Multi-Machine Fabrication

An Integrative Design Process Utilising an Autonomous UAV and Industrial Robots for the Fabrication of Long-Span Composite Structures

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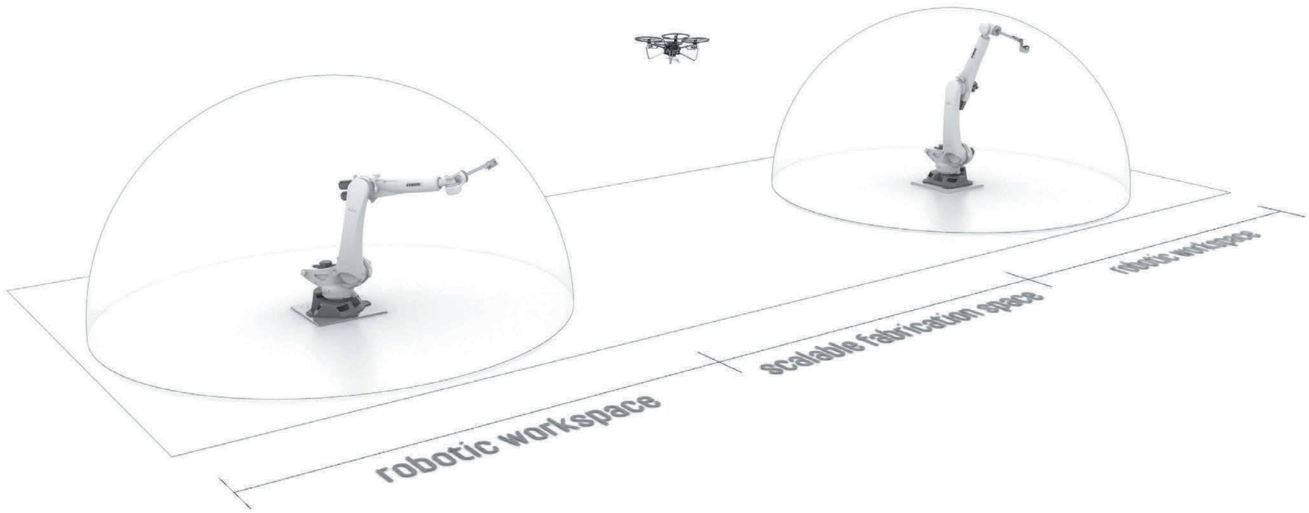
1 A long-span composite produced through a collaborative fabrication process between industrial robots and a UAV

ABSTRACT

Fiber composite materials have tremendous potential in architectural applications due to their high strength-to-weight ratio and their ability to be formed into complex shapes. Novel fabrication processes can be based on the unique affordances and characteristics of fiber composites. Because these materials are lightweight and have high tensile strength, a radically different approach to fabrication becomes possible, which combines low-payload yet long-range machines—such as unmanned aerial vehicles (UAV)—with strong, precise, yet limited-reach industrial robots. This collaborative concept enables a scalable fabrication setup for long-span fiber composite construction. This paper describes the integrated design process and design development of a large-scale cantilevering demonstrator, in which the fabrication setup, robotic constraints, material behavior, and structural performance were integrated in an iterative design process.



2 Concept for a scalable multi-machine fabrication process utilizing a custom made UAV and two industrial six-axis robots

INTRODUCTION

For long-span structures, where the material's strength-to-weight ratio is of high concern, lightweight fiber composites provide unparalleled performance in applications within the nautical, aerospace, and automotive industries. The potentials within architecture, however, largely remain unexplored. Traditional methods of fabrication require full-scale surface molds and often restrict the process to serialized production of identical parts. There are a lack of adequate fiber composite fabrication processes to produce at an architectural scale without incurring unnecessary material or labor costs or compromising the design freedom, system performance or adaptability required for the architecture and design industries (Menges and Knippers 2015).

