Collaborative Construction

Human and Robot Collaboration Enabling the Fabrication and Assembly of a Filament-Wound Structure

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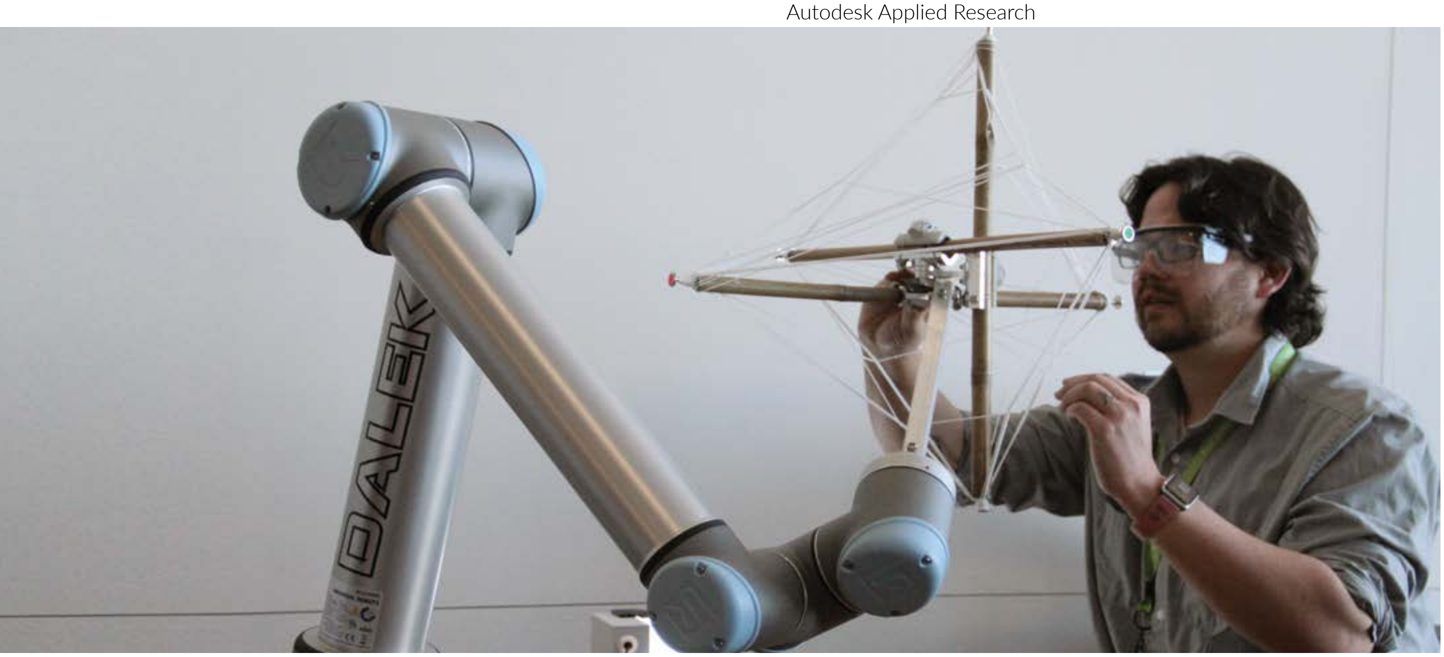

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ABSTRACT

In this paper, we describe an interdisciplinary project and live-exhibit that investigated whether untrained humans and robots could work together collaboratively towards the common goal of building a large-scale structure composed out of robotically fabricated modules using a filament winding process. We describe the fabrication system and exhibition setup, including a custom end effector and tension control mechanism, as well as a collaborative fabrication process in which instructions delivered via wearable devices enable the trade-off of production and assembly tasks between human and robot. We describe the necessary robotic developments that facilitated a live fabrication process, including a generic robot inverse kinematic solver engine for non-spherical wrist robots, and wireless network communication connecting hardware and software. In addition, we discuss computational strategies for the fiber syntax generation and robotic motion planning which mitigated constraints such as reachability, axis limitations, and collisions, and ensured predictable and therefore safe motion in a live exhibition setting.

We discuss the larger implications of this project as a case study for handling deviations due to non-standardized materials or human error, as well as a means to reconsider the fundamental separation of human and robotic tasks in a production workflow. Most significantly, the project exemplifies a hybrid domain of human and robot collaboration in which coordination and communication between robots, people, and devices can enhance the integration of robotic processes and computational control into the characteristic processes of construction.

1 Human and robot collaborative building process.

2 Final assembled structure composed of over 200 unique modules.

3 Tensegrity Module.

4 Pin-hooking detail.

INTRODUCTION

Though robotic fabrication has challenged standardized means of production for the architecture and manufacturing industries, the specialized knowledge and skill set that robots require, and the organization and development of customizable robotic processes, are significant logistical challenges which increase costs, compartmentalize production and assembly tasks, and favor linear, file-to-factory production chains.

Though active research is being done to introduce robots and other fabrication equipment directly onto the construction site (Helm et al. 2012, 2014), the use of robotic fabrication in large-scale projects often necessitates a workflow in which components are processed offsite in a factory or lab by specialists to be later transported, organized, and then assembled onsite by hand. This type of workflow provides little recourse if unexpected tolerances or deviations are encountered during the assembly and construction process.

