Slack Pack: Fabrication System for the Dual Robotic Winding of Spatial Fiber Structures

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Abstract. Advancements in technology are ushering in an era in architecture in which new design methods and tools are being developed that necessitate entirely new means of fabrication, and, inversely, novel innovations in fabrication require completely new ways of designing. Coreless filament winding is a contemporary fabrication method in which fiber reinforced polymers are robotically wound on frames. Even though research on the frame design has reached promising levels of adaptability and material efficiency, these frames limit fabrication flexibility and increase fabrication time and costs. This paper introduces *Slack Pack*, a novel fiber winding technique for the fabrication of deployable spatial structures. It eliminates the use of frames by introducing slack into the fabrication process through the controlled tensioning and un-tensioning of fibers. *Slack Pack* employs a cyber-physical fabrication system that combines a generative design workflow and a multi-agent robotic fabrication setup with a custom end effector. The proposed method is evaluated through a series of physical experiments and digital simulations, demonstrating its potential for the fabrication of spatial fiber structures.

Keywords: Robotic fabrication · Multi-agent · Fiber reinforced polymers · Coreless filament winding · Spatial structures

1 Introduction

This research explores the development of a fabrication system that integrates digital and physical methodologies in order to produce spatial fiber structures. Spatial fiber structures are non-surface geometries, such as a space frame or 3D truss, made from fiber-reinforced polymers [FRP]. FRP are composites consisting of structural fibers, such as carbon, glass, or flax fiber, combined with a polymer matrix (Bakis et al. 2002).

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Coreless filament winding [CFW] is a contemporary method of fiber winding that produces geometries by robotically winding FRP around anchor points supported by a frame. Rather than use surface-based formworks typically found in filament winding, CFW achieves its desired morphological outcome through a sequence of fiber-fiber interactions and the use of discretized frames (Prado et al. 2014).

Despite the advantages of CFW, winding frames still limit geometric customizability and production flexibility, represent a high cost and time investment, restrict achievable typologies to hyperbolic, anticlastic surfaces (Bodea et al. 2021), and interrupt the design-to-fabrication workflow. These limitations were the drivers behind developing a new filament winding method in which the fabrication process utilizes a multi-robot system to produce customized spatial fiber geometries **without the use of premade winding frames**.

The system proposed in this paper uses two industrial robotic arms equipped with custom hardware to wind fibers in alternating states of tension and slack in order to eliminate the reliance on premade winding frames and increase the range of achievable typologies. Through the use of slack, the resulting spatial fiber structure can be collapsed and deployed on-site via tensioning and curing. The development of this system necessitated novel geometry generation workflows, automated control and path planning algorithms, and custom hardware and fabrication methods.

2 Context

2.1 Coreless Filament Winding

Developed over the past decade at the University of Stuttgart's Institute of Computational Design and Construction [ICD] and Institute of Building Structures and Structural Design [ITKE], CFW allows for the fabrication of fiber composite components without using costly, single-use formwork or mandrels by replacing surface molds with skeletal-frames that can be removed after the FRP is fully cured (Solly et al. 2018). The evolution of winding frames began with the ICD/ITKE's 2012 Research Pavilion (Fig. 1a) which utilized a single temporary rigid frame to shape the full pavilion (Knippers et al. 2015). The 2013/14 Research Pavilion (Prado et al. 2014) as well as 2019's BUGA Fibre Pavilion (Fig. 1b) (Menges et al. 2022) utilized adjustable frames that could be reconfigured depending on the geometry of the component being fabricated. In 2021's Maison Fibre (Fig. 1c), components were wound in stages with different parts of the frame being added at different periods of the winding process (Gil Pérez et al. 2022).

2.2 Robot Collaboration in Fiber Winding

Multi-Robot Collaboration [MRC] consists of multiple robots working together to complete a task. Recent research has demonstrated the possibility of MRC in the fabrication of complex architectural structures without the necessity of prefabricated formwork. Spatial Metal Structures (Parascho 2019) used a dual robot system to construct a complex metal spatial structure in stages. Spatial Winding (Duque Estrada et al. 2020) and Spatial Lacing (Yang et al. 2022) utilized MRC in the fabrication of spatial fibrous structures. Such studies demonstrate the potential of multi-robot systems, particularly in CFW. The benefits of MRC in fiber winding include:

Fig. 1. Winding frames of: **a** ICD/ITKE Research Pavilion 2012 (Knippers et al. 2015) **b** BUGA Fiber Pavilion (Menges et al. 2022) **c** Maison Fibre (ICD and ITKE 2021)

- **Multi-Tasking** (Fig. 2a): It is possible to perform various operations on the same workpiece simultaneously. The 2013–2014 ICD/ITKE research pavilion utilized two robots to manipulate frame orientation simultaneously, share loads, and improve geometric accuracy (Prado et al. 2014).
- **Material Exchanges** (Fig. 2b): Material can be exchanged from one robot to another. Spatial Winding (Duque Estrada et al. 2020) used a multi-agent system for the exchange of materials in order to produce spatial fiber structures.
- **Multi-Materials** (Fig. 2c): Multiple different materials can be manipulated in parallel. Spatial Lacing (Tucker et al. 2022) utilized a mobile robot system to manipulate different threads of fiber at the same time.