CONTEXT

Research at the ICD and ITKE has explored integrative computational design, simulation and fabrication processes for fiber composite construction without the need for wasteful, and potentially costly, surface molds or formwork (Reichert et al. 2014). The previous work investigated large-scale coreless filament winding (Knippers et al. 2015), modular coreless filament winding (Dörstelmann et al. 2015; Parascho et al. 2015; Prado et al. 2017) and fiber placement on pneumatic bodies (Dörstelmann et al. 2015; Vasey et al. 2015). These novel robotically driven manufacturing processes have been utilized to create highly differentiated multilayered structures, functionally integrated building systems and large element assemblies, therefore introducing greater design freedom in working with this relatively formable material. However, the scale of these earlier investigations and the ability to utilize a continuous fiber structure has been limited by the working space of the robotic setup.

Drone Fabrication

Existing research has investigated the potential for fabricating architectural systems with unmanned aerial vehicles (UAVs). In Flight Assembled Architecture, quadrotor helicopters were developed to autonomously stack lightweight polystyrene bricks (Willman et al. 2012). More recently, flying robots were used to weave tensile bridge structures (Mirjan et al. 2016). While these previous projects demonstrate advanced drone control and the architectural potential therein, the limitations of drones—in particular, their relative imprecision, low payload and constrained working area due to the utilized motion tracking system—limited the possible tectonics of the resulting material systems. In contrast, this investigation attempts to use the UAVs merely for material transportation, where the precision and payload required for the placing and tensioning of material is provided by industrial robots. Furthermore a more scalable localization method allows for an easily extendible area of operation.

Multi-machine Fabrication Processes

Multi-machine and multi-robot work cells are commonplace in industrial applications, particularly in the automotive industry, where their use is primarily constrained to repeating identical operations on assembly lines. In application scenarios more specific to the field of architectural design and fabrication, the

3 Biological role model: *Lyonetia Clerkella* (© Steve Wullaert)

extended fabrication possibilities of multi-robot cells have been investigated in several different fabrication processes, including robotic bending, robotic sheet cutting, robotic assembly, and robotic winding (Parascho et al. 2017; Saunders et al. 2016; Rust et al. 2016; Prado et al. 2014). The majority of these investigations have used identical robots with similar specifications. In contrast, when considering the capabilities of various machines and the affordances of a lightweight material system, an alternative concept for fabrication becomes possible that combines low-payload yet long-range machines, such as UAVs, with strong, precise, yet limited-reach industrial robots. By doing this, the varying advantages are combined to accomplish a manufacturing task beyond the capabilities of a singular machine or system of similar machines.

Research Aims

This research investigated the viability of utilizing UAVs to supplement the limited working envelopment of industrial, high-payload, six-axis robots in a collaborative fabrication process for the production of a lightweight, materially efficient, long-span fiber composite structure. This presented research can be divided into three core components: (i) an investigation of functional morphologic principles and novel construction logics for lightweight, long-span composite structures in biological role models; (ii) the development of a fabrication concept and experimental setup for a collaborative fiber-winding process that would allow the UAV and robots to interact and exchange fabrication tasks; and (iii) the development of scalable design principles, computational methods, and construction strategies that would enable the production of a long-span fiber composite structure. The UAV was specifically chosen as the means of transportation over alternative solutions because of its limited requirements for further deployment infrastructure, its high maneuverability and its ability to operate in a virtually unlimited working area.

These research aims were investigated through the design and production of a 12-meter-long cantilever in a controlled fabrication work cell. The cantilever typology was selected because it requires structural performance criteria typical of load-bearing building systems, as well as to demonstrate a feasible production process for achieving a continuous long span that could not have been produced with another fabrication setup. Though the demonstrator was fabricated indoors in a controlled laboratory environment, the project was developed to address both scalability, in which the number and arrangements of robots could vary, as well as repeatability, with particular consideration for results that could be extrapolated to outdoor, in-situ or on-site conditions.