Augmenting physical construction practices with digital mechanisms and just-in-time production can offer several benefits to existing protocols. By involving humans directly within the robotic fabrication process, and providing them with instructions through wearable interfaces, the separation of tasks within the production pipeline can be specialized according to ability: a robot's precision can be augmented by the fine motor control and cognitive ability of the human, and the monitoring of the process and feedback enabled through user interfaces allows the seamless trade-off of tasks between human and machine.

In this paper, we present a live exhibit and fabrication project that investigated whether humans and robots could work collaboratively and safely towards the common goal of fabricating and assembling a pre-designed large-scale structure. A prototypical robotic fabrication process was created that allowed the production of unique tensegrity modules which aggregated in a system. Tracking and monitoring of the current build status of the assembly enabled just-in-time instructions to be distributed to the participants via a smartwatch interface. The ultimate application of such an investigation is to question whether global system monitoring instructions delivered through devices could enable the organization and coordination of workers, robotic processes, material, and components in a deployment scenario such as a construction site.

CONTEXT

Human and Robot Collaboration

In applications for the architecture, engineering, and construction (AEC) industries, the shift from robots engineered for task specificity towards robots capable of generic tasks has enabled the development of customizable fabrication processes and robotic control protocols (Menges and Schwinn 2012). The ability to further augment these robotic fabrication processes through connected devices and sensor feedback enables increased integration and cross-linking between physical and digital domains (Menges 2015).

While robots in industry were originally purposed for the execution of repetitive tasks, they are becoming increasingly involved in less structured and more complex tasks, including interacting directly with humans, an interdisciplinary field of research broadly considered human and robot interaction (HRI) (Goodrich and Schultz 2007). Production processes in the architecture and construction industries, which involve complex tasks in unstructured environments, are thus a highly relevant application scenario for the investigation of human and robot collaboration.

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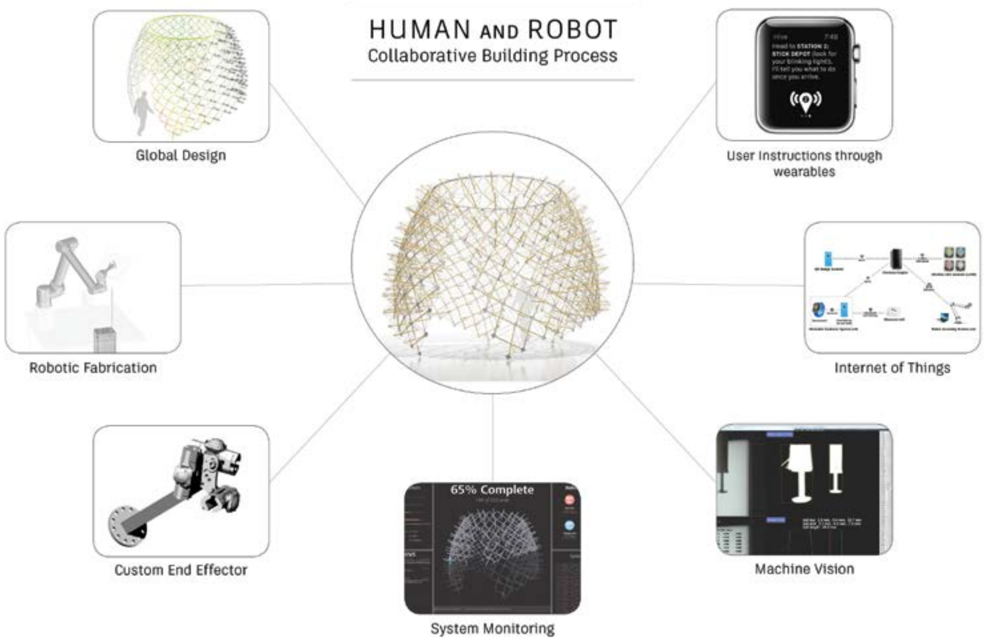

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5 System monitoring, connected devices, custom tooling, robotic fabrication, and computational design enabled the development and realization of a human and robot collaborative building process.

User Interfaces for Fabrication

Within robotic fabrication research, user interfaces have enabled the possibility of connecting robotic actions directly with user input: Dörfler and Rust developed a set of tools and a flexible open interface to enable on-line control of a KUKA robot (Dörfler and Rust 2012). This investigation and others have primarily leveraged user interfaces as a medium by which the designer might influence the outcome of the process according to targeted feedback (Johns et al. 2014). In contrast, the investigation provided here utilizes wearable interfaces as a means to communicate task instructions and protocols to an audience completely unfamiliar with the physical system and task. This investigation also builds upon investigations in industry. For example, sHop Architects utilized RFID tagging and a custom iOS application to organize fabricated building components for the Barclays center (Grogan 2014).

Filament Winding

Coreless filament winding is a fabrication process whereby an industrial robot incrementally lays fibers on a minimal or temporary formwork. This process is highly relevant as a customizable method which allows the formationof filament-based materials, such as glass or carbon fiber. Coreless filament winding significantly differs from other fiber application processes in the aerospace and automotive industries, where a mold often serves as the basis on which fibers are applied. These alternate production methods are very limited, in that they can only be utilized to produce serially identical units. Robotic fabrication expands the limitations of these methods (Prado et al. 2014) and enables the deposition of material precisely where it is needed, thus facilitating the fabrication of highly differentiated structures.

