MACHINIC MORPHOSPACES:
BIOMIMETIC DESIGN STRATEGIES FOR THE COMPUTATIONAL EXPLORATION OF ROBOT CONSTRAINT SPACES FOR WOOD FABRICATION

ABSTRACT

The paper presents research into computational design processes that integrate not only criteria of physical producibility but also characteristics of design intelligence and performance. In the first part, the use of an industrial robot's design space for developing differentiated finger joint connections for planar sheets of plywood is introduced. Subsequently, biomimetics is proposed as a filter for the possible geometric differentiations with respect to performative capacities. The second part focuses on the integration of vwfabricational and biomimetic principles with structural and architectural demands, as well as the development of a custom digital data structure for the fabrication of finger joint plate structures resulting in the construction of a full-scale prototype. The paper concludes with an evaluation of the tolerances inherent in construction through 3D laser scan validation of the physical prototype.

Tobias Schwinn
Institute for Computational Design
University of Stuttgart

Oliver David Krieg
Institute for Computational Design
University of Stuttgart

Professor Achim Menges
Institute for Computational Design
University of Stuttgart

Boyan Mihaylov
Institute for Computational Design
University of Stuttgart

Steffen Reichert
Institute for Computational Design
University of Stuttgart

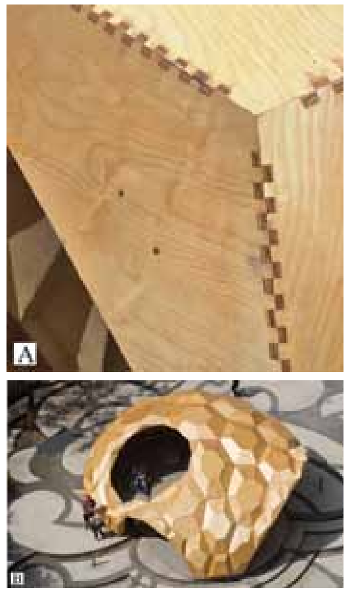


figure 1

1 INTRODUCTION

Current research in the field of digital fabrication in architecture is characterized by a shift from CNC machinery designed for a specific task toward more generic fabrication equipment such as industrial robots. This offers a vast, ever increasing space of design possibilities. While design computation has been employed to explore this space according to machine constraints and material characteristics, surely the next step is to develop computational tools and techniques that focus this exploration on populating particularly promising areas of the solution space without setting a priori limits.

In this context, biomimetics offers both the systematics of conceptualizing the space of robotic fabrication possibilities through the biological concept of morphospaces (Menges and Schwinn 2012; Eble 1999), and design strategies for higher performance and effectiveness based on biological principles. The research presented in this paper is based on a biomimetic approach for both the development of construction systems (Knippers and Speck 2012) and generative computational design processes (Menges 2012). This approach was introduced in previous research as a theoretical methodology for extracting morphological principles related to structural and architectural demands as drivers in the context of performative morphologies in architecture (Krieg et al. 2011). This paper presents the practical implementation through a case-study project conducted in collaboration with architects, structural engineers, biologists, and geodetic engineers, which resulted in a full-scale prototype (Figure 1b). A particular innovation consists in the possibility of effectively extending the recognized biomimetic principles and related performance criteria to a range of different geometries through computational processes, which is demonstrated by the fact that the complex morphology of the pavilion could be built exclusively with extremely thin 6.5 mm (1/4 inch) sheets of finger joined plywood (Figure 1a).

2 MATERIAL-TOOL-MACHINE

2.1 Wood Jointing

As a regionally available and renewable resource in temperate climate zones, wood is again increasingly being used as a construction material in the building industry. Due to wood's long history in timber construction and architecture, particularly throughout the preindustrial era, traditional wood jointing techniques were developed and refined over a long period of manual fabrication characterized by limited material supply and laborious production. In consequence, wood fabrication techniques not only make advances in production technology visible (Schindler 2007; Hoadley 2000) but also show that these original constraints drove the development toward very performative wood joints (Figure 2a). These joints were adapted to the slow, yet highly geometrically complex range of possibilities in manual fabrication in order to match the requirements of material behavior and durability. However, contemporary timber construction shows the same issues symptomatic of all industrial mass-fabricated construction techniques, as the joint is considered the most complex part of the design for which manually fabricated solutions cannot be taken into account (Schindler 2009). Mainly because of a break in the material's fibrous connection, a material change from timber to steel seems industrially necessary and feasible, which leads to further problems such as different temperature behavior and corrosion.