METHODS

Morphologic Principles and Construction Logics from Nature

Examples of highly performative fiber composite structures can be found in nature. These structures utilize fibrous materials similar to the glass and carbon fiber used in technical composites. Because of these similarities, the understanding and abstraction of the structural morphology and fabrication processes of these natural structures can offer new insights that can be transferred into architectural applications that employ technical composites (Menges and Knippers 2015). This led to a parallel bottom-up design strategy for the biomimetic investigation of natural construction processes of long-span fiber composite structures and the development of novel robotic fabrication methods for fiber-reinforced polymer structures. Two species of leaf miner moths, the *Lyonetia clerkella* and the *Leucoptera erythrinella*, whose larvae spin silk "hammocks," were identified as particularly promising for the transfer of morphological and procedural principles for long-span fibrous construction. Several concepts were abstracted from the biological role models and transferred into fabrication and structural concepts. The winding process of the hammocks sequentially bends the leaf to which it is attached, further reinforcing the hammock through this elastic deformation. The combination of a substructure that is actively bent into shape and coreless wound fiber reinforcement creates an integrated composite winding frame without a need for complex framework. The fiber orientation, hierarchy over a long-span structure and multistage volumetric laying processes were all morphological principles that could be transferred for the generation of complex three-dimensional geometries.

Fabrication Setup

In previous research, the limitation of the reach envelope of an industrial robot was overcome either by modularization of the built structure (Prado et al. 2017), the use of a mobile robotic device (Helm et al. 2014) or the collaboration of multiple robots

4 Fabrication setup with industrial robots, UAV, landing stations and a tension mechanism

(Parascho et al. 2017). Rather than simply adding the work ranges of two robots together, and in order to develop a fabrication method suitable to a less structured, in-situ environment, the heavy industrial robots are kept separate and static. The composite is then wound within the interstitial space between the robots by using a custom-developed lightweight UAV for material transport. This setup ultimately leads to a favorable division of labor, in which the advantages of both systems are multiplied. Winding resin-impregnated roving around the winding frame requires the precision and strength of the robotic arm to place a fiber under tension. The untethered freedom of the UAV, meanwhile, is well suited for transporting the fiber over longer distances whilst having fewer kinematic limitations.

Two landing platforms adjacent to the robots facilitate the multi-machine interaction. A removable winding effector carrying a resin-impregnated fiber is passed between UAV and robot (Figure 5). Both KUKA KR 210 R3100 Ultra robots were equipped with steel extensions to increase their reach, a hydraulic gripper to grasp the winding effector from the UAV and an infrared (IR) camera used to synchronize the robot's location to the position of the UAV and to compensate for landing imprecisions. A custom tension mechanism, based on dancing-bar tension control in industrial extrusion and rolling applications, provides control over the fiber tension as it is passed from the fiber source to the UAV or robot. This tension mechanism includes the dancer-bar with an active weight, integrated sensors and a motorized drum that either actively extrudes or provides a brake between the spools and dancer bar. A belt connecting each spool and a motor acts to rewind overextruded fibers. This setup could be altered so that non-impregnated carbon and glass fiber spools could be pulled by the drum through a resin bath.

The custom-built UAV (Figure 6) was made out of standard electronic devices and custom-made CFRP components. It was the result of multiple successive prototypes and gradually tailored towards stable flight, relatively high payload, low weight and scalable self-localization. The onboard electronics include control units like a flight controller (Meier et. al 2012) and a mobile CPU running a lightweight Linux distribution. Two on-board sensor systems enabled it to localize itself in space and thus to correctly interpret movement commands: a shutter camera with a visual fiducial system of unique tags (Olson 2011) mounted to the ceiling and a bundle of a sonar sensor with an optical flow camera (Honegger et. al 2013). This system was chosen over a motion tracking system (MTS), as it is often used in UAV research (Mellinger et. al 2011) and UAV-aided construction in lab environments (Lindsey et al. 2011; Augugliaro et al. 2013), because it does not rely on the relatively small working area of an MTS. A switchable magnet on the UAV's underside provides the ability to carry and release the winding effector.

