Robotic Softness

An Adaptive Robotic Fabrication Process for Woven Structures

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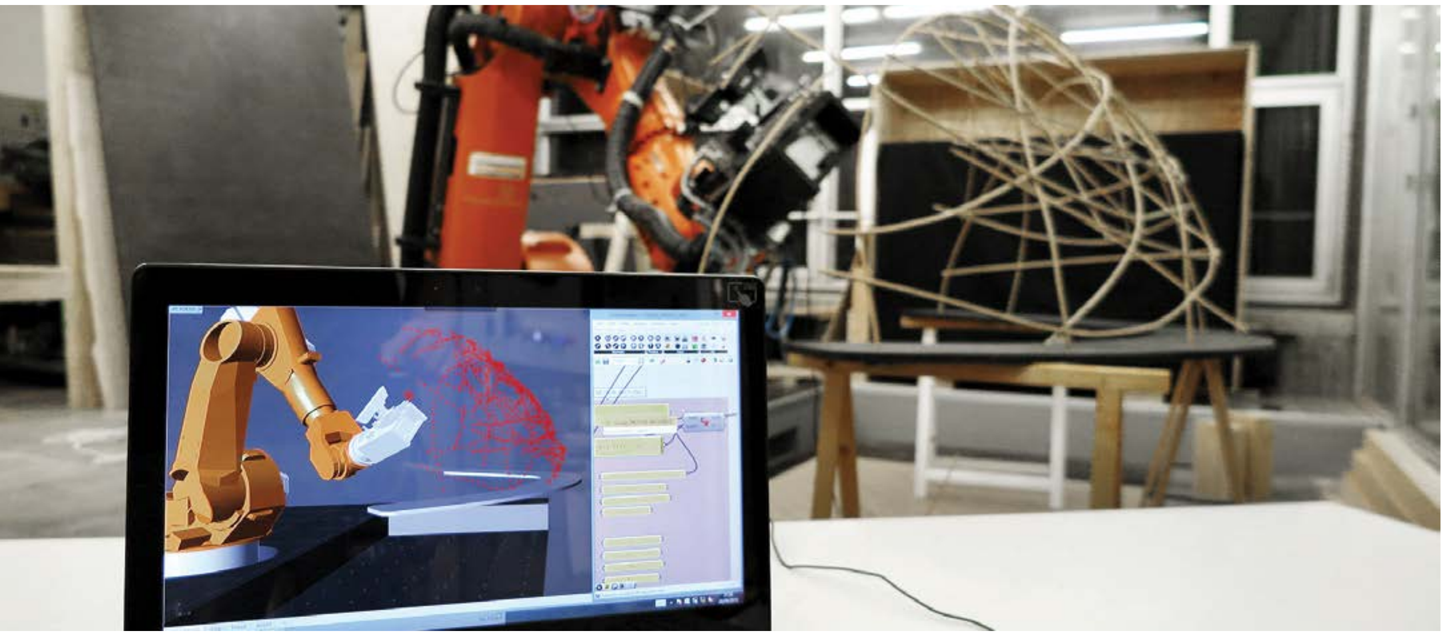

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ABSTRACT

This paper investigates the potential of behavioral construction strategies for architectural production through the design and robotic fabrication of three-dimensional woven structures inspired by the behavioral fabrication logic used by the weaverbird during the construction of its nest. Initial research development led to the design of an adaptive robotic fabrication framework composed of an online agent-based system, a custom weaving end-effector and a coordinated sensing strategy utilizing 3D scanning.

The outcome of the behavioral weaving process could not be predetermined a priori in a digital model, but rather emerged out of the negotiation among design intentions, fabrication constraints, performance criteria, material behaviors and specific site conditions. The key components of the system and their role in the fabrication process are presented both theoretically and technically, while the project serves as a case study of a robotic production method envisioned as a soft system: a flexible and adaptable framework in which the moment of design unfolds simultaneously with fabrication, informed by a constant flow of sensory information.

1 The robotic soft system unfolds simultaneously in the physical and digital realms through a real-time updating interface.

2 Southern Masked Weaver (*Ploceus Velatus*) (Photo by Chris Eason, 2008. Distributed under the Creative Commons Attribution 2.0 Generic license).

INTRODUCTION

Current methods for architectural production are based on notational and geometrical representation, where only what can be drawn and measured can be built (Carpo 2011). Moreover, these methods are usually organized in a linear progression from design intention to materialization, which impedes any feedback among the different stages of the realization of a project. This hinders the design and realization of systems which require a more explorative approach based on a constant exchange of information between the stages of design and fabrication (Sharif and Gentry 2015). In order to move beyond a linear design and realization process, this paper proposes the use of robotic fabrication processes for architectural production not as mere standard fabrication environment, but as a soft system, according to the definition given by S. Kwinter:

> "A system is 'soft' when is flexible, adaptable, and evolving, when it's complex and maintained by a dense network of active information or feedback loops, or, put in a more general way, when a system is able to sustain a certain quotient of sensitive, quasi-random flow" (Kwinter 1992).

Within this understanding, the resulting object is not a separate entity from the process that produces it: the whole workflow is envisioned as an integrated system that adapts and evolves according to design intentions, fabrication constraints, performance criteria, material behaviors and specific site conditions.