FABRICATION SYSTEM

To investigate whether humans and robots could collaboratively fabricate and assemble a structure, a prototypical fabrication system utilizing a process of robotic filament winding was developed based on the following criteria:

- Complexity of tasks: The fabrication system could not be overly simple, neither so difficult that someone unfamiliar with the task could complete it.
- Minimization of participation time: The total time required for a single participant in an exhibit was limited to 10 to 15 minutes.
- Utilization of machine vision: Adaptive regeneration of robotic control code would enable the use of non-standard materials and compensate for human error.
- Task allocation: A system in which the human user does the tasks that require fine motor control, and the robot those that require high precision, in which tradeoffs are facilitated through instructions delivered via wearable interfaces.
- User safety: Typical robotic safety procedures require that robotic control code is simulated before execution, or run in a safety mode at low speed. The exhibition format necessitated extra precautions to guarantee the reliability of the control code and safety of participants.

Module Development

A single tensegrity module was developed whereby three compression elements are held apart in a precise position during fabrication in order to align with each other in a global system. Bamboo was utilized for the compression members due to its energy efficiency and relative stiffness to weight, though it is non-standard material and thus ill-suited to traditional automation techniques. A custom pin detail inserted into the end of the bamboo is utilized to catch and hold the string during winding.

Global Design

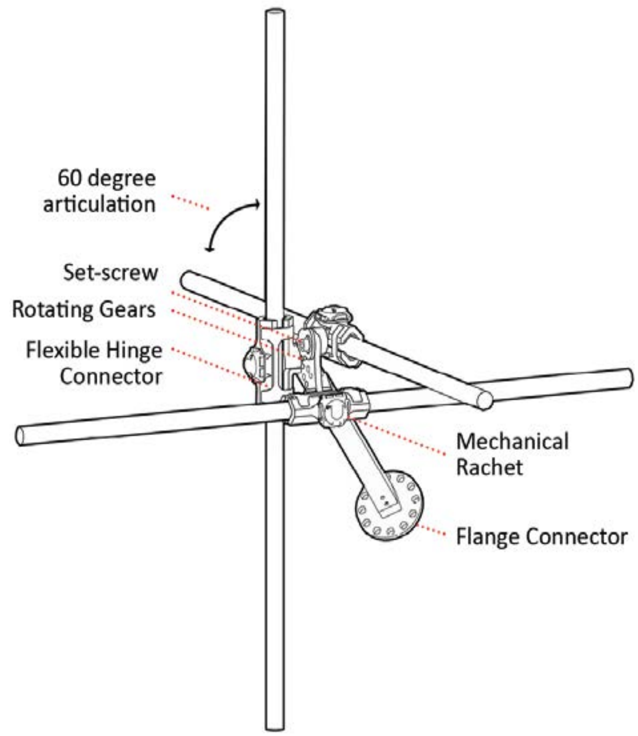
The main driver of a global structure's design was to describe a continuous doubly curved surface using modules of non-uniform shape composed of uniform length members. Assuming the modules are placed in the correct positions, the unique geometry of each module ensured that the structure would take the desired final form without any human oversight.

FABRICATION SETUP

A collaborative Universal Robot (UR) 10 robot was utilized because of its precision, its adaptive force control, and its ability to have instructions directly streamed and executed over socket communication (Universal Robots 2009). A CNC-milled custom end effector was developed that could precisely control the unique rotation between two of the three bamboo sticks through the rotation of two kinematically linked gears (Figure 4). When the filament is secured on a pin, and the robot incrementally re-orients the end effector, fiber is pulled from the fiber source and wound onto the bamboo frame. A lightbox and USB-connected webcam enables the scanning and digitization of each bamboo tip (Figure 7).

In robotic filament winding processes, one of the main challenges is to control the system tension, which naturally fluctuates throughout the process. During winding, a simple mechanism utilizes a hanging weight and a spiral compression spring, which provides frictional resistance between the weight and the fiber source to maintain an approximately constant tension on the string source, thus acting when the robot is moving towards or away from the fiber source (Figure 7). This type of system is derived from similar dancing bar tension control systems in industrial extrusion and rolling processes, but has the advantage that no signal processing or actuated braking is necessary (Becker 2000).

For the exhibition, four identical robotic stations are arranged to operate simultaneously. Secondary stations which contain the LED-embedded connection details and the bamboo pieces are located around the perimeter of the exhibit. For user safety, it was necessary that the exhibit itself have a single entrance so that only users registered in the system could enter the space.



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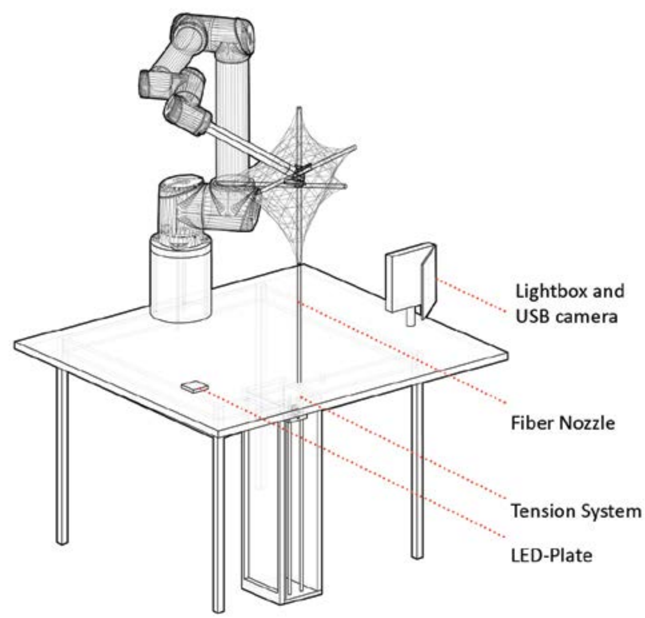