Collaborative Winding Process

The collaborative winding process is enabled through an iterative exchange of the fiber effector between robot and drone. To wind a single anchor point, the robot travels around the frame, keeping the fiber high above the composite before winding it on around an anchor point. It then returns the winding effector back to the

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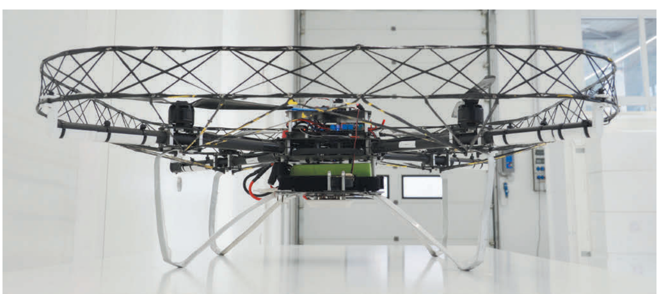

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5 Interactive Fiber exchange through passing fiber carrying winding effector between robot and UAV

6 Custom made UAV

landing platform where the UAV is waiting to pick it up and carry it to the opposite platform. After the exchange through magnet activation is confirmed, the tension mechanism switches to low tension mode by lowering the weight on the dancer bar. While unspooling the fiber,the drone carries the effector to the other landing platform, and the process repeats.

The distribution of tasks between robot and drone is achieved via a centralized control strategy with a Robot Operating System (ROS) server that dispatches tasks in the form of single-line instructions over Ethernet or wifi. Any given syntax of multiple fibers is represented as a sequential set of tasks between robot, drone, tension mechanism, magnet, and gripper. Additionally, each task is executed in sequence through a custom-developed web interface. A confirmation that one task has been completed must be received by the server before the next task is dispatched.

Online control of the robot is facilitated through the Robot Sensor Interface (RSI) signal processing package for KUKA. To enable adaptive execution of the control code at runtime, the robotic control code was modularized into a set of sub-procedures that rely on a minimal number of descriptive input parameters. These robotic behaviors include winding, traveling, and returning to or retracting from the platform.

INTEGRATED DESIGN DEVELOPMENT

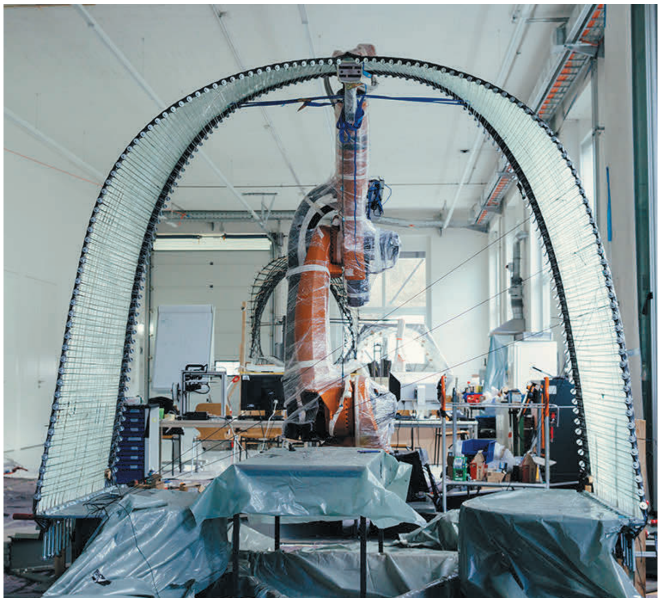
The iterative design process for the composite cantilever included several considerations, goals and constraints, including: (i) minimizing necessary formwork, (ii) guaranteeing reachability of all anchor points, (iii) minimizing fiber collisions with the pre-existing structure, (iv) creating a fiber-viable syntax that generated surface geometry through fiber to fiber interaction, (v) and integrating structural performance criteria, material differentiation and material efficiency.

Boundary Conditions and Frame Development

In previous instances of coreless filament winding, fibers have been wrapped around minimal steel skeletal frames that are later removed and, in the case of modular structures, reused for subsequent components (Prado et al. 2014). For this project, where a single monocoque form was created, two methods were utilized to minimize the complexity of the perimeter winding frames, which must resist high tensile forces.

The first strategy was to integrate and embed a composite winding frame (Figure 7) within the finished pavilion where the structure connected to the base. To create this integrated frame, a planar sheet of glass fibers was wound, cured, then bent elastically into shape. Later, an internal body of fibers was wound to create structural depth and thus rigidify the form. This enabled the creation of a complex winding frame with programmable form and stiffness without the need for a stiff, geometrically complex metal framework. Threaded aluminum sleeves embedded within the composite sheet exist as connection details for anchor points in later winding stages. These integrated sleeves enabled the elongation of winding points, when necessary, as wound fibers began to fill the frame.