In this regard, the habitats built by animals are a great source of inspiration for fabrication processes. Rather than following a predefined blueprint, their strategies are based on a set of building behaviors triggered by external and internal stimuli, medium-low level assumptions and a constant sensing of the environment (Gould 2007), which altogether create an evolving feedback-based system for construction. In order to investigate these concepts in an actual fabrication case study, the research focused on the design and robotic production of three-dimensional woven structures inspired by the behavioral fabrication logic used by the weaverbirds (Ploceidae) (Figure 2) during the construction of their nests (Collias and Collias 1962).

CONTEXT

Behavior-based robotic strategies, within which this project finds precedence, affirm the importance of observation and sensing procedures in contrast to symbolic representation (Brooks 1990). Pure reactive systems are exclusively based on sensory information with no internal representation of the world, yet they are able to generate even complex behavioral responses responding to a set of stimuli or conditions (Matarić 2007). Furthermore, the importance of biological role models for this field of research was

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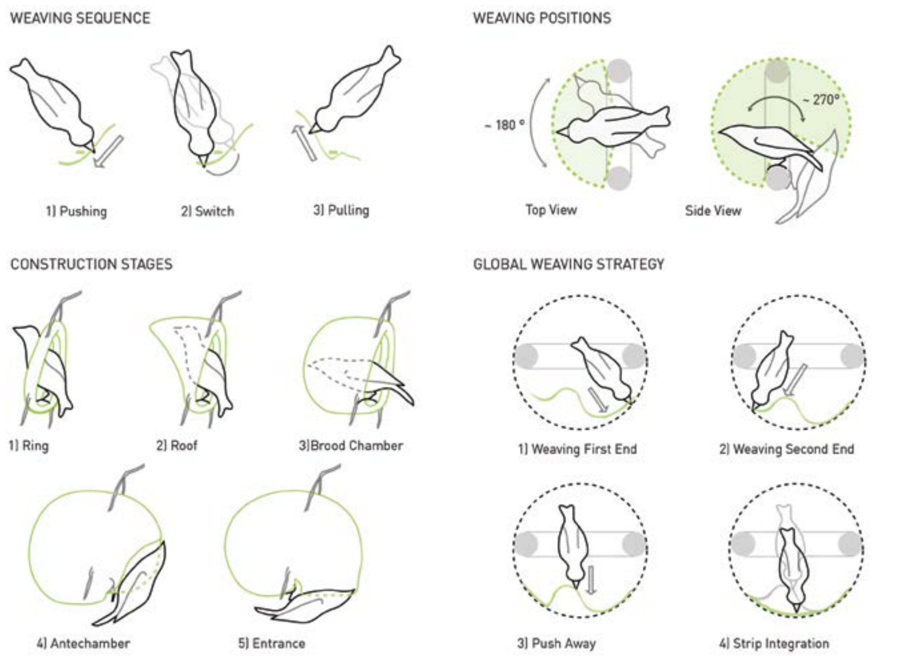
identified by R. C. Arkin, "the study of behavior-based robotics should begin with an overview of biological behavior" (1998).

In recent years, a series of pioneering projects introduced robotic fabrication procedures based on sensor-actuator feedback loops into the field of robotic architectural production. In 2012, K. Dorfler and R. Rust, with the project "Interlacing," presented a digital interface equipped with a network of sensors that allowed on-line control of the robot (Dorfler and Rust 2012). In 2014, R. L. Johns presented the project "Augmented Materiality," in which real-time updating fabrication tools dealt with unpredictability of the material system (melted wax) which had not previously been possible to simulate accurately (Johns 2014).

More recently, A. Menges introduced the concept of cyber-physical making in architecture, defined as construction processes which intensively link the realm of physical production with the virtual domain of computation. Within this context, behavior-based construction is based on "real-time physical sensing and computational analysis, material monitoring, machine learning and continual (re)construction" (Menges 2015), instead of relying on explicit instructions and predictive modelling. One of the first practical applications of these concept in the architecture field is represented by the "ICD/ITKE Research Pavilion 2014–2015," where an adaptive robotic fabrication process was devised to construct a composite compression shell with a pneumatic formwork monitored in real-time during the construction. (Vasey et al. 2015).

Within the project "TailorCrete," the University of Southern



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3 The principles abstracted from the the analysis of the weaverbird's construction behavior were used to inform the robotic fabrication process. The main reference for the diagrams are the studies by Nicholas and Elsie Collias (1962).

4 An adaptive robotic fabrication process for woven structures inspired by the behavioral fabrication logic used by the weaverbird during the construction of its nest.

5 Rattan was chosen as suitable weaving material for its flexibility, bending behavior and variable length.

6 Rattan's flexibility was determined through material tests which involved fixing the two ends of a stick at different distances in order to compute the range of possible bend radii. In this image, for a stick diameter of 8 mm, the bend radius goes from 215 to 20 cm.

Denmark presented an offline robotic fabrication process to model unique concrete reinforcement structures made out of bent metal bars, creating double-curved three-dimensional meshes (Cortsen et al. 2014). However, in this case, the bars were not woven together in an active-bending structure, but were plastically deformed and kept in place by metal wire knots. Although the structure and the robotic actuation were predefined before the fabrication process, the project results are relevant because of the integrated use of sensor feedback: laser positioning was used to enable adjustments to tolerances between horizontal and vertical rebars.

