Bio-inspired and fabrication-informed design strategies for modular fibrous structures in architecture

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Research pavilions can serve as architectural scale demonstrations for the materialization of experimental forms and structures. Pavilions seek to prove and change methods of design and construction mechanisms in order to achieve desires such as material efficiency, novel spatial qualities and performative needs. The case of the ICD/ITKE Research Pavilion 2013-14 highlights the use of fiber composites in order to achieve a core-less filament winding modular system from bio-inspired lightweight structures through robotic fabrication. This paper describes the multi-disciplinary design and construction process of this pavilion that created a structure of out 36 unique components.

Keywords: *bio-inspired, fiber composites, multi-disciplinary design, robotic fabrication, modular system construction*

INTRODUCTION

Biology-inspired projects often involve a team of researchers and students who work through a collaborative design methodology. For example, the Silk Pavilion by the Mediated Matter group at the MIT Media Lab involved a team of researchers and students who worked on a holistic and sustainable design of "non-woven fiber-based constructions". By studying the material and fabrication methods of Bombyx-mori Silkworm and the use of simulation tools, the team constructed a large scale pavilion through a species that naturally prints in 3-D and a digitally fabricated framework (Oxman, 2011). Furthermore, the ITKE at the University of Stuttgart also explored and implemented the use of a biomimetic façade shading system, Flectofin, whose characteristics were derived from a multidisciplinary study on the elastic deformation of the Strelitzia reginae flower (Knippers and Speck, 2012). Such projects stimulate the integration of fields of study such as biology, architecture and engineering in order to implement innovative designs and novel construction processes.

Utilizing a collaborative design methodology to facilitate a biologically informed product allows for greater exactitude of all stages of the project from design to product. The joint research studio between the University of Stuttgart and the University of Tübingen which consisted of both researchers and students from an architectural and biological background, working together to combine knowledge and implement it into a full-scale demonstrator. A parametric design tool was used to fuse the research, fabrication, and progression of the work from various fields of study.

By combining topics such as architecture, biology and robotic fabrication, new levels of creativity are developed with a scientific basis while adopting a reliable robotic fabrication method. Due to the set schedule of the project, the prototypes evolved from hand-made models to a single-robot setup, and finally matured into a robust two-robot method to produce core-less filament modules. The abstraction of natural morphologic principles allows for the opportunity to use robust solutions, which when adapted to robotic fabrication strategies can create a precise and performative system. This research leads to a 1:1 pavilion as a demonstrator for testing the tolerances, material behavior and form of this system. (Figure 1)

CONTEXT

Biomimetic design strategies in architecture

The term biomimetics was formulated in the 1960s by American engineer Otto H. Schmitt by combining the Greek words bios (life) and mimesis (imitate). It refers to a method of abstracting principles found in biology to solve complex problems in technology (Schmitt, 1969). With the increasing sophistication of tools and methods we can now not only study patterns and techniques in nature that were previously out of scope but also garner further understanding of the guiding natural principles, in order to abstract, transfer, and successfully apply them to the built environment.

Biomimetics has different methodologies: "(a) Bottom-up process of biomimetics (biology push).

Figure 1
Full-scale prototype at the University of Stüttgart (ICD/ITKE)

(b) Top-down process of biomimetic research (technology pull)" (Knippers and Speck, 2012). This paper describes a bottom-up process from which a biological role model investigation led to an innovative use of robotic tools for filament winding. The use of robotics in architecture is implemented by adopting industrial machinery through custom software interfaces and personalizing end-effectors (Brell-Crokcan and Braumann, 2012). This design process took advantage of CAM (computer-aided manufacturing) methods using pre-existing 6-axis robotic arms, and profiting from the ease of use and variability that is pertinent in both iterative and flexible CAD (computer aided designs).

Fiber composites are an active area of research in industrial or engineering arenas. They allow products to become structurally efficient and light and are traditionally manufactured by applying malleable material over molds. In natural systems, fibrous structures can achieve a wide range of performative qualities such as flexibility, a greater diversity of material density through anisotropic material organization, as well as differentiated structural reinforcement without the need for molds. In the ICD/ITKE Research Pavilion 2012, a core-less filament winding system was developed where a robotic arm placed the fiber around a framework that was removed after the prototype was cured and complete (Weigele, 2012). The ICD/ITKE Research Pavilion 2013-14 further developed a bottom-up methodology utilizing a reconfigurable and removable framework to create core-less winding modules with a two-robotic setup (Prado and Dörstelmann, 2014).