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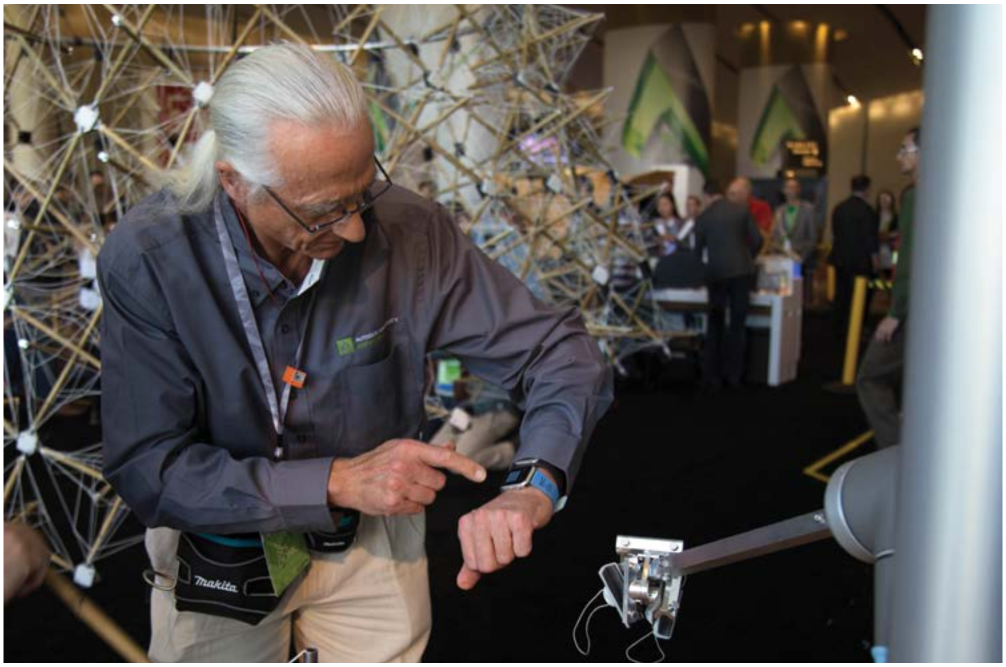
6 CNC-milled customizable end effector.

7 Single robot station setup with simple mechanical tension control.



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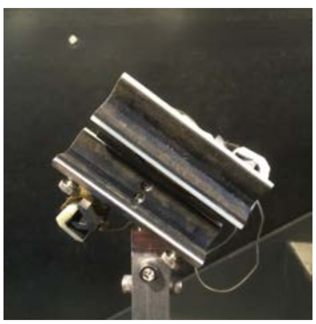

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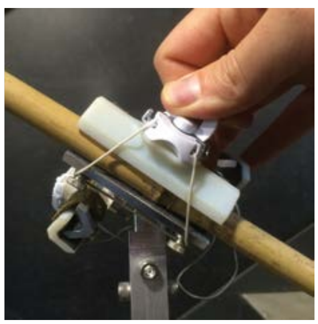

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8 The Smartwatch delivered just-in-time instructions to participants.

9 The CNC-milled customizable end effector without a part loaded.

10 The effector could be fastened around an irregular piece of bamboo through the tightening of a ratchet.

COLLABORATIVE FABRICATION

Collaborative Fabrication and Assembly Process

Upon entrance to the exhibition, users would be outfitted with an Apple Watch, an Apple iPhone, and safety glasses. The user would then be guided by just-in-time instructions through the exhibition, beginning by obtaining materials. The custom iOS application and the specifics of the user interface are discussed in a separate paper, "Crowd-sourced Fabrication" (2016).