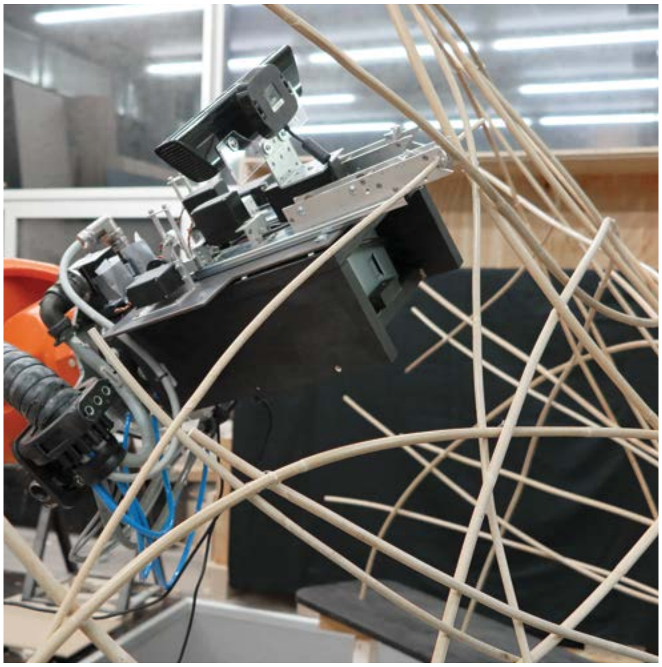
BIOLOGICAL ROLE MODEL

The analysis of the biological role model determined a catalogue of relevant abstracted principles that informed the robotic soft system both locally and globally (Figure 3). On the local level, the sequence of how the bird holds the grass strip and then weaves it into the woven mesh inspired the design of the robotic end-effector and the local weaving logic of actions. Globally, the different weaving positions and the sequence of construction stages, together with responsiveness to the environment and boundary conditions, influenced the overall global robotic behavior. Studying the construction principles utilized by the bird to construct the nest and their variation throughout the process (e.g. the varying density of the woven mesh to filter light and protect the interior) played a key role in informing the robotic actuation with performance criteria that are constantly evaluated and gradually determine the unfolding of the weaving procedure.

SYSTEM DEVELOPMENT

Following the analysis of the biological role model, the key features of the weaverbird's building behavior were abstracted and applied within a robotic fabrication environment for the production of three-dimensional woven structures (Figure 4). The properties and shape of these architectures keep evolving as the process gradually unfolds; one stick is added after another, thus creating a stable active-bending morphology after each step. The studies of the weaverbird's construction process revealed the importance of finding a suitable material for weaving, especially considering flexibility, bending behavior and variable length. Rattan, widely used for furniture and basket production, proved to be a good choice in regard to these parameters. The material derives from a family of palms named Calamoideae, mostly harvested in South-East Asia, with long and slender stems that grow like a vine over other local vegetation. Compared to bamboo, rattan has a full circular section and it is much more flexible (Figure 5). Its bendability depends significantly on its diameter (Figure 6), which ranges from a few millimeters up to approximately several centimeters (Johnson and Sunderland 2004). The diameter used for this project ranges from 5 to 12 mm and was determined empirically according to the size of the robotic fabrication prototypes and tools.

The mechanism implemented in the weaving robotic end-effector is derived from the weaverbird's behavior, though the dual actuation deviates from the weaverbird's single articulated beak. Threading in and out is achieved by pushing the fiber or stick into the woven system, releasing it and catching it in on the



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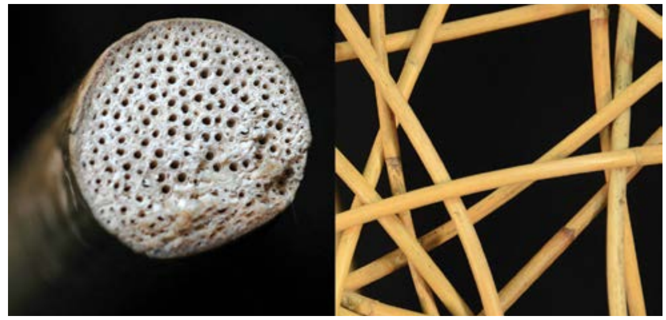

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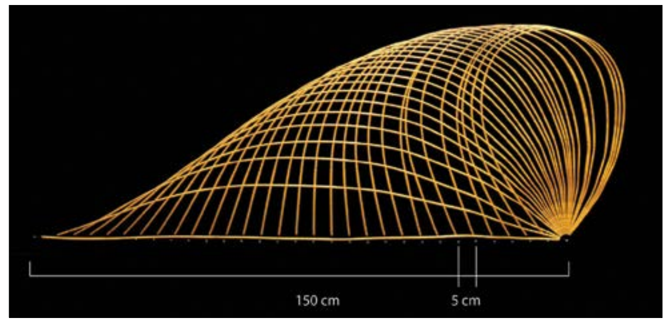

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other side. and then pulling it away toward the intended weaving direction. During the weaving process, the rattan stick is bent and passed through the woven mesh, deforming and shaping the ongoing flexible structure. At the end of each weaving sequence, the stick assumes a position impossible to simulate precisely beforehand because of the complex interaction of forces.