At the cantilevering tip, a minimal metal frame holding the winding points was supported by standard reconfigurable steel formwork typically used for concrete construction. To allow the incremental tensioning of the structure, due to the continuous fiber-laying process, both frame structures were connected to support rails in the floor of the fabrication laboratory (Figure 12).



7 An elastically bent glass fiber sheet is incrementally reinforced through a process of winding volumetrically with glass and then carbon fiber.

Fabrication Constraints

The main fabrication consideration informing the development of the global geometry was to guarantee the reachability of all anchor points while minimizing collisions between the current fiber and the previously laid shell geometry. For any given fiber, a line with slack must be able to be stretched between the last wound anchor point and the fiber end effector, as well as between the end effector and fiber source.

In addition, the fabrication laboratory was a highly constrained rectangular volume, and safe drone flight required a two meter corridor. These boundary conditions, as well as the constraint of the large frame being both developable and reachable by robot, resulted in an iteratively refined, linear morphology.

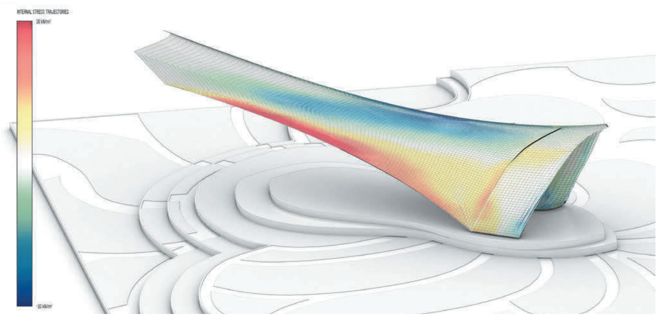
Fiber Syntax Development

The fiber syntax is the series of sequential fiber placements that result in an integrated composite surface. The sequence in which the fibers are laid have a dramatic effect on the resulting geometry and structure of the finished surface (Dörstelmann et al. 2014). Based on previous research at the ICD/ITKE, a series of workflows were developed that integrated computational tools with empirical testing at both model and full scale to generate, analyze, and test fiber syntaxes. These included consideration of fiber physics over a long span, fiber tension, material characteristics and geometric and structural analysis to explore and iterate alternatives throughout the fabrication process.

A combinatorial algorithm was used to generate any set of possible fiber paths between two discrete sets of fiber anchors. A set of relaxation tools utilizing a spring-based physics simulation could then be applied to fibers to determine slack under self-weight and tension. When applied to a group of fibers, these relaxation techniques could estimate the curvature of the resulting surface geometry. Additionally, evaluation methods would assess the fiber-to-fiber interaction of a single fiber under tension relative to a pre-existing surface geometry. For example, this computational tool would assess whether the fiber would exist above the surface and therefore be invalid, or wrap around the surface and therefore have good interaction. Physical model making on a small scale was used to verify whether a computed syntax created the intended surface geometry. Physical modeling was essential to reveal problematic fibers that created ridges in the surface. These physical and digital workflows were critical to develop a surface that had consistent fiber-to-fiber interaction.

Structural Refinement

The constituent elements of FRP are thin. The diameter of a carbon filament is on the order of 7μm (human hair is 70μm) and a bundle of 50,000 continuous filaments, called a tow or roving, has a diameter of approximately 1.5 mm dry, or 2 mm including resin. Even winding with 4 x 50,000 rovings per pass, it takes many passes to build up a composite lattice surface. Thus, rather than simply adding material to achieve the required strength for a pre-defined form, the global geometry of the pavilion was carefully manipulated to enable very thin structural surfaces to support the external loads (wind, snow, etc.). This was achieved through the use of a parametric surface model that allowed the optimization of the winding frame geometries (within an allowable range defined by the design aspirations), as shown in Figure 9. To prevent buckling of the thin compression edges, the lower edge of the form was “folded” inwards as seen in Figure 10 to