METHODS

Biomimetic investigation

The process of abstracting biomimetic principles makes it possible to design architectural pavilions whose role is to optimize material usage and weight, provide new architectural qualities and structural systems, and therefore understand natural systems on a deeper functional and methodological level (Knippers and Speck, 2012). The biomimetic investigation was searching for new performative morphologies, as well as innovative fiber composites material organization principles which could be developed into robotic fabrication strategies.

Four topics were sought as a basis for preliminary biomimetic investigations: 1) fiber layouts, 2) fabrication methods, 3) joint-systems, and 4) functional morphology, all through conceptual biological role models. Arthropod cuticles, known for their high-performance fibrous structures, were researched by biologist for potentials to adapt and perform in an architectural realm. Simultaneously, there was a continuous effort to investigate fiber models that pursued an understand of fiber behavior and their construction framework. (Figure 2)

Figure 2
Hand-made models of the construction system

The elytra are protective hind-wings for beetles can withstand bending and compression forces and demonstrate high aerodynamic performance. (Van de Kamp, 2010). This role model first became a focus of investigation due to its lightweight capacity and the structural height that serves as the protective characteristic for beetles' flying wings. After further investigation by the biologists, the elytra also presented several species morphological variations that influenced the performative characteristics of the pavilion design. Hence, influencing the concept of the pavilion both in terms of its micro-fiber arrangement and also regarding the geometric layout of the fibrous structures on a global scale.

The biological investigation provided a notion of the construction of the system of the elytra. The fibers are embedded in a matrix of proteins, and piled into a series of helicoidal fiber layers in order to resist stresses in all directions (Lomakin, 2004). These are hollow fiber bundles that connect upper and lower surfaces act as a "bridge pier" in between the wings (Figure 3). The trabeculae, or hollow fiber bundle columns, are arranged throughout the elytra in a non-uniform manner, while the remaining areas constitute blood cavities. In ground beetles, the blood cavities are reduced and there is a higher density of fibers. Flying beetles, which tend to be more lightweight, have a reduced number of fibers and larger cavities (Van de Kamp, 2010). Therefore, the investigation focused on eight different flying beetles that showed density patterns on the trabeculae, proportionate to the thickness of the elytra, and their mechanical characteristics vis-a-vis the beetle's body.

Part of the project's investigation was to develop a modularized system of fabrication. This would allow for reuse of construction parts of variable elements, and would create a pavilion that could be easily transported. Furthermore, the fabrication constraints would not permit a creation of an entire beetle elytra structure, but rather abstracted individual trabeculae, as components for a global system. These components resembled hyperbolic columns that were fabricable as coreless filament-wound modules. Although biologists had presented more interest in the micro-scale fiber arrangements, the need for architects to analyze the elytra as a whole presented an opportunity to study the arrangement of the hyperbolic columns along the wing in order to abstract the pattern in which the fiber columns are located. The analysis of particular species also showed the cantilevering capacity of the elytra as well as the multiple connection of hyperboloid columns. (photo) The matrix found in the fiber layers translated into the resin epoxy-based mixture used in composite systems.

Development of the fabrication logic

The building components for the double-layered system required two set of frames made up of rim-shaped polygons. Each side of the polygons was divided with a regular spaced set of hooking points, or control points, where the fiber was wrapped around, creating a hyperboloid in an iterative way. This constituted the fiber syntax. The frames could change in size, symmetry, angle and position shift, as well as in their winding logic. This provided the opportunity to optimize the material usage by reinforcing areas where more fiber was required to ensure fiber interaction. The components, or hyperboloids, each had seven layers of fibers that included a glass fiber base followed by a number of carbon fiber structural vectors. (Figure 4) These were differentiated codes that ensured the structural capacity of each element by itself and transferred a cross-bracing system of rein-

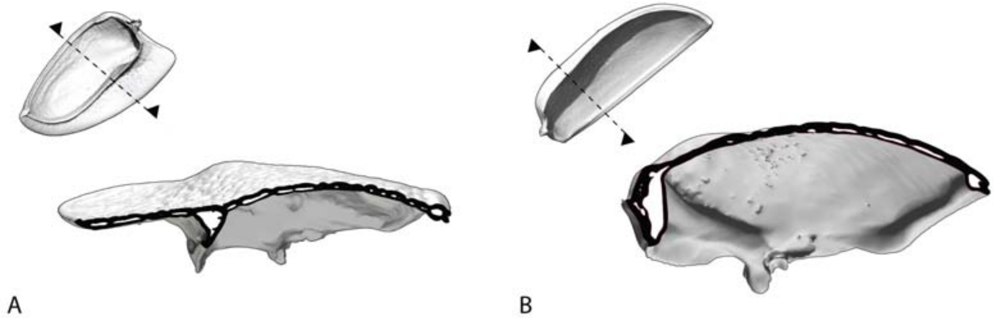

Figure 3
Sections of the elytra: A) Cassidia Beetle , B) Chrysomela vigintipunctata Beetle