To deal with the system tolerances, the main strategy has been to establish a tight loop of sensor-actuator feedback, where information extracted directly from the real woven mesh was processed and utilized within the soft system to drive the robotic actuation. The designers maintain some control over the system and can observe and inform the evolution of the woven structure through a set of computational tools which compile sensor data and visualize in real-time the robotic movements and effector actuation. In this way, the project created a direct link between the digital and physical, and established a feedback system that informed the computational system with sensor data from the real world.

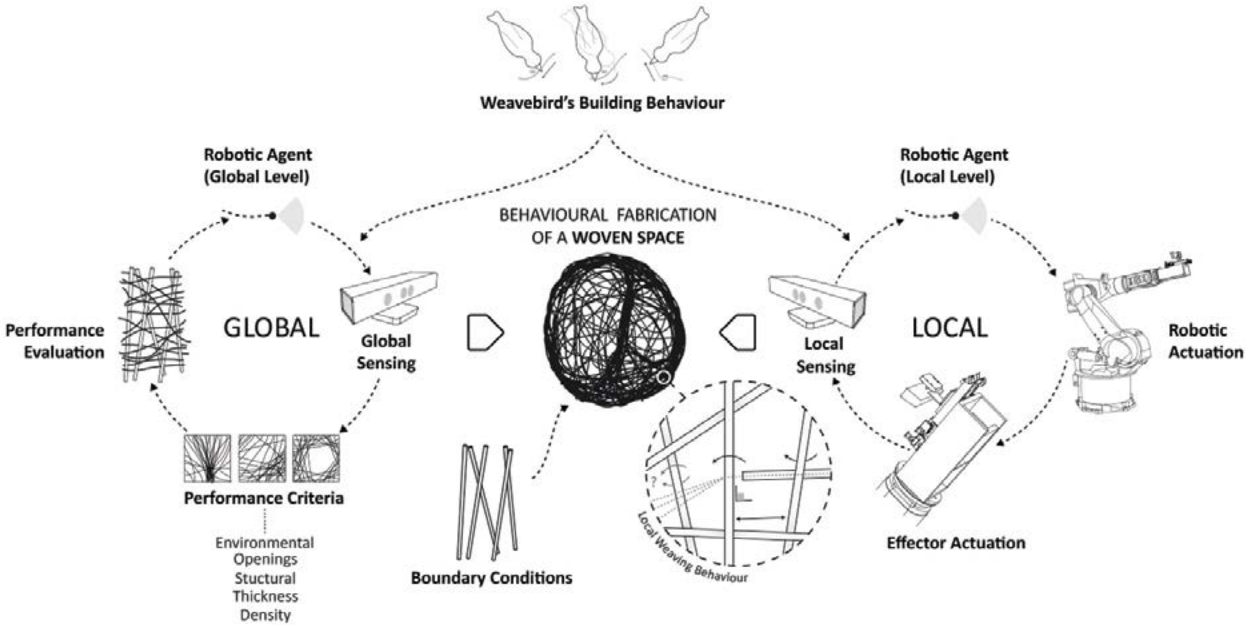
The research developed through a series of small-scale experiments and prototypes, and culminated in a final prototype as a partition of a larger woven structure. The main construction concept for this prototype, derived significantly from the weaverbird's construction logic, was to start from an initial stable core of boundary conditions generated by the robot, then extend beyond them by using a loose hierarchical structure that evolved as each member would rely reciprocally on its adjacent neighbors to stand.

BEHAVIORAL ROBOTIC FABRICATION

While many standard fabrication processes are organized as a linear progression from design intention to materialization, behavior-based fabrication strategies depend on constantly updating sensor-actuator feedback loops.

At the core of the soft system is an Agent-Based System (ABS), where robots become "autonomous-decision making entities called agent" able to assess the environment where they operate, in this case the woven structure as reconstructed through sensor data, and make decisions according to a set of predefined rules (Bonabeau 2002).

For this research, the architecture of the soft system is composed of two integrated loops operating at two different scales, one acting locally (1) and the other globally (2), constantly exchanging information (Figure 7). The local loop (1) deals with the direct manipulation of the material with the weaving robotic end-effector and its coordination with local robot movement. The sensor data is gathered at this level with a depth camera (Microsoft Kinect 360) and is only related to a small portion (about 50 x 50 cm) of the woven mesh ahead of the effector's weaving direction. The global loop (2) utilizes scanning to process the density of the current overall woven structure, iteratively comparing it to the initial intended densities. which act as loose guidelines for the development of the overall system. Thus in each iteration, the global ABS utilizes a behavior-based process to decide where to begin the weaving sequence for the next piece or rattan.



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Because behavioral fabrication processes significantly rely on real-time data streams between all the components of the loop, it was very important to implement network communication that would allow computation and motion planning to happen smoothly and efficiently. Building upon online control methods which had been developed previously at the Institute for Computational Design, a system of communication was utilized including three main components: the "Client," where the Agent-Based System (ABS) is running in real-time within an interface designed in Rhinoceros3D and Grasshopper/RhinoPython, the "Server," responsible for maintaining the consistent pace of information exchanged, and finally, the "Robotic Controller," which controls the actuation of a standard 6-axis industrial robot, a KUKA KR 125/2.