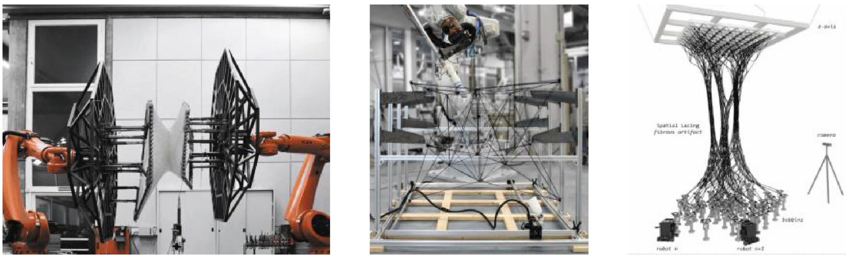

Fig. 2. **a** Two robots share a workpiece (Prado et al. 2014) **b** 6-axis robot exchanges fiber with 2-axis gantry (Duque Estrada et al. 2020), **c** Two mobile robots manipulate fiber bobbins simultaneously (Tucker et al. 2022)

2.3 Restrictions of Winding Frames for Spatial Structures

Despite the benefits of using CFW to wind surface geometries, there are several fundamental restrictions of using a frame to wind spatial structures. These include:

- **Frame-to-Fiber Collisions** (Fig. 3a): The frame elements supporting anchor points must penetrate the structure's convex hull, causing collisions with fiber members.
- **Incremental Reachability Reduction** (Fig. 3b): The robot's reachability decreases significantly with the addition of each wound member, incrementally reducing the ability to wind new members.

- **Upwind Limitation** (Fig. 3c): In CFW, fiber is secured to an anchor by winding around the anchor's circumference. If an anchor has both a member pointing in the negative Z direction (down) as well as in the positive Z direction (up), no additional members can be wound around that anchor, except for at shallow angles, since the upward member will block the robot.

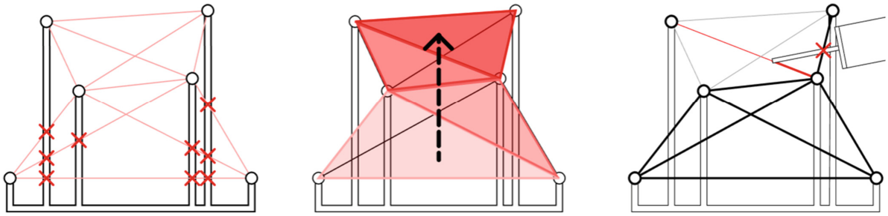

Fig. 3. **a** Fiber colliding with frame **b** Robot reachability decreasing (red areas) with the addition of members **c** Robot colliding with upward pointing members

3 Methodology

In CFW, the winding frame (Fig. 4a) is considered to be **a component in the winding process that is not part of the desired final geometry that constrains fiber at specific anchor points (Fig. 4b) until it is cured**. In the remaining context of this paper, these anchor points are referred to as nodes. These nodes as well as the resulting fiber-to-fiber interactions determine the structure's final shape and maintain fiber relationships until the resin cures (Fig. 4c). At the most abstract level, nodes are all that are required to create a fiber topology.

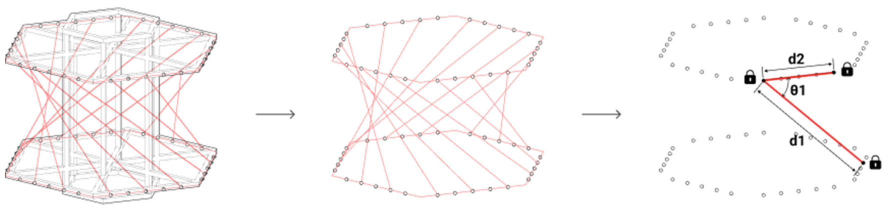

Fig. 4. **a** Conventional winding frame in CFW **b** Location of anchor points **c** Geometric relationships of anchor points

In a spatial structure, topology is determined by the length of members and the angles at which they connect (Fig. 4c). Thus, as long as these lengths and angles are fixed, the structure can go slack and return to its global form by being tensioned—similar to how a child alternates between states of tension and slack to create a shape in the string game Cat's Cradle (Fig. 5). In fiber winding, the ability to have members go slack means that

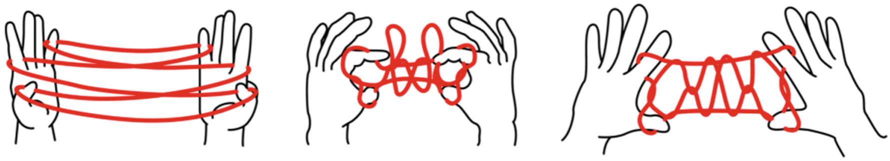

Fig. 5. Cat's cradle, children's game involving tensioning/un-tensioning of string [figure adapted from (Gupta 2002)]

nodes do not have to maintain the same position throughout the fabrication process, eliminating the need for a frame.