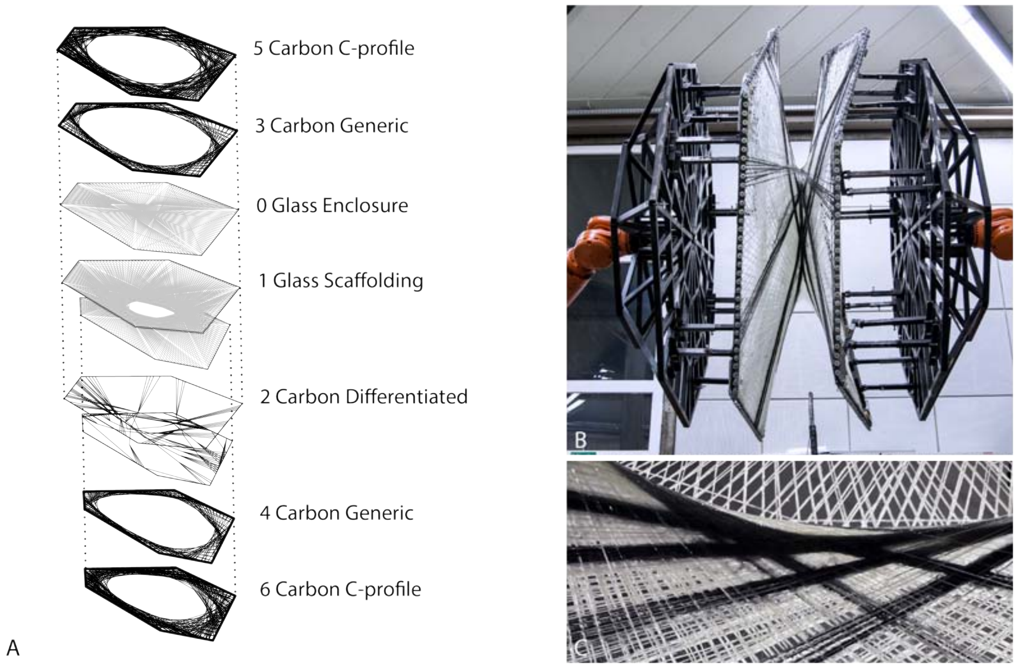

Figure 4
Fiber layer system of the hyperbolic column and the robtic setup

forcements along the whole global system when the elements were connected.

Handmade models were created to test construction parameters such as polygon shape, binding tension, and fiber manipulation, in order to transfer proper winding patterns and fiber interactions onto a computational domain. The winding logic of each component was transferred as CAD information by creating a winding syntax polyline that was able to easily store the order of the hooking points and at the same time gave a rough visual control of the fiber mandrel. This translated into a two-robot system setup that guaranteed the precise and automated fiber placement. It also meant simplifying the process since the robots ensured the code-based winding logic and also provided the opportunity to iterate or change the logics to create a stable hyperboloid component.

Synthesis of biomimetic research and development of suitable fabrication strategies

The production was based on a non-woven concept, meaning that the layering of winding logics and their binding tension was necessary. The density of the fiber of each component varied according to its position in the global design, aiding in force transfer among the various components. However, the fiber syntax also integrated restrictions on a fabrication platform, so all elements needed to be conceivable for material manipulation and on a robotic domain.

The exploration of the different beetle species, furnished enough information to transfer to the global design. According to the abstracted principles, the double layered system could have the following characteristics: 1) hyperbolic column arrangements with a higher density on the outside rim, 2) a bifurcation of the components leading to a 3) cantilever, 4) proportions of the thickness of the components from a thicker base to a thinner apex and 5) differentiated winding logics that would transfer forces parallel on each individual surface and through helicoidally wound elements connecting bottom and top surfaces.

The fabrication was led by these preliminary characteristics, but at the same time had its own restrictions: 1) winding logics that left enough space for the frame to be removed, 2) size manipulation to avoid collisions of the end-effector and the robotic arm, 3) sufficient thickness for the elements to be wound inside and 4) polygon shape and angle ranges for the robots to construct their own frames and wind comfortably. Winding codes were developed through algorithms that made them applicable for all the elements comprised in the system.