The overall coordination of the system was made possible using the KUKA RSI module (Robotic Sensor Interface), which allows the exchange of XML packages over Ethernet. This allowed the client and design environment to receive information regarding the actual position and orientation of the robotic Tool Center Point (TCP) and send back the next target frame calculated by the ABS.

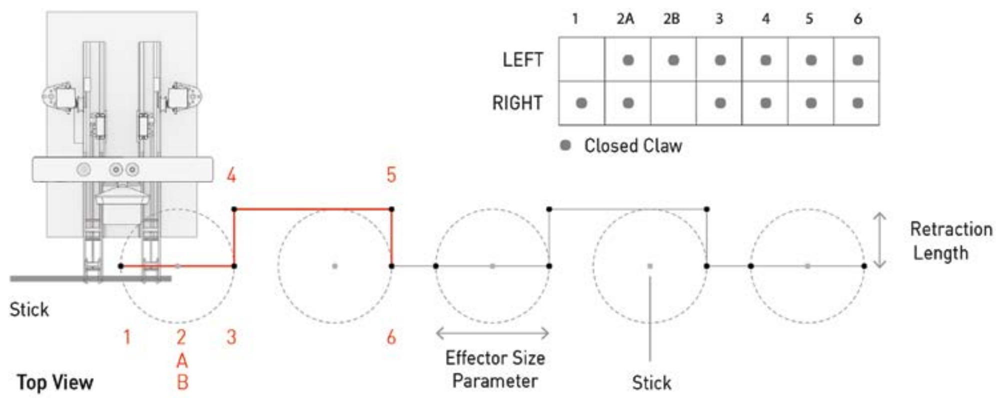
Local Weaving Agent-Based System

The ABS is an online computational design tool responsible for local relative motion planning for the robot as well as synchronized effector actuation. At any moment, the ABS calculates a vector direction towards the next ideal weaving position, and solves for the vector which would allow the effector to stay perpendicular to the pieces of rattan currently being woven. The target orientation of the effector is in a plane perpendicular to the overall weaving direction and the local tangent of the stick where the weaving procedure is acting (Figure 9).

In coordination with this movement, the ABS simultaneously outputs synchronous serial commands for the effector actuation. These outputs are specifically timed according to the local positions of the woven pieces where the weaving procedure will be executed. Because the precise positions of all elements are not known, and the rattan sticks shift during the process of weaving, these outputs must be generated in real-time while the robot is operating based on the sensor data. The weaving procedure is achieved when a series of actuations is executed in order around pre-existing rattan elements (Figure 8). Particular attention was given, on one hand, to ensuring that sequential curvilinear movements would not collide with the ongoing woven structure, and on the other, to the effector constraints and tolerances: ideally the two sticks being woven were locally close to perpendicular and the distance between them was greater than three times the tolerance of the local scanning process.

Weaving Robotic End-Effector

The weaving end-effector is the device responsible for manipulating the material during the robotic actuation. As already mentioned, though actuated gripping is common place, there were no industrial precedents for weaving in three dimensions. It was thus necessary to design and fabricate a custom robotic end-effector to enable an automated and mechanical weaving procedure (Figure 10).



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7 The soft system is composed of two coordinated feedback loops, one acting on a local level while the other on a global one, unfolding together in real-time.

8 The weaving sequence, composed by a series of key points in sequential order, adapts each time according to the specific stick's configuration captured by sensor data.

One of the main required features to operate within a behavioral fabrication process is the inherent adjustability of the tools, which can be attuned as the system unfolds and do not require a high level of precision. In order to achieve this inherent adjustability, the device is equipped with two coordinated robotic claws that are significantly inspired by the weaverbird's strategy to hold the grass strips with its beak during the construction. Because of their ability to incrementally close, they could grab different diameter sizes of rattan sticks (Figure 11). To further enhance the adjustability of the tool, the claws are mounted on two linear rails that actuate at different times to grab and release the piece currently being woven on the other side of a preexisting rattan member.

Effector control was achieved through serial commands from the client to an Arduino board, controlling four servo motors (two for the linear rails, two for opening and closing the claws). Together with the mechanical weaving procedure, the devices responsible for the sensing strategy were integrated on the effector itself, following at any time the robotic trajectory.

Performance Criteria

The performance input criteria investigated in the project is related to the modulation of material density within the woven system. This quality is translated into useful information through a gradient density mapping of the current and target density map. This acts as a loose guideline of intended density for the ABS, which uses agent vision and a weighting system to negotiate design intentionality with the fabrication constraints and material parameters previously described. Though the final prototype only included a limited number of rattan elements, if the system was developed further, this strategy could allow the system to achieve specific light gradients, to reinforce local areas, and to control the level of openness and visual permeability.

A scalar field generated as a color gradient mapping (in this case in grayscale) offers an intuitive way to visually understand and control density. By utilizing a scalar field mapped over the entire system, it is possible to instruct the ABS (global) with a simple behavior, for instance to avoid lighter areas and prefer darker ones, in order to vary the amount of material distributed in the structure (Figure 13).