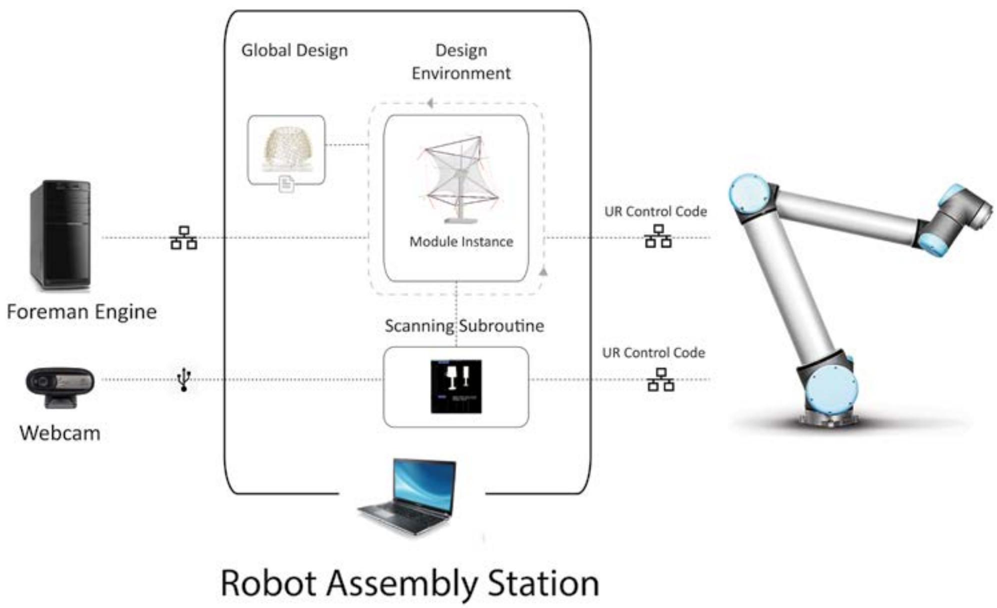
To fabricate a specific module at a robot station, the geometric properties of this unit are accessed from a database and then applied to an instantiation of the module in a CAD design environment. Correspondingly, the robot aligns itself perpendicularly to a reference surface for each bamboo part, so that the correct position and orientation is achieved, which allows the user to load the mechanical end effector by fastening and tightening a mechanical ratchet, a maneuver which utilizes the human's dexterity and the robot's precision. Confirmation that each part has been inserted correctly in the effector is confirmed from the user's watch before the robot proceeds. The robot then executes a custom scanning routine to re-digitize each tip correctly in space, re-generating the control code based on these deviations. Before uploading this code, the smartwatch interface prompts the user to confirm they are behind a safety line, and the winding routine executes at full speed.

During winding, a preliminary scaffolding layer is wound first to connect each end of bamboo to each of its neighbors without crossing or doubling the previously laid fibers. Final nebulous layers are wrapped, allowing the system to achieve an equilibrium condition, after which the tensegrity module can be removed from the effector by hand without significant deformation. Instructions on the Apple Watch, and LED lights embedded within the connective modules between the parts themselves, then indicate to the user where to fasten the module on the existing structure by tightening two zip ties on the connection detail.

System Communication

The robotic winding process was embedded in global control framework, which coordinated active users, robotic stations, and the current build status. The "Foreman Engine," the central brain in this framework, monitored and managed the overall progress of the construction and assembly, and systematically assigned the next part to the next available robot station (Lafreniere 2016).

The smartwatch devices worn by participants of the exhibit provided step-by-step instructions, and each user's current



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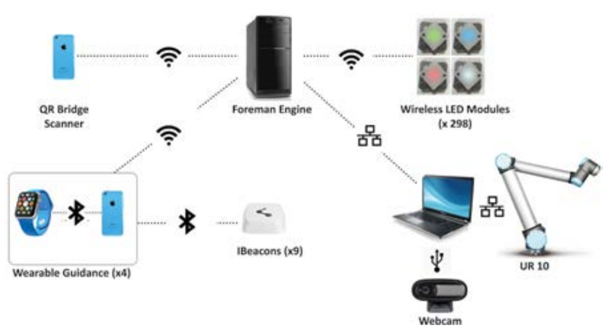

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11 Detail of the robot server on a control PC.

12 The full inter-process system communication.

status within the app was reported to the foreman engine. A series of iBeacons were additionally distributed throughout the exhibit to track the physical location of the workers, so that instructions could be presented automatically when a user arrived at a specific location (ibid.).

The robot server was configured as an in iteratively updating CAD environment on an individual PC (Figures 11 and 12). An update to a file structure on the control PC of each robot station communicated to the design environment to update the data structure of the current part, thereby triggering an update to the control code. Additional changes signified what control code to be immediately uploaded to the robot: either loadStick (A, B, C), scanParts(), or executeWinding().

Machine Vision

There were two main sources for error within this workflow: one being the deviations from an inherently variable material, and the other being the inherent source of error which arises when humans make mistakes or cannot be precise. For example, by not tightening the ratchet of the end effector holding the part in its entirety, the pieces of bamboo could rotate slightly due to the high applied torque.

To mitigate these sources of error, a scanning process was implemented to individually measure each bamboo tip, recalculate the position of the tip relative to the robot flange, update the object-oriented structure of the module in the design environment, and regenerate all of the robotic control code. A simple image analysis was utilized: for each of the 6 points of interest, the robot moves to a position in alignment with a plane in space. Based on simple image processing of two images, one taken through reflection, and the known mathematical location of the robotic position in space, the measured deviations of this pin are directly applied as a transformation of the pin in its local coordinate system (Figure 13).

Robotic Motion Planning for Filament Winding

In order to develop consistent and predictable robotic motion, it was necessary to develop algorithms that produce robotic winding patterns, methods that simulate these robotic paths, and methods that converted these paths into unambiguous robotic control code. Though software for the development and output of robotic control code exists by third party developers (Braumann and Brell-Cokcan 2014; Schwartz 2012; Elashry 2014), the kinematic complexity of the maneuvers necessary in a winding process, and the rather restrictive nature of the axis limits of Universal Robots, necessitated a stand-alone library for a computer-aided design environment (CAD) that would allow definitive

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control over motion type (linearly interpolated or axis specific), interpolation parameters, and inverse kinematic configuration data.

There were three main challenges in the robotic control of the process: (i) maximize reachability of all potential points with tolerances by correctly positioning the fiber source relative to robot and module relative to effector flange (ii) to derive feasible fiber patterns which would not run out of axis due to the discontinuous axis 4 and axis 6 of UR10 robots, and (iii) to guarantee that the robot control code would be executed reliably for each unique unit geometry despite deviations.