2.2 Finger Joints

The following case study commenced with an investigation into extending traditional wood jointing techniques through digital fabrication. Finger joints have been an ancient and commonly used corner joint for over 3,500 years and are still being used today (Kirby 1999). Finger joints connect planar elements in a specific angle through multiple interlocking teeth with a straight or tapered shape in a force- and form-fitting manner, resulting in high structural capacity to withstand normal and particularly shear forces without the need for additional fasteners. Wood's ecological aspects and performative capacities combined with material-efficient design and manufacturing holds the potential for a sustainable and highly differentiated building process (Krieg et al. 2011).

figure 1

A: Detailed view of the developed finger joint connection; B: Top view of the built full-scale prototype.

figure 2

A: Manual fabrication of dovetail joints; B: Tools for machine-based fabrication of different finger joints restricted to a 90° connection; C: Customized milling tool for newly developed robotic fabrication technique.

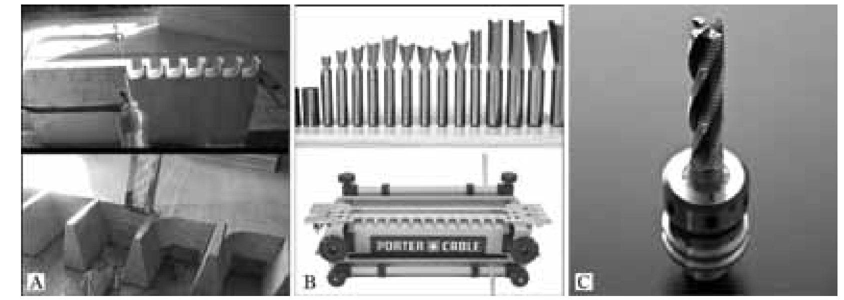


figure 2

figure 3

2.3 Robotic Milling

In traditional woodworking the finger joint's structural and aesthetic quality is achieved mostly through manual fabrication. Although machine-controlled manufacturing processes standardized the connection, due to the finger joint's complex geometry an economically feasible fabrication method for joints of varying angles does not yet exist for CNC production (Figure 2b). The development of a combined milling and cutting tool by one of the industrial partners of this research undertaking (Figure 2c) and a highly precise, yet individual finger joint milling technique lead to a novel finger jointing system for connecting plates at varying angles producible only through a kinetic range of at least seven degrees of freedom (DOF).

The presented development of a new digital fabrication process is based on an industrial robot consisting of six revolute axes linked to an additional turntable on which an unprocessed piece can be machined from any direction (Figure 3). This novel fabrication technique extends the machine's design space considerably further than that of traditional CNC machinery as it now allows the production of complex finger joint plate connections (Figure 4). Therefore the high degree of geometric freedom in joint production and thus of differentiation within plate structures raises the question of how the related design space can be explored in areas of high performative capacity.

3 BIOMIMETIC DESIGN STRATEGIES

3.1 Biomimetics as Filter

"In biology material is expensive but shape is cheap. As of today the opposite was true in the case of technology" (Vincent 2009). Many examples in biology show how morphological differentiation on several hierarchical levels allows for adjustments and adaptations to system-internal and system-external constraints while employing as little material and energy as possible. Through the introduction of the developed digital fabrication process it is not only possible to transfer biomimetic

figure 4

figure 3

Machine setup: a six-axis industrial robot connected with a separate turntable as an external axis.

figure 4

Robotically fabricated finger joints. A: Connecting two plates with different material thickness at a specific angle; B: Prototype with differentiated finger joints; C: Spatial connection of finger joined plates.