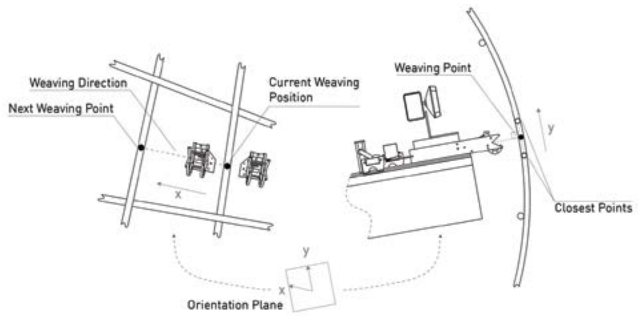
While this performance mapping is initially defined at the beginning of the design process, the system development is continuously informed by this mapping. An "In-progress Density Map" reflecting the current status of construction is generated with two different methods: 1) Recording the previous robotic movements and relating them to the ongoing woven structure. 2) Directly from sensor data which calculates the physical material density in each discretized area of the woven system. Furthermore, the designer could also intervene and decide to manipulate the system development by altering this intended density map during production.

Global Weaving Agent-Based System

While the local agent's environment acts only locally, a global agent acts on a digital reconstruction of the whole structure to determine where to place the next piece of rattan. This virtual agent navigates the boundary conditions to find a position in which the intended final density is highest, but the actual constructed density is low, by using the values of the in-progress density map. This virtual representation is updated at the end of every weaving sequence. After locating a start position, the agent then determines its direction as a weighted average of scalar values within its field of vision, determining where the rattan stick will be woven next (Figure 12).

Sensing Strategy

To obtain the necessary information regarding the physical



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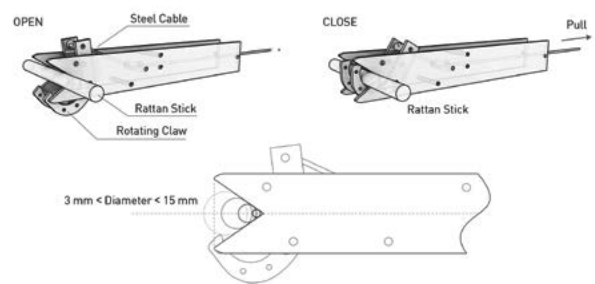

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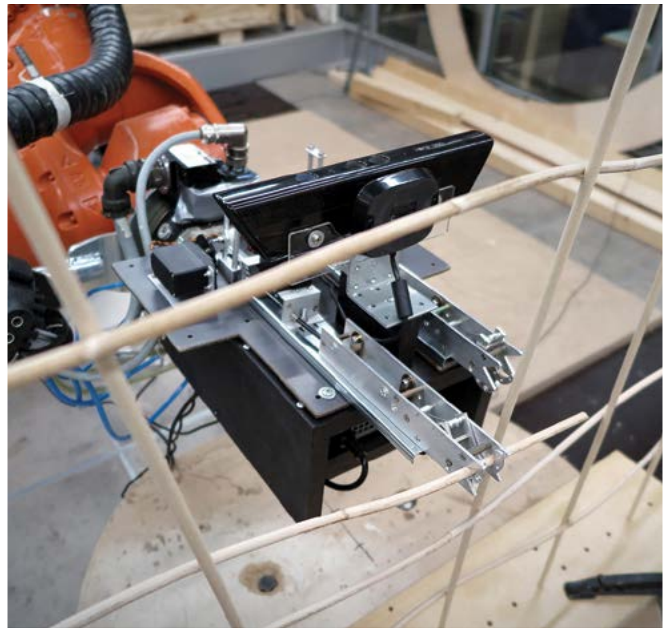

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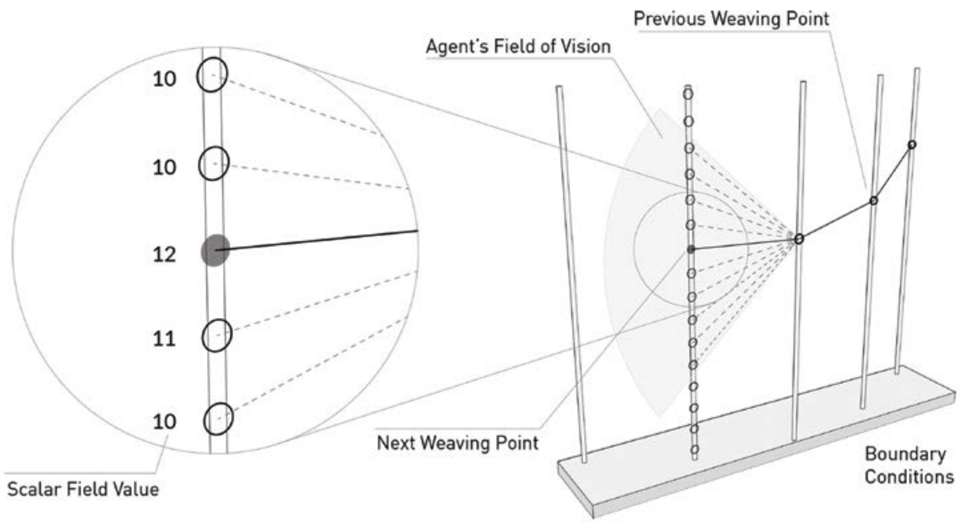
evolving structure, a depth camera with a lower accuracy but large field of vision (Microsoft Kinect 360) was preferred over more accurate sensors which return only a single numeric distance or point, such as a simple proximity sensor or laser range finder. The Kinect, mounted on the weaving robotic effector, returns into the design environment a raw point cloud representing the scanned geometry located in three-dimensional space relative to the robot base. Because this importation is computationally heavy, in the local behavioral loop, the Kinect scans only a specific area (about 50 x 50 cm) in front of the effector's moving direction. As in the reactive control paradigm, which enables responsivity without internal representation of the world (Mataric 2007), this data is only temporary: it is used to compute the next weaving sequence in real-time and is not stored in the system (Figure 14).