INTEGRATIVE DESIGN AND CONSTRUCTION PROCESS

Collaborative studio experience

The project was established as a vertical integration in a design-to-build oriented studio. An interdisciplinary team of students and researchers provided the opportunity to test and investigate on many aspects thoroughly, producing large-scale prototypes that entailed a robust production with real structural results. The studio workflow divided students into eight different groups of research: 1) biology, 2) component, 3) component system, 4) material system, 5) structural system, 6) joints, 7) effector, 8) robotics. The students took the conceptual design and preliminary investigation of the beetle elytra, and expand on the topics assigned to them. Through this methodology, the hyperboloid component required enough information to work structurally as a component on its own, connect itself to another component, and be part of a component system global design. Moreover, the material system team was in charge of examining the fiber spool setup and epoxy resin base properties, leading to a robotic setup which required a personalized end-tool or effector in order to wind the differentiated building elements.

Group work was separated in order to grasp all the factors regarding the elytra and plausible abstractions, both individually and as a loop-feedback system for the pavilion construction. The research consisted of generic test models to inspect the software or tools used by each particular group, which would mature into descriptive characteristics able to feed a production loop. Furthermore, the limitations of time and availability of tools made some steps more dynamic or static, leading to a faster progression of some characteristics that started to create a number of rulesets. For example, before the arrival of the two robots for the setup, the fiber tests and code generation would be first based on a single robotic system. The wooden frame used as an effector showed structural weakness and therefore led to an empirical appreciation of the capacity that the effector required in order to diminish the deviation of the wound prototype to its minimum. The effector group then established a highly structural yet flexible system, whose frame assembly had geometrical restrictions but ensured reconfigurability for all elements in the production. (Figure 5)

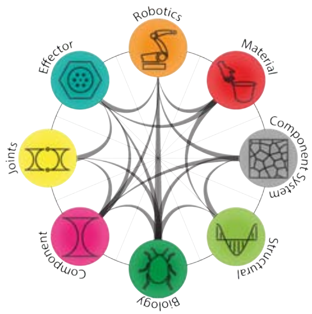

Figure 5
Project group division and collaboration

The collaborative group work was organized in order to represent, test through prototypes, and set constraints that would guide the other aspects of the project. Working on the same virtual platform facilitated the possibility to make any adaptations to the design and fabrication strategies. Every aspect was of equal importance, meaning that the construction system evolved was perfected in every detail towards the culmination of the project.

Fabrication setup and organization

The fabrication process consisted of a 12-axis robot setup. This was composed of two synchronized 6-axis industrial arms KUKA KR210 R3100. Each robot was equipped with custom made steel space frames, on which two outline rims were mounted made out of reusable steel bars that defined the shape of the component as explained above. The bars were connected with 5 axis cut plywood guides that were unique for each component. The fiber source, where the fiber was dipped into an epoxy resin before it was hooked around control points, was attached to a concrete slab between the two robots.

The construction of each component was divided into four stages: 1) end-effector prefabrication, 2) end-effector assembly, 3) core-less filament winding and 4) component survey. Every stage in the process depended on the previous one, creating a closed production loop. In line with the concept of prototyping digital fabrication processes contrast to prototyping products, the fabrication method could be improved with every new component produced, based on the feedback from the previous one. The component survey also allowed the opportunity to measure the real result of the prototype, making the research complete by having concrete data of what was being produced. The measurability was an aspect that arose due to the facilitation of working with robots, emphasizing the importance of combining robotics and architecture during a learning architecture experience.

The time schedule of the production loop is explained in the critical path diagram (Figure 6). The main critical path was the time when the robots were working on assembly, winding, and curing. Therefore, it was possible to easily fast track the whole process and shorten the path average up to two days per component, even to one day fabrication loop for the smallest ones. The whole production phase was organized as student-to-student tutoring part of the new design studio semester. It was a good opportunity for students who developed the process to pass on the knowledge to the new students and help them familiarize with the material and techniques as well as with the robotic fabrication itself.

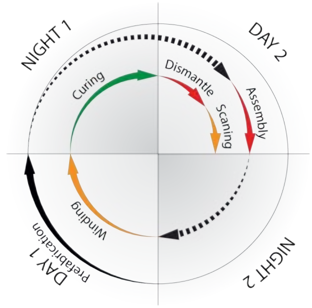

Figure 6
Time-flow diagram of the fabrication loop explaining processes overlaping in the production of the components.

CAM process development

Robots can be usually programmed in two ways: 1) an online/automatic method, in which the robot is receiving the information indirectly and the "programmer" has only limted control over the program itself (e.g. programing by demonstration or inductive programming), 2) an offline/manual methods, in which the behavior information for the robot is generated offline and the robot is provided with precise commands in specific programming language (e.g. the KUKA Robot Language - KRL). (Biggs and MacDonald, 2003). In this project an offline method was applied due to the parametric nature of the design and thus the possibility to take advantage of a CAM solution.