Slack Pack establishes the connection nodes as **manipulatable objects** and secures fiber around them using a technique called "localized fiber curing". Consequently, the fiber member can go slack after each wind and be placed on a two-dimensional storage plane without losing its geometric properties, such as length or interaction angles. This is achieved by utilizing a custom end-effector and a dual-robot system (Fig. 6) where one robot (NodeBot) holds two nodes, while a second robot (FiberBot) winds fiber around them. This process of retrieving a pair of nodes, winding between them, and returning them to the storage plane is repeated until a network of slack fibers is completed (Fig. 7). The result is an un-tensioned spatial structure that can be fabricated without a frame, stored and transported in a collapsed state, and deployed onsite via tensioning and onsite curing.

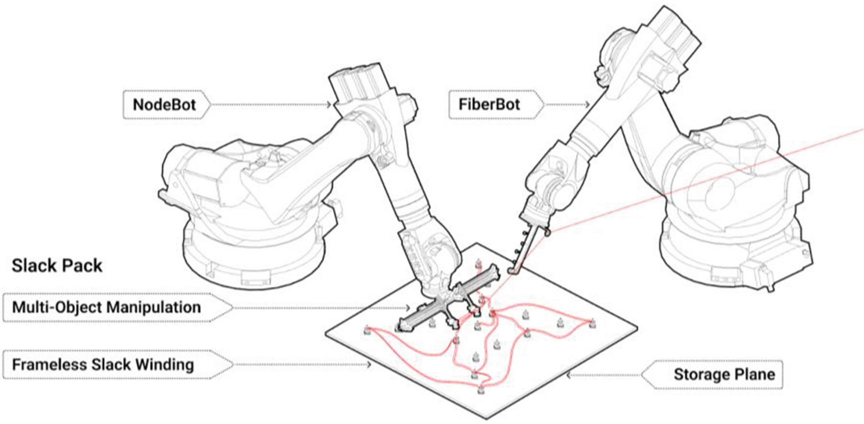

Fig. 6. Overview of Slack Pack system

This system requires the use of both custom digital and physical tools. The development of these tools was divided into two sections: **Fabrication Planning** and **Fabrication Execution**.

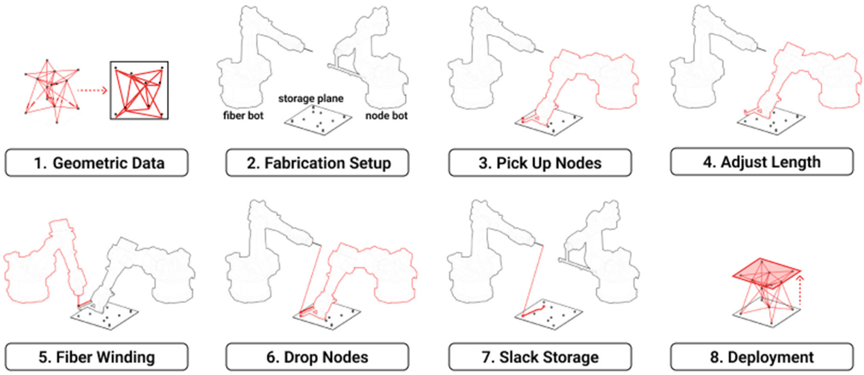

Fig. 7. Fabrication sequence of *Slack Pack* system

3.1 Fabrication Planning

Prior to the fabrication planning steps, a custom generative design tool is used to generate a fabricable global geometry using an agent-based model [ABM]. A detailed description of the geometry generation is beyond the scope of this paper.

The algorithm for the fabrication planning steps was written in IronPython—a.NET implementation of the programming language Python (.NET Foundation, n.d.) and implemented into the 3D modeling software Rhinoceros 3D through the RhinoCommon SDK and Grasshopper, a visual coding plug-in for Rhinoceros 3D (Robert McNeel and Associates 2023).