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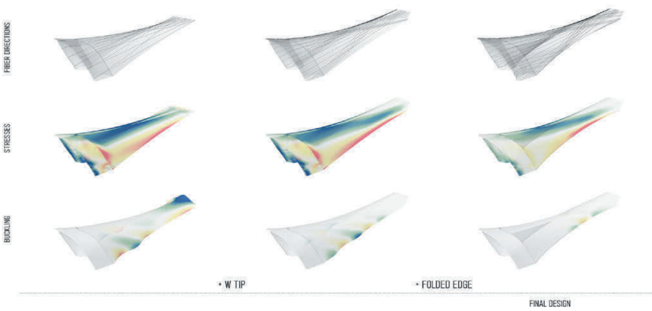

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create a channel-like form capable of withstanding the significant compression forces. To create this edge required a modified fiber transfer from outside to inside the composite frame without using the drone. With further development, it would be possible to fly the drone through the frame itself.

Material Differentiation

The composite structure went through several stages of refinement to develop the final form, material arrangement and density (Figure 11).

First, the global geometry was built up from glass fiber, without formwork or molds, following the logics of fabrication, syntax and shape optimization. This provided a dense fiber "body" or substrate on which the carbon fibers could be applied. The glass fibers, which are less expensive than the more structurally performative carbon fibers, were initially laid with directional variety to generate a dense mesh surface with minimal material. Additionally, the glass fiber composite material is translucent and partially reflective, making the interior layer of the cantilever visually lighter and less obstructive.

This glass body was then reinforced with carbon fiber ribs following the logics of surface topology optimization. To achieve this, a structural model was created that considered the pavilion as a generalized layer of isotropic composite material and allowed the determination of areas of high and low stress and regions susceptible to buckling. This model of critical and non-critical regions was then aligned with a model of geometrically possible fiber bundles, created by the syntax-development tools, to determine which paths were performing best and should therefore be utilized within the final structure.

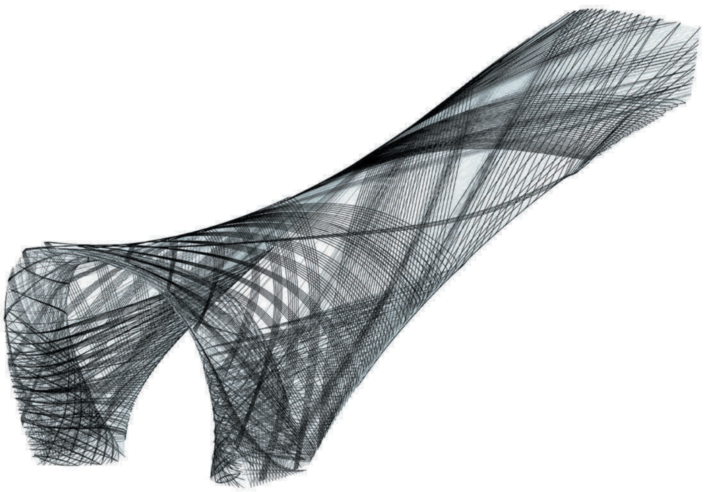
A more detailed beam-element structural model was finally created, which allowed the correct amount of material for each syntax path to be determined in response to the expected loading scenarios.

These steps were used iteratively and adaptively throughout the fabrication process and at various stages of winding, e.g., integrated frame, global surface, or folded-edge generation and reinforcement.

Verification of Structural Model Through Digitization of As-Built Geometry

Compared to previous projects, the scale of this pavilion was much larger and thus engaged a greater degree of unpredictability. Understanding how well the fiber syntax strategies created the designed geometry was an important consideration. To relate the digital design iterations to the as-built geometry of the pavilion, a process of iterative surveying with a MultiStation was used.

The project was set up in a local coordinate system in the laboratory. The robot bases were defined relative to this coordinate system. After the first stage of winding on the bent fiber frame was completed, the laid fibers were laser-scanned using the MultiStation. The comparison of intended



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8 Stress trajectories within the structural surface model, used to inform the final carbon fiber rib placement

9 Structural development from flat-tip/straight-edge (left) to folded-tip/straight-edge (center) to folded-tip/folded-edge (right). Each geometric manipulation reduced peak stresses and improved buckling performance

10 Realized folding edge

11 Pavilion Fiber Layers. Bottom to top: Glass-fiber geometry formation, first carbon-fiber reinforcement, glass fiber folding edge creation, carbon fiber folding tip reinforcement, carbon fiber folding edge and frame reinforcement.

and produced geometry was crucial to (i) determine geometry and future position of the cantilever sheet and (ii) to verify the shape assumptions informed by the deformation of the structural model. The deviation in terms of normal distances ranged between 10 and 50 mm. The pointcloud was meshed and used for further development of both the structural and the architectural model.