For the global sensing strategy, the Kinect was attached on the top plate of the weaving effector and oriented along a plane orthogonal to the TCP (Figure 15). Every session started with the calibration of the sensor with a known geometry and a first explorative scan to approximately locate the woven structure in space. Because the field of vision of the Kinect is small, and because of the difficulty completely synchronizing the position of the robot with the incoming data, it was not possible to scan the whole structure from either a single position or in a single continuous movement. For this reason, it was necessary to develop a procedure that creates a series of scanning positions in front of the structure and, in coordination with the robotic movements, triggers the Kinect when it reaches one of these locations. Because the orientation plane of the sensor and its relation with the TCP is known, it has been possible to correctly re-orient each scan in the digital space even if the position of the Kinect was constantly changing (Figure 16). Subsequently, the point clouds are combined together, duplicated points removed and the point cloud reduced to a minimal collection of points describing the linear axis of the sticks.

RESULTS AND REFLECTIONS

The research succeeded in developing a behavioral fabrication strategy for the production of three-dimensional woven structures based on a series of principles abstracted from the analysis of the weaverbird's building behavior. The framework of the soft system, even if specifically tailored for the weaving procedure, is potentially transferable to other fabrication tasks with different materials and robotic production workflows.

In order to automate a process heretofore only present in vernacular handmade processes or biological construction methods, a custom robotic weaving effector was constructed and utilized to successfully enable robotic weaving. Understandably, the process had some difficulties: while at the beginning of the fabrication the woven structure is really flexible and unstable, after several iterations it becomes progressively rigid. The friction generated to weave a stick across the ongoing mesh also increases. Both conditions could determine significant deformations in the structure while the weaving procedure is happening, therefore it could be challenging to complete the sequence of the effector's actuations without any error. Further improvements to the mechanical parts and reduction of the effector's size would improve the usability of the tool to enable even more complex geometrical



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9 Behavioral re-orientation of the weaving end-effector according to the local configuration of the woven structure.

10 The design of the end-effector enabled the development of the robotic weaving procedure, constantly adjusting to operate in different local configurations of the woven mesh.

11 The shape of the gripping claws, closing incrementally, allows to hold sticks of different sizes.

12 The robotic weaving agent travels across the woven mesh adjusting its direction according to the user-defined performance field, determining this way how the weaving sequence will unfold.

configurations and constructed morphologies. Significantly, the process implied the development of a bridge between the physical and digital realm, maintained by a series of integrated sensor-actuator feedback loops acting at different scales, where the moment of design blurs with fabrication, unfolding together in real-time (Figure 17). The agent based system enabled the system to use behavioral rule based logics to develop, integrating initial design intentions with material behavior and fabrication limitations. The sensing strategy represented one of the key components of the system and enabled the behavioral feedback loop, however, it was quite challenging to extract extremely accurate information from the Kinect 360 sensor and process it in real-time to the ABS. From time to time, the low level of precision and errors in the calibration undermined the quality of the behavioral responsiveness and, in this regard, a depth camera with higher resolution and precision would be beneficial to the consistency of the overall process.

From an architectural design perspective, the fabrication process outlined a series of potential applications and relevant features for robotic fabrication processes. First, the construction process could be initiated from only a few boundary conditions and generate a complex doubly curved interwoven system without the need of an expensive formwork. Furthermore, the system could be locally tailored to achieve specific architectural features, for instance, openings or reinforcement ribs, in relation to structural and environmental considerations, while the overall system remains flexible and structurally redundant.

CONCLUSIONS

The main driver of this research was the investigation of behavioral fabrication processes and their potential application in the field of architecture, opposing standard linear construction methods and geometrically static notational systems of design representation and construction. This expands possible methods and production systems for architectural production thanks to a novel use of already existing computational tools and robotic technologies, including machine vision and online control.

Fusing together design and production, the system got closer to natural construction processes which evolve based on behavioral adaptation to external and internal stimuli (Vasey et al. 2015). The project more broadly suggests an alternative approach for production where the design process is not centered on realizing a predefined solution, but instead embraces explorative and experimental processes. In this regard, one of the future research's directions is to envision possible ways of utilizing these methods in larger scale projects to reconsider the role of robots in construction processes.

ACKNOWLEDGEMENTS

The work here presented was developed in a year-long individual Master Thesis by Giulio Brugnaro and supervised by Prof. Achim Menges, Ehsan Baharlou, Lauren Vasey and Tobias Schwinn within "ITECH: Integrative Technologies and Architectural Design Research" Master Program at the University of Stuttgart, Germany.

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IMAGE CREDITS

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Figure 2: Chris Eason, 2008 (Distributed under the Creative Commons Attribution 2.0 Generic license).
Figures 3–17: Giulio Brugnaro, Institute for Computational Design, University of Stuttgart, 2014–2015.