To achieve these goals, a geometric inverse kinematic solver for non-spherical wrist robots was implemented to calculate correct joint values for any given target position in each of 8 possible kinematic configurations.

Motion Planning

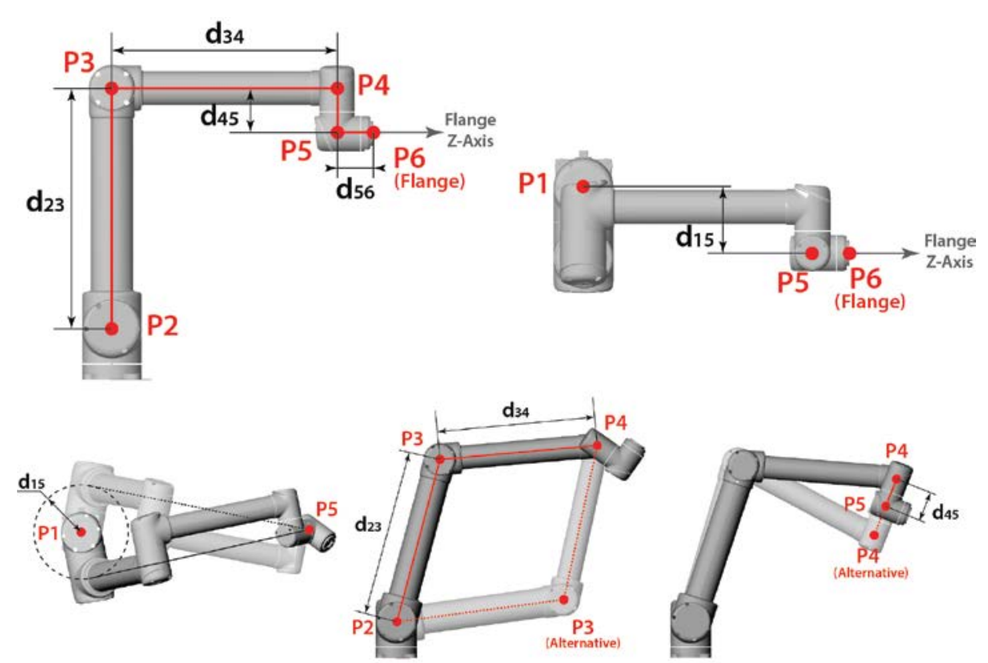
While typical motion planning positions a single tool coordinate frame in a world coordinate system, in this fabrication process, the position of interest on the end effector of the robot is constantly changing. During a hooking movement, the frame of interest acts at the pin of the end of the bamboo, and during the winding, a plane offset from a position on the module being wrapped. To solve for the planes for the machine code for a specific module, the planes which exist within the flange coordinate system of the end effector are aligned onto the base coordinate system of the fiber source, and through a backwards transformation, the position of a tool coordinate frame is solved in the world coordinate system (Figure 18).

Each target plane has an additional degree of freedom because it can be rotated about its Z-axis, affectively rotating the end effector around the Z-axis of the fiber source. To limit unnecessary robotic movement, the X-axis of the plane is solved as the plane with the greatest component in the direction of the default flange extension (Z-axis, flange coordinate system), so that the orientation of the robot flange projected in the world XY plane can be precisely controlled.

Reachability

To establish a task-specific reach envelope which would represent the three-dimensional solution set of reachable positions, a two-dimensional set of planes are generated in the flange coordinate system in which the Z-axis points towards the approximate center of the module. This set of planes is tested for reachability in each configuration. The generalized three-dimensional solution set of reachable positions can be achieved by rotating this set of planes around the flange Z-axis, which is the equivalent of rotating the sixth-axis of the robot (Figure 16).
This procedure:

- Enables the precise definition of the ideal fiber nozzle relative to robot base.
- Enables precise position of the length of effector extension.
- Defines the height of the fiber nozzle above the table to avoid collision.
- Determines which kinematic configurations of the eight



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13 Image processing is used for part digitization; For each pin, the robot aligns the local pin frame to a known base frame. The deviation of the pin from the expected position can be applied as a transformation in the local coordinate system of the pin frame.

14 Two bitmaps, one captured through reflection, are utilized to calculate the deviations of the pin.

15 A geometric inverse solution for non-spherical wrist robots is used to solve for the axis positions of any given target position. Three of the axis positions can be mirrored, resulting in 8 unique kinematic configurations for any given position. Depicted are the two possible solutions for joint1, the two possible solutions for joint2, and the two possible solutions for joint3.

possible have the most significant envelope and should be utilized.

- Illustrates that the most problematic area on the module to reach are positions close to the Z-axis of the flange where the solution for the X-axis is singular.

Path Planning for Axis Limitations

UR10s pose a kinematic challenge in that their fourth and sixth axes are discontinuous. In many industrial robots, including most KUKA and ABB robots as well as UR5s, the fourth and sixth axes are configured with infinite motion. This capability facilitates any motion or task that would cause a single axis to always increase or decrease, for example, tightening a screw. Though this limitation is specific to this setup, it is worth considering as a general case: any fabrication process with externally connected wires or power sources can similarly not allow an infinite twisting of either the fourth or the sixth axis.