After completing the carbon fiber reinforcement of the bent frame, it was load tested in multiple steps and configurations with horizontal loads up to 10 kN. The deformations were recorded at five characteristic locations on the frame using reflective tape markers. The deformation values were overlaid with the structural model, resulting in very close correlation of the two.

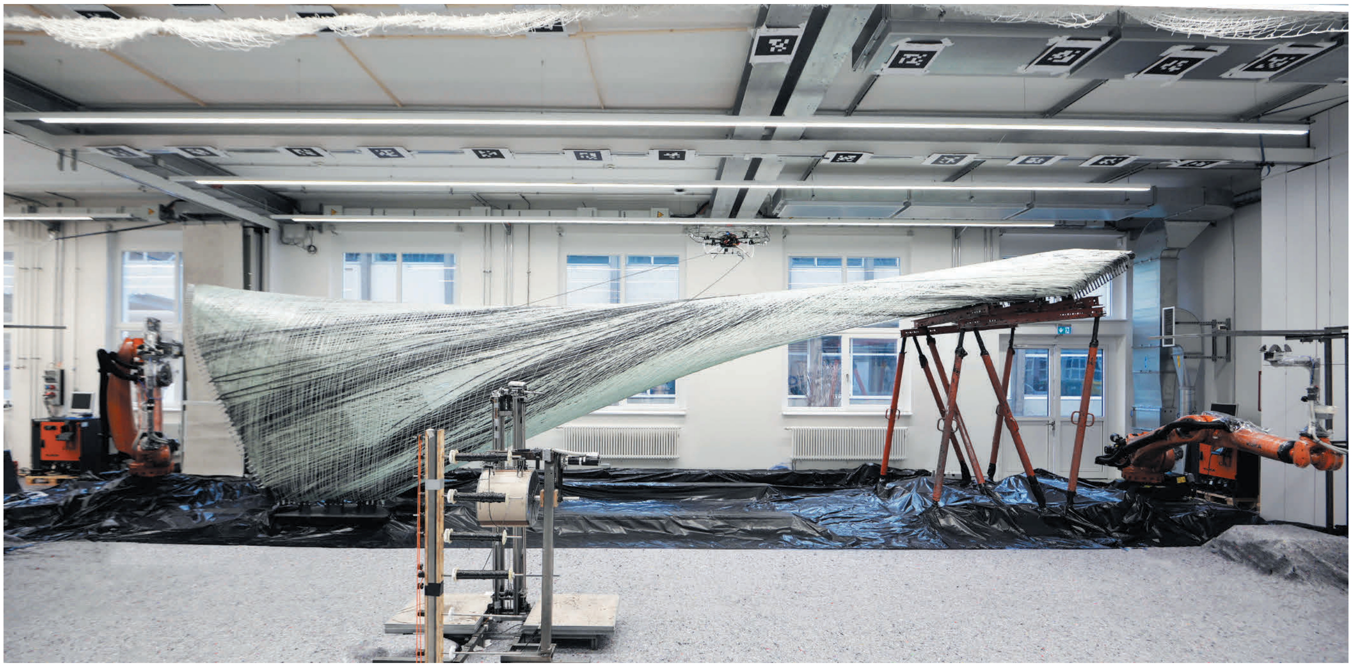
The geometry of the first carbon fiber ribs, which carry the main load of the structure, was surveyed. This allowed for the incremental calibration of the beam-element structural model, due to the possibility to compare computed deflection to actual deflection.