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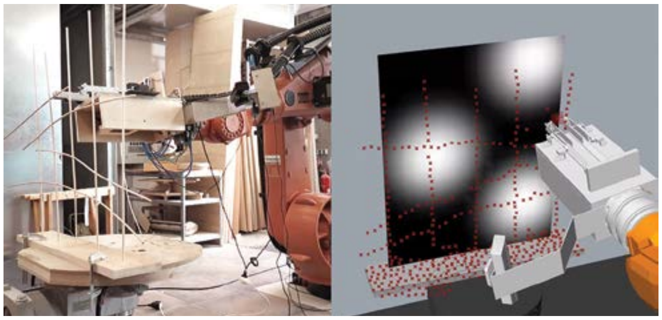
Professor Achim Menges, born 1975, is a registered architect and professor at the University of Stuttgart, where he is the founding director of the Institute for Computational Design since 2008. He is also Visiting Professor in Architecture at Harvard University's Graduate School of Design since 2009.



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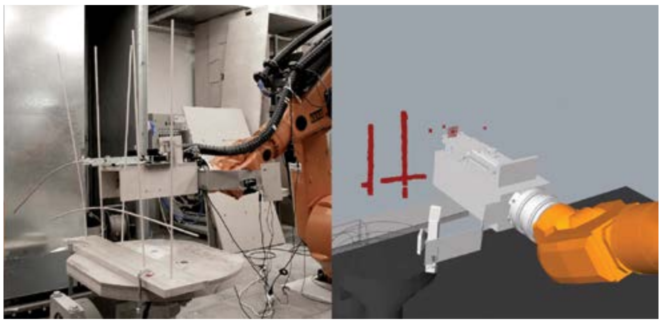

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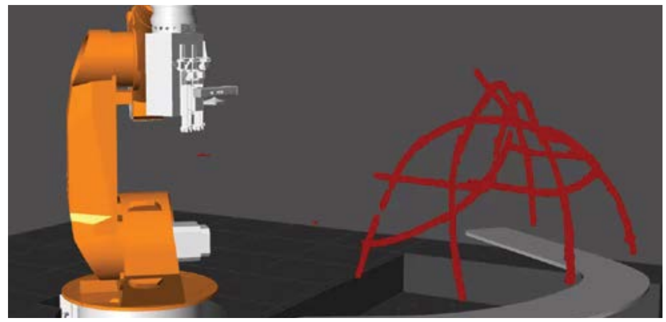

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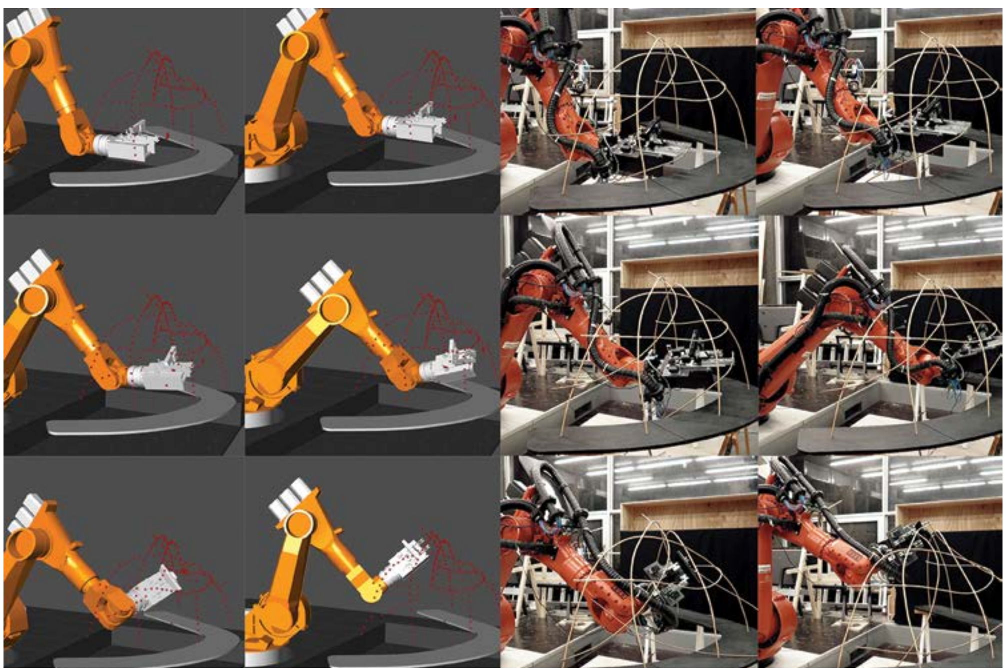

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13 The robotic weaving process is guided by a user-defined scalar map, which represents intended material density.

14 The depth camera scans only a small portion of the mesh ahead of the effector's weaving direction, reducing the computational intensity and allowing real-time responsiveness.

15 The robotic agent scans the ongoing woven structures before each weaving sequence to obtain a description of the current configuration.

16 The global pointcloud is updated with sensor data of each partial scan and subsequently processed to inform the ABS.

17 The robotic agent performs the weaving sequence based on previously acquired sensor information which locates the position of each woven stick with an accuracy of 1 cm.