Topological Model for Path Planning

To come up with a feasible fiber sequence that would not run out of axis, an object-oriented topological computational model was produced that included pins, the ends of each bamboo tip, and lines, the set of all lines which connect two adjacent pins. This model embeds the following relationships:

- From a single pin, it is possible to move to 4 lines (the four not connected to the pin)
- From a line, it is possible to move to 2 pins (inverse of rule one) or 4 lines, but only moves in the positive direction of the previously laid fiber paths are valid; otherwise unwrapping would occur.

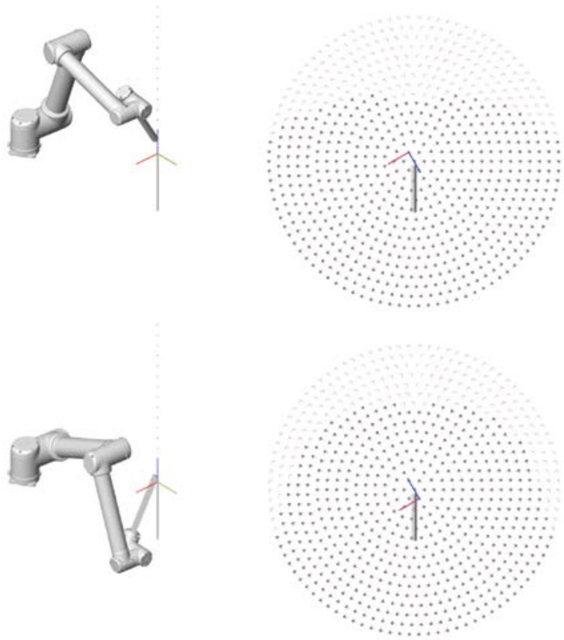
Through these embedded relationships, all possible paths between any two pins can be generated combinatorically as a sequence of right (0) and left turns (1) between end pins (-, 00, 01, 11, 000, 111, 101,110, 001, 010, 101….). This method allows all paths to be evaluated, sorted, and compared for their relative effect on the axes during path planning (Figure 19).

Post-Processing Algorithms for Evaluating Sequences

The inverse kinematic solver returned the correct joint position for each axis as a value between -180 and 180, but this value added to any multiplier of 360 is also valid. A set of post-processing algorithms was implemented to evaluate any sequence of robotic positions for the relative impact on axis values to determine if the sequence would stay within axis limits. This algorithm implements the assumption that the UR robot will always move to the axis position closest to the previous position in the same configuration during linear movement. For any sequence of moves, the summation of the relative axis change of all sequences when added with the joint values at the start of the motion must stay within -360 and 360 degrees for each axis.

Fiber Syntax Generation and Unambiguous Control Code

The robotic control code for the filament winding can be divided into two portions: the scaffolding, which connected all pins in one continuous line, and subsequent fiber winding. The scaffolding was in principle more challenging, as previous positions could not be revisited in the case that an axis was close to its



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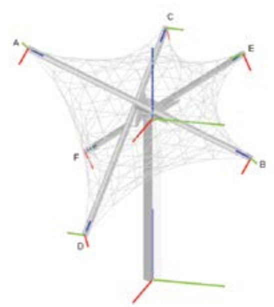

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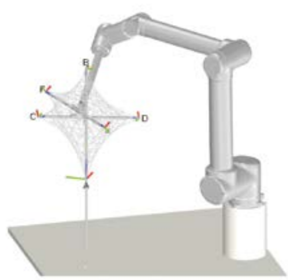

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limits. Axis-specific joint movement for each pin was utilized in the control code, so the change in configuration was defined unambiguously as the robot moved from one pin to the next. If a purely Cartesian-based positon strategy for motion control had been utilized, the robot would have run out of axis in three to four moves.

For the final wrapped layers, a sequence was produced utilizing topological path planning which touched all edges at least once and minimized winding time. All robotic positions were defined unambiguously in pseudocode with fully descriptive geometric and kinematic information, re-constructed from the module geometry in the design environment, and then translated into control code linking linearly interpolated positions. The same syntax was used for each module to minimize troubleshooting during the exhibition.

RESULTS AND LIMITATIONS

Though exhibit visitors were shadowed by the exhibition designers to ensure quality control, this project demonstrated that untrained workers—unfamiliar with both the necessary tasks required of them and the physical system itself—could successfully collaborate with robots to build a large structure when provided with just-in-time instructions delivered through a wearable device. Over 200 visitors came to the site to help build the 12 foot pavilion composed out of 224 unique tensegrity modules. The final structure was on display as a live collaborative building process and exhibit for over three days.