3.1.1 Member Order Based on Node Z Heights

Winding is done with a continuous fiber and follows a winding order determined by the following rules: The ending of one member must be the start of the next member. members are wound in order of the winding layer they are in (Fig. 8a). The winding layers are dictated by the z heights of each node. Multiple members within a single winding layer are wound in ascending order of the winding layers they connect to (Fig. 8b). Winding the members in ascending order ensures there are no undesired fiber collisions in the final deployment.

3.1.2 Storage and Winding Position Data

The geometry is projected onto a plane to get the necessary data for the manipulation and storage of nodes. This provides the **location of the nodes** on the storage plane, the **2D interaction angle** of members, and their **projection length** which is **scaled further** to increase the amount of slack available during storage (Fig. 9).

3.1.3 Fiber Length Restriction

Because nodes are mounted on a storage plane, when two nodes are picked up, they will be tethered to other nodes on the plane. If these tethers are not long enough, the

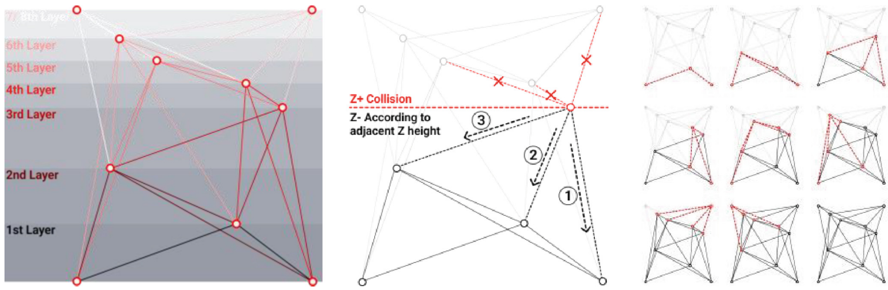

Fig. 8. **a** Winding layers **b** Winding order within winding layer **c** Overall winding order

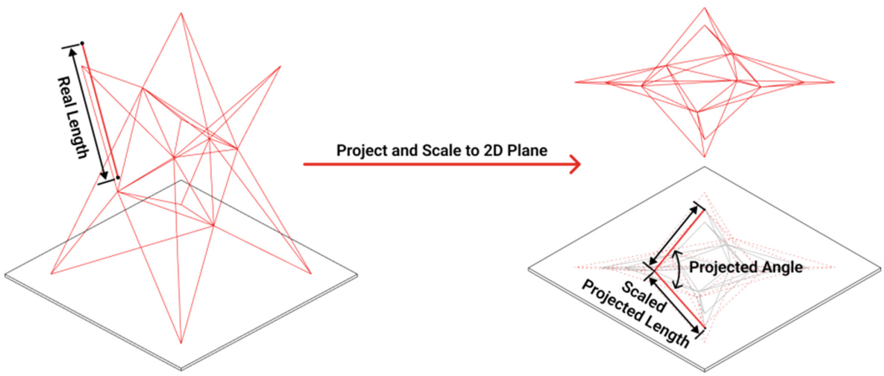

Fig. 9. Storage position data based on geometry projection

node cannot be picked up (Fig. 10). This is algorithmically checked. Two nodes can shift along the end effector following the direction of their projected member until a valid solution is found. If no solution is found, the global geometry must be regenerated.

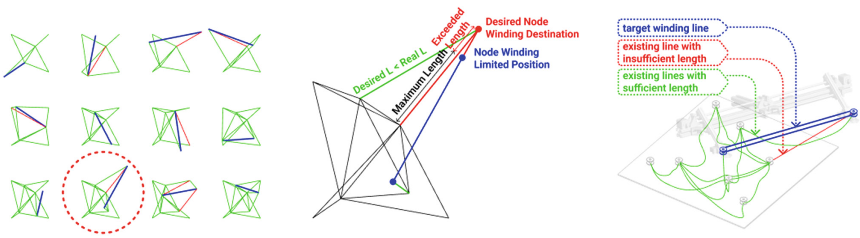

Fig. 10. Example of a fiber length restriction error

3.2 Fabrication Execution

Fabrication execution includes both the computational tools used to generate the robot control commands as well as the physical hardware that were used to carry out the fabrication. The robot that performs the winding processes is referred to as the FiberBot and the robot that manipulates the nodes is referred to as the NodeBot. The NodeBot manipulates the nodes via the custom [NodeBot] end effector. The fabrication setup is shown in Fig. 11.

Fig. 11. Fabrication setup

A bespoke algorithm uses the fabrication planning data to create TCP-planes to control the robots. KUKA|prc, a Grasshopper plug-in for robot control developed by the Association for Robots in Architecture (2023), takes these planes along with real world calibration data to generate the KUKA Robot Language (KRL) (KUKA AG 2023) for controlling the FiberBot and NodeBot (Fig. 12).