For each step of the production a new custom-made algorithm was developed. However, since the beginning, the main focus was placed on developing the winding path generation that was based on the syntax polyline, shapes of the component's outline polygons and the orientation of their parts (fig. 00). The algorithm itself had three main steps: 1) sorting - breaking down the syntax polyline and transforming it into frames based on the orientation of the sides of the outline polygon, 2) generating - defining the safe path for the fiber source by hitting checkpoints around its way from point- to-point and adding a hooking movement in the end and 3) translating - reorienting control points frames to end effector frames, transferring the position data into a KRL structure and saving it in a text file. (Figure7)

Each line in the robot code represents one specific position of the end effector within the working envelope. The movement is therefore accomplished by aligning the frame of the end-effector with the target frame by repositioning the arm as little as possible. Although the robotic setup was comprised of two robots, only the master robot was running the winding code. The slave robot locked a specific offset position of its flange in the coordinate system of the master's flange and kept it unchanged during the entire winding and curing phase.

After a few test runs with the largest components, it was also evident that the size of the components made it necessary to optimize the workspace. The most viable solution, without readjusting the physical position of the fiber source, was to rotate the virtual frame of the base, which was set as the tip of the fiber feeding tube. To be able to do that, all positions outside the working envelope were located. Moreover, an evolutionary algorithm was created and tested before each winding sequence to minimally rotate the base to fit in all these crucial positions. Subsequently, an effector frame optimization algorithm was added to position the space frames of both robots as parallel as possible to each other as well as simple collision detection.

RESULTS AND CONCLUSION

The ICD/ITKE Research Pavilion 2013-14, based on the beetle elytra as a fiber reinforced double-layered lightweight system, developed a two-robot robust setup that was able to create differentiated core-less filament elements. The design allowed the structure to have a parameter based on material efficiency and fibrous geometric performances.

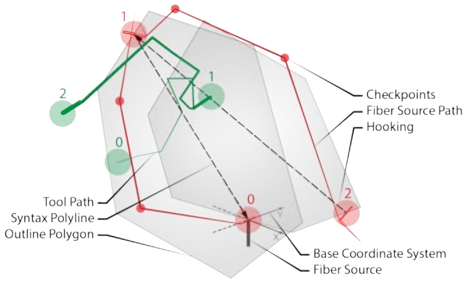

Figure 7
Based on the syntax polyline (black) is generated path of the fiber source (red), that is further translated into the end effector path (green).

The research on biological role models, the transfer of performative principles of structural morphology as well as the further development of a coreless robotic filament winding technique resulted in a proposal of a double layered modular structure able to adapt geometrically according to the set of defined parameters. Fiber layout, component geometry, and global component arrangement were principles abstracted from the microscopic fiber layouts and global distributions of the fiber bundles of the beetle's elytra. The ability to construct many unique components using a minimal amount of material resources led to a modular-based system design. This paper presents the fusion of computational data from biological analysis, computational design and robotic manufacturing, resulting in the prototypical structure composed out of 36 unique components. (Figure 8)

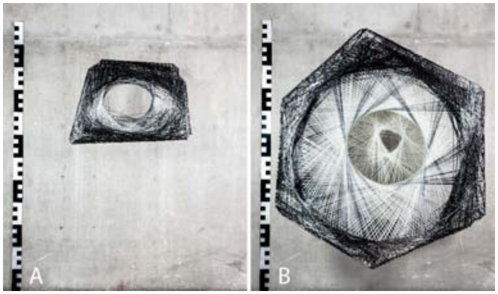

Figure 8
Two unique components that demonstrate the scalability of the system that was created

Figure 9
Interior of the Pavilion showing the scale of the components (ICD/ITKE)

The research process provided the opportunity to create a modular construction system, that was not only tested on a full-scale scenario, but also provided to measure and analyze the result of its construction. The pavilion's elements each have an individual fiber layout which results in a material efficient load-bearing system. The diameter of the components range from 0.536 to 2.5 meters (Figure 9). The biggest element weighs 24.1 kg. The research pavilion covers a total area of 50 m^2 and a volume of 122 m^3 with a total weight of 593 kg. The structure reaches a height of 3.4 m. The multidisciplinary design and fabrication strategies from a bottom-up biomimetic implementation resulted in the construction of the pavilion as well as a robust fabrication system for the construction of core-less filament wound hyperbolic components.

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