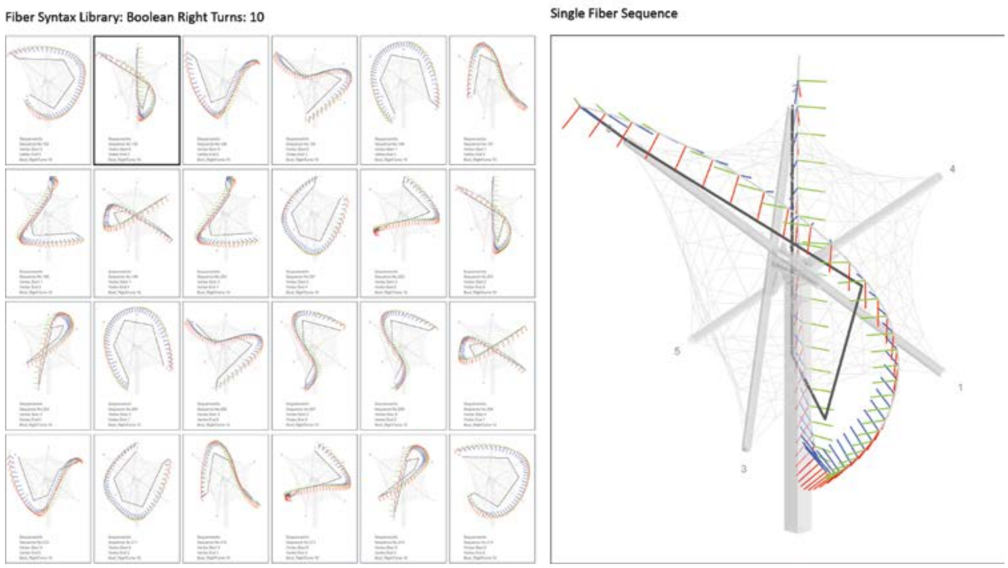
Despite the project's successes, several aspects could have been improved. When an unanticipated error occurred, for example, the tension was too high for the safety settings of the UR robot, it triggered an error, and the entire part had to be discarded. Thus, one next step to improve the process would be to identify common errors, to determine how they are easily detected from sensor feedback or input from the user interface, and to tailor the information sent to the user based on this analysis.

One of the most significant limitations of the project was the use of a robot that had limited axis ranges. To enhance the interactivity of the process, and to make use of the robot's inherent ability to achieve customizability, the design of the fiber layout could have become interactive or differentiated, in which case performance criteria, fabrication constraints, and user choice could have been integrated into a computational design tool and interface.

Scanning and digitizing the parts successfully enabled the utilization of non-standard materials. However, one missed opportunity was to store the deviations of the as-built geometry, and regenerate subsequent control code, allowing tolerances to be compensated for computationally as the construction and assembly process progressed (Vasey, Maxwell, and Pigram 2014).

DISCUSSION

As a demonstrator, the project illustrates that interconnected devices, sensor feedback, and responses enabled through user interfaces enable new possibilities for reconsidering protocols for humans and robots to work together, particularly as applied in construction or fabrication processes which involve the coordination and organization of many parts, processes, and people. More significantly, the project demonstrates the new possibility of a hybrid domain of robot and human collaboration in construction, in which coordination and communication between hardware and software facilitates new possibilities. These possibilities, including just-in-time production, tolerance compensation, and task monitoring and allocation can serve the purpose of more fully integrating robotic processes and computational control into the characteristic processes of construction during all design and production stages.



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16 Reachable positions relative to the robot flange in two kinematic configurations. Every module and all toolpaths in the global design had to fit within this envelope.

17 Frames existing in the coordinate system of the robotic flange.

18 Mapping of the frames onto the base frame of the fiber source and solution of the tool frame location in the space of the world.

19 Topological motion planning and move evaluation: All paths can be generated through embedded topological relationships as a sequence of right and left turns. Any sequence of moves can be evaluated for its relative effect on axis values and sorted during path planning.

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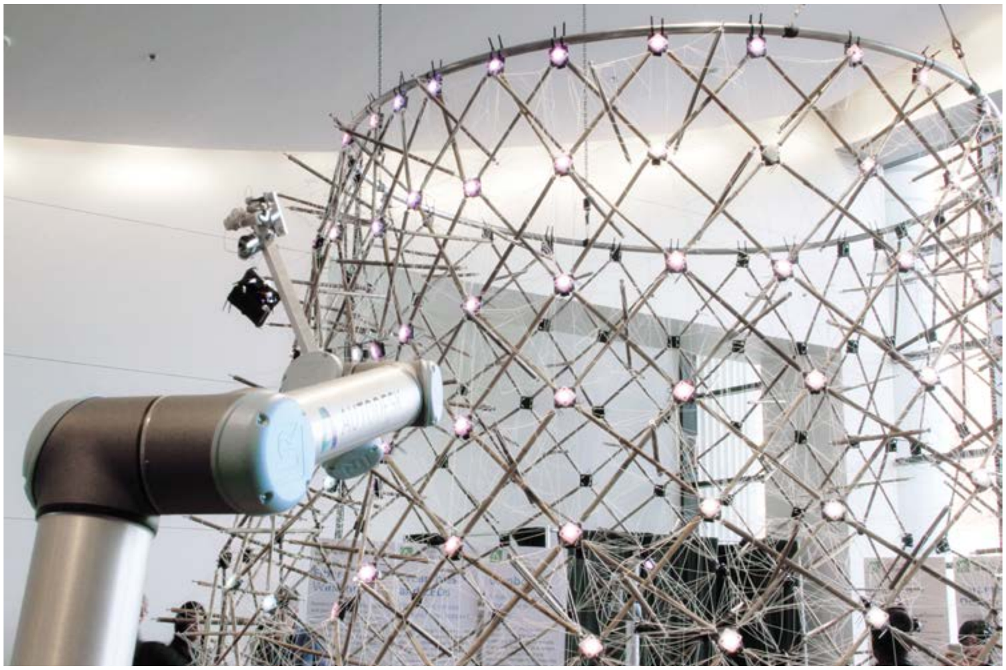

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20 Final structure composed out of 224 unique modules fabricated and assembled by human and by robot.

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