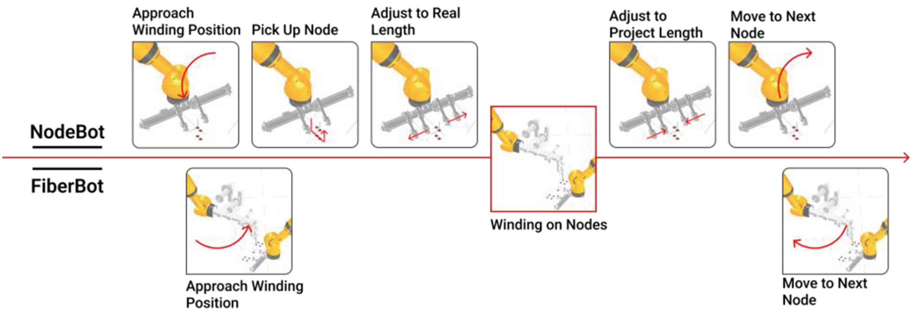

Fig. 12. Robot collaboration workflow

3.2.1 FiberBot

The generation of FiberBot toolpath planes follows the offset of each node's position (Fig. 13). The offset distance is defined by the node diameters. Once the NodeBot is positioned, the FiberBot begins winding around the nodes and the winding process is repeated according to bundle size and member thickness.

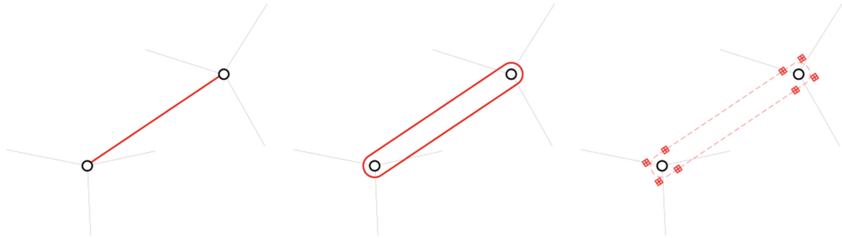

Fig. 13. Toolpath generation for FiberBot

3.2.2 NodeBot

The generation of NodeBot toolpath planes requires the projected node positions, a defined winding height, and a node pickup offset distance. The planes at each member's midpoint act as the reference planes for all the NodeBot sequences. The NodeBot moves in the XY plane perpendicular to the member at distances defined by the pickup offset (Fig. 14a). The movement in Z direction is defined by the winding height (Fig. 14b).

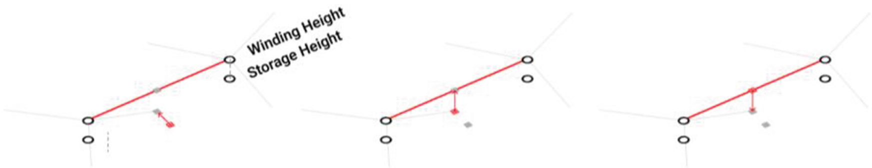

Fig. 14. Toolpath generation for NodeBot **a** Node pickup position at correct offset **b** Raise nodes to winding height **c** Return nodes to storage plane

3.2.3 NodeBot End Effector

In order to manipulate the nodes, the NodeBot end effector (Fig. 15a) carried out the following tasks:

- **Node Retrieval**: The node retrieval mechanism used a SMC MHZ2-16D Parallel Pneumatic Gripper with 3D printed claws to grip and release nodes.
- **Length Adjustment**: Two symmetrical belt driven linear axes adjust the distance between the nodes.
- **Localized Fiber Curing** (Fig. 15b): The localized securing of the fiber is achieved using resistive curing. By passing electrical current through the electrically conductive carbon fiber, the carbon fiber dissipates electrical resistance as heat in a process known as Joule heating (Britannica 2022). This heat causes the curing of the thermoset resin matrix of the FRP. *Slack Pack* uses a power supply of 12V and 4.5A applied to the fiber for approximately 1.5 min per node to achieve localized curing.
- **Control**: The end effector is controlled via an Arduino Uno with a CNC shield and the grippers are actuated with a pneumatic valve. Arduino receives custom GCode from a laptop via serial communication.