DEMONSTRATOR AND CONCLUSION

The demonstrator was completed in March 2017 and moved from the production site to its current location on the campus of Stuttgart University. It weighs approximately 1,000 kg and covers an area of 26.50 m² at a length of 12.00 m and a width of 2.60 m. The cantilever is able to withstand all external loading scenarios required by the European building code for temporary building structures. It demonstrates that it is possible to create a strong, thin-shell structure that is both able to resist local buckling and is fabricatable through collaborative multi-machine coreless filament winding. It shows that through careful geometric control, this material and fabrication system is suitable to be used for large-scale structural and architectural applications.

The scale of the demonstrator is only an indication of the achievable size of such a structure. While the spatial limitations of the two ends are directly informed by the robotic systems and the constraints of the lab, the length is a result of the capability of the used fiber transport and tensioning systems. The unspooling and respooling of the fiber, the travelling speed of the transportation system and the tension control need to be perfectly coordinated for longer distances and feasible production times. In addition, tension control is not sufficient to guarantee that a given fiber syntax will produce desired fiber-to-fiber interaction. Creating desired curvature through geometry is particularly important.

The demonstrator in its final shape is a cumulative and negotiated result of material performance criteria, structural stability parameters, fabrication limitations, and a design desire for a bold structural expression in the form of a cantilever. The lattice-like, multilayered and porous texture of the fiber-wound surface, together with the differentiated qualities (density, directionality and depth) of the structure, are byproducts of material-structure-fabrication-informed design. Once documented and



12 Fabrication setup with completed glass fiber form and early carbon fiber placement, the tension mechanism is shown in the foreground

analyzed, these qualities could systematically fulfill specific architectural envelope functions, such as light diffusion and shading, or be simply utilized because of their visual qualities. The novel aesthetics brought forward by coreless fiber winding are not only prerequisites of a design-tailored and flexible fabrication concept, but also a novel method of interdisciplinary design workflow.

The advantages of fiber composites, in terms of material performance and structural efficiency, have been thoroughly discussed in previous research projects and are well established. The ongoing strand of research focusing on coreless filament winding pursued by ICD and ITKE has aimed to tackle the problems that arise when adapting this technology for architectural applications. By investigating geometric, structural, computational and material logics in an interdisciplinary design workflow, this research-based and prototypical approach aims to address obvious economic and design obstacles, and to develop new architectural tectonics and structural typologies in unison. This notion contrasts the current architectural top-down design approach, where design intent often overrules structural feasibility, material logic and fabrication constraints. The presented multi-machine fabrication system was designed with a strong focus on scalability, where both the physical and the digital infrastructures are theoretically extendible. With a variety of robotic machinery becoming more relevant in the construction industry, the localization and communication of these devices becomes more important when opting for automated large-scale construction systems. Though tailored towards the material system of carbon reinforced polymers, the presented fabrication setup of UAV-aided construction through multi-machine collaboration generally aims to serve as a model for future developments.

OUTLOOK AND NEXT STEPS

This project verified that a collaborative fabrication process between multiple fabrication agents, in particular short-range high-precision robots and a long-range low-precision UAVs, was possible. In addition, the project developed important system components, including tension control mechanisms and volumetric winding strategies that could be used in future investigations for long-span composite fabrication.

The biggest shortcoming of the process, however, was the relatively slow process speed and the inconsistency of each of the software and hardware components. The UAV provided the largest bottleneck for speed, particularly when using the resin-impregnated fiber, which added substantial friction and tension to the system. If all parts were running, the process with UAV could enable the transfer and wrapping of a single bundle with 50,000-filament rovings in six minutes. In contrast, transporting the fiber via a secondary method enabled four times the amount of material to be laid in one quarter of the time. In addition, hardware failures often caused the workflow to run in semi-automated mode, in which certain subroutines, for example, IR localization of the UAV on the landing station, were bypassed.

Thus, the fully automated fabrication process was only utilized for a small portion of the completed structure. Individual parts of the automated setup, such as the robots and the tension mechanism, were utilized for up to 50% of the production time. The remainder of the fibers were placed robotically without the UAV but with manual assistance. Though the project provided a proof of concept for a scalable fiber laying system, further development is now required for this system to be utilized efficiently in an industrial production scenario. Such an endeavor could follow the proof-of-concept stage as it requires a longer development time than the scope of the project allowed.

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IMAGE CREDITS

Figure 5: © Steve Wullaert, September 28th 2014

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