especially true for instances that could not have been premeditated prior to construction, such as 1) material malfunctions during spraying, which meant quickly swapping out defective cans of SPF with new ones, or 2) a mesh being cut too short, and thus being unable to reach the end-point, which necessitated the manual and timely repositioning of base and tripod jigs.

Construction also demonstrated that the feedback system successfully incorporated error, which yielded unexpected results while maintaining structural stability (Figure 31, 32, 33). Furthermore, despite the gap between drying time and human movement, the registration of variation in the final outcome produced a quality in tune with that of craftsmanship.

The human movement and materialization used in this research were the individual's arc and spray foam. However, the system as a methodological framework (Figure 18) is open ended, and could incorporate a number of other movements and materials in order to achieve a variation of outcomes in terms of process, form and function, demonstrating a potential in hybridized human-machine methods for the integration of humans in different kinds of on-site fabrication.

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IMAGE CREDITS

Figures 1, 31: (Vranovský, 2015)
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