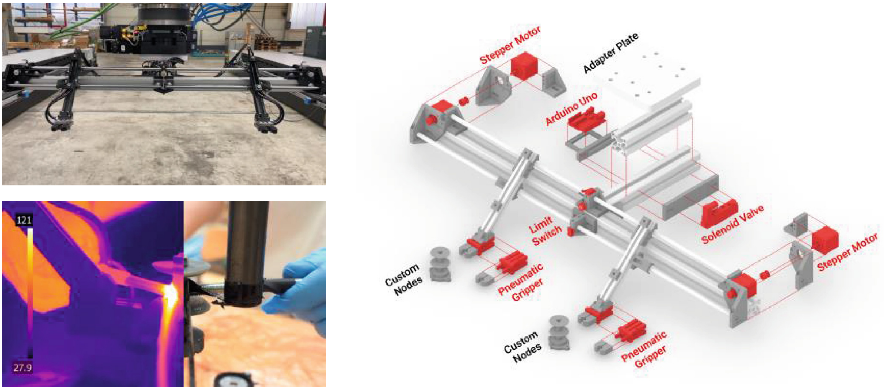

Fig. 15. **a** End effector installed on the robot **b** Resistive curing and thermal imaging of node **c** Exploded view of end effector

3.2.4 Robot Sequence

The robots' choreography is determined and verified using the following methods: Both robots are calibrated to the same base plane. KUKA|prc is used to generate the KRL for each robot based off the common base coordinate system. Reachability of the planes by each robot is verified using the simulation tools in KUKA|prc. Collisions between robots during winding are eliminated because during winding, the fiber winding end effector always remains perpendicular to the node end effector. Collision avoidance of the robots during travel movements is visually verified in the KUKA|prc simulation as well as during fabrication testing.

3.2.5 Onsite Deployment

In addition to removing the frame and reducing reachability issues, winding in slack allows the completed structure to be stored and transported in a collapsed state, improving transportation efficiency (Fig. 16a). The structure can then be deployed onsite via tensioning and cured in an expandable oven (Fig. 16b). Furthermore, because the structure is fabricated in a collapsed state its final size is not limited by the work envelope of the fabrication setup, allowing for the scalability of components which is traditionally accomplished through a modular approach. In the context of this research, only unidirectional (vertical) tensioning was tested. While multi-directional tensioning could yield more complex geometries, it also requires more complex deployment strategies and equipment. It was determined that these increased equipment requirements could undermine the benefits of the frameless process. One scenario, however, where multidirectional tensioning could be achieved with minimal equipment is the deployment of fiber geometries onto existing structures, but detailed exploration of this scenario was out of the scope of this research.

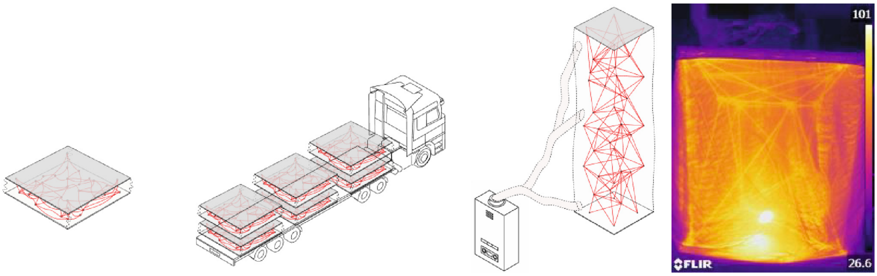

Fig. 16. **a** Transportation and deployment strategy of a wound structure **b** Thermal image of prototype in deployable oven

4 Results

4.1 Prototypes

Early prototypes were made using a single robot for positioning and a manual end effector (Fig. 17a) and were deployed with the robot in a separate step (Fig. 17b).

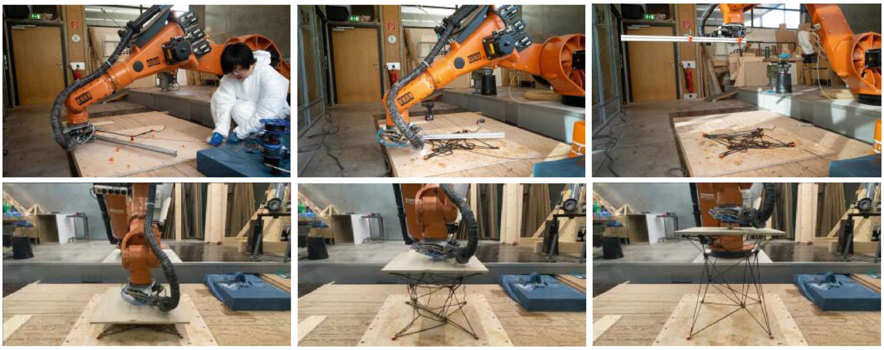

Fig. 17. **a** Semi-robotic winding of early prototype **b** Deployment of prototype structure

4.2 Demonstrator

A furniture scale structure was developed as a final demonstrator to test and evaluate the *Slack Pack* system as a whole. The demonstrator geometry was designed using the geometry generation tool and included variable member cross sections based on axial stress. All the fabrication planning steps were done using the tools discussed in this paper, including the automatic generation of FiberBot and NodeBot TCP planes (Fig. 18).

The fabrication of the demonstrator was carried out on a dual robot platform consisting of two KUKA KR210-R3100 robots mounted on linear axes (Fig. 11). The Cluster of Excellence Integrative Computational Design and Construction for Architecture (IntCDC) provided the two robots as well as the FiberBot end effector. The FRP used was

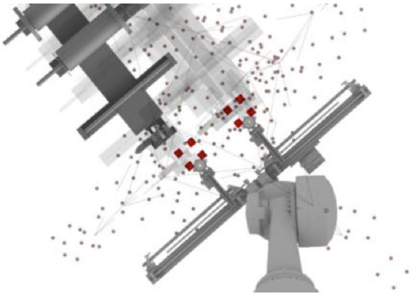

Fig. 18. Fully cured demonstrator with load bearing capabilities

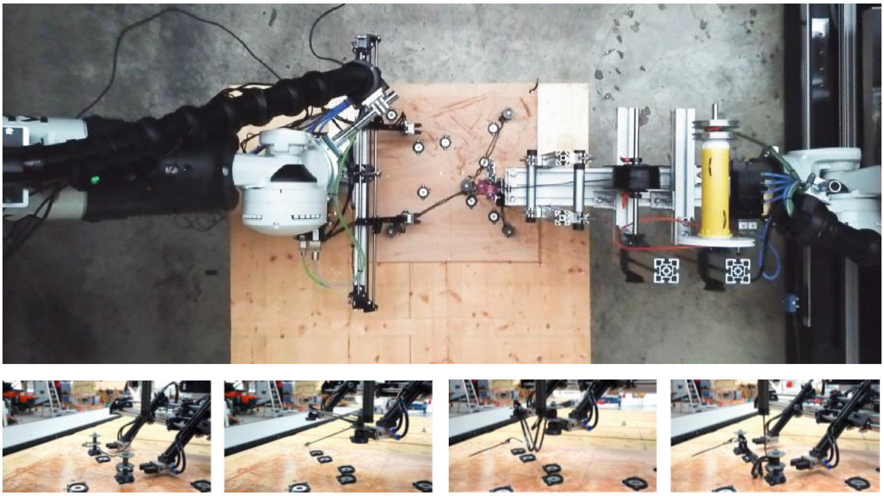

Fig. 19. **a** verlay of FiberBot simulation **b** Overlay of NodeBot simulation

a pre-impregnated fiber comprised of Tenax-E STS40 E23 48K 3200 tex carbon fiber from Teijin Carbon and EPIKOTE Resin MGS LR 135 and EPIKURE Curing Agent MGS LH 137 with a 100:35 resin-hardener mix. The structure was wound completely on the robot setup and deployed using a gantry crane (Figs. 19 and 20).

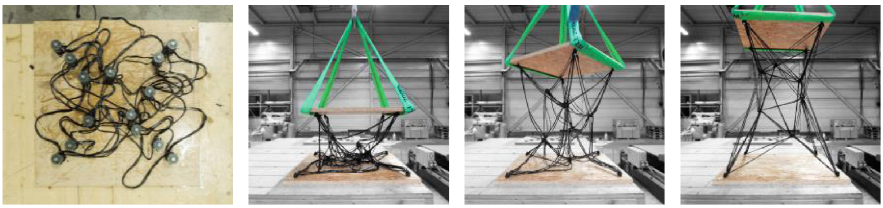

Fig. 20. **a** Arial view of fabrication setup **b** Robot winding sequence including picking up nodes, winding fiber member, and returning nodes and wound member to storage plane.

The final demonstrator (Fig. 21) was comprised of 14 nodes and 36 members, used 101.3 m of fiber, and weighed 0.820 kg. It was computationally designed, completely robotically fabricated with the dual robot setup, and could support over 55 kg before deforming. For comparison, the previous prototype of a similar typology (Fig. 17), which was not algorithmically generated and only partially robotically fabricated, weighed 0.630 kg but could only support 15.7 kg. This represents only a 30% increase in weight in the demonstrator but over a 250% increase in load capacity (Fig. 22) and illustrates the value and strength of the integrated *Slack Pack* system.

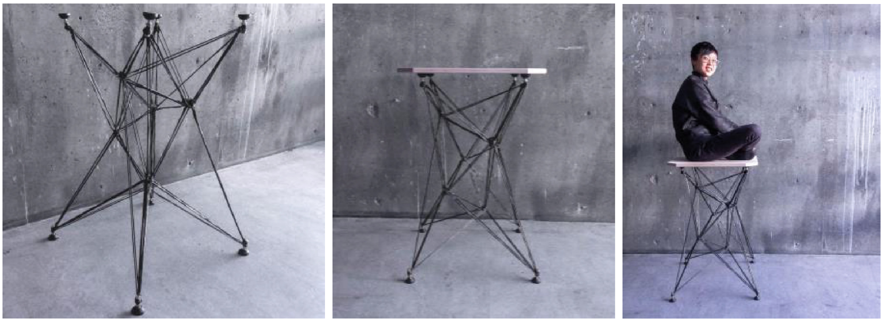

Fig. 21. Comparison of prototypes produced with and without complete *Slack Pack* system

Method	Dimensions	Weight	Fiber Used	Node Count	Max Load
By hand	61.3*61.3*70 cm	0.63 kg	77.9 m	14	15.7 kg
Slack Pack	60.1*60.1*90 cm	0.82 kg	101.3 m	14	55 kg
Percent Increase	23.6%	+30.0%	+30.0%	0%	+250.3%

Fig. 22. **a** Pre-tensioned state of demonstrator **b** Deployment of the demonstrator

5 Discussion

The specific contributions of this research include the development of a robotic winding process that can produce spatial geometries without the use of an external winding frame. It explores the use of multiple robotic agents that each manipulate separate material systems in order to achieve a task that neither could do independently. The direct manipulation of winding anchors and the localized curing of fiber through resistive heating are significant research outcomes that open the door for further developments, particularly as they relate to the use of slack in the winding process. The system's ability to produce collapsible structures that can then be erected onsite reduces logistical inefficiencies, helping to improve prefabrication in architecture and reduce carbon emissions from transportation.

While the methods detailed in this paper successfully present a novel CFW process, it is recognized that this research serves as a starting point and that further investigation and collaboration will be essential to fully explore the system's potential, particularly in areas such as geometry exploration, structural analysis, joint detail development, and deployment strategies. Despite having an integrated geometry generation tool, the system needs to have more reciprocity between geometry generation, structural analysis, and fabrication planning. The robot coordination should be synchronized between the two robots using a tool like KUKA.RoboTeam, a native software package provided by KUKA that allows geometric coupling of multiple robots (2023). Additionally, the hardware and material systems need to be developed further. Automated spot curing should be directly integrated into the NodeBot end effector and the effect of the rapid, localized curing on the structural capacity of the joint should be benchmarked and analyzed. In the current method, the management of slack fibers on the storage plane was not considered in detail. In order to improve slack management, alternative methods of storage have been hypothesized, such as storing each winding layer on its own storage plane or level. During prototyping, it was observed that early in the winding process slack fibers did not stick to the storage plane or to other fibers, but towards the end of the winding the earliest members began sticking to one another. The resin system in these prototypes had a gel time of approximately 10 h and the fiber volume ratio (the amount of fiber in the FRP by volume) of the composite was not accurately measured. By using a resin system with a much longer gel time and by more thoroughly exploring different fiber volume ratios, unwanted interactions between fibers in the slack state could be mitigated. Furthermore, understanding and precisely controlling the behavior of the resin system is crucial in improving the deployment and scalability of the system. Another area of future development is the behavior of nodes in the transition from the planar state to the spatial state. Currently, members are wound and stored in a 2-dimensional plane (based on projections of 3-dimensional angles). Thus, as the structure transitions from 2D to 3D the nodes rotate in a semi-uncontrolled manner. In order to improve this behavior, early prototypes of a 3D node were developed, with alignment grooves that contained fiber at custom angles. These custom grooves allow fiber members to meet at truly 3-dimensional angles and reduce or eliminate the rotation of nodes during deployment. These nodes require additional rotational axes to be added to the NodeBot end effector. Detailed integration of 3D nodes and the impact they have on the overall load carrying capacity of the structure should be explored and benchmarked in future iterations of the system. In order to thoroughly evaluate the system, more robust structural tests should be performed to evaluate how different parameters affect structural capacity. These parameters should be isolated and tested individually, beginning first with the nodes to understand the effect of node geometry and localized curing, then moving to the members to evaluate the impact of bundle size and buckling length, and lastly to the overall geometry to evaluate the effect of the global design and fabrication process. These results would better inform the fabrication process and could be used to validate the simulation and predictive tools.

6 Conclusion

This research successfully developed a method of robotic fiber winding that can produce spatial typologies without the need for premade winding frames. Using multi-robot collaboration, *Slack Pack* leverages the introduction of slack into the winding process, removing the requirement for a frame and extending achievable structure sizes far past the dimensions of the fabrication envelope. The outcome is an un-tensioned spatial structure that can be stored and transported in a collapsed state before being deployed onsite via tensioning and onsite curing. This novel fabrication method necessitated a fully integrated workflow in which the geometric design was informed by the structural and fabrication constraints of the system and the fabrication methods were directly controlled by the design and computational workflows. It required custom hardware, new robot interactions, bespoke geometry generation methods, and integrated path planning tools to be developed.

The use of FRP offers opportunities to explore new fiber typologies, leverage efficient material usage, and advance additive manufacturing techniques. The research detailed in this paper contributes to these opportunities and expands the realm of possibilities for spatial fiber structures in architecture.

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