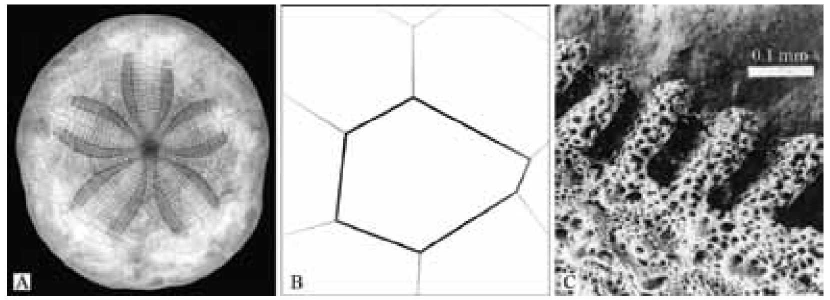


figure 5

figure 5
A: Top view of a sand dollar's test; B: Schematic view of the sand dollar's polygonal plate outlines and arrangement in which only three plates meet at one point; C: Microscopic view of a plate's margin showing the calcite projections similar to finger joints (Seilacher 1979).

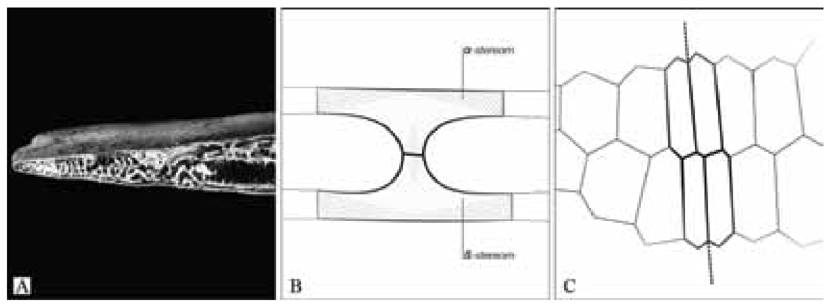


figure 6

figure 6
A: Section through a sand dollar revealing its internal tethering; B: Schematic section showing the connection and material density of two plates from the upper and lower layer; C: Unrolled view of the plates' arrangement around the sand dollar's margin showing their geometric differentiation along areas of high curvature.

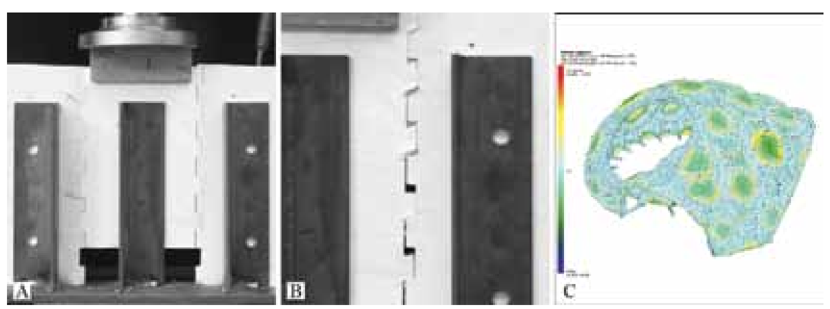


figure 7

figure 7
A: Setup for physically testing the load-bearing capacity of robotically fabricated finger joints; B: Close-up of deformation under shear stresses; C: Finite-element analysis of the full-scale prototype (La Magna et al. 2012).

principles of natural morphologies into architecture, but also to suggest biomimetics as a filter for the previously established design space in order to develop a finger joint plate structure material system with regard to a range of performance criteria.

3.2 Clypeasteroida

For this purpose the focus was set on the development of a modular system that allows a high degree of adaptability and performance due to the geometric differentiation of its plate components. Based on the premise that in constructional morphology, taxa with morphological extremes are especially relevant as they show apparent fabricational and functional principles (Seilacher 1979), different biological structures were analyzed. During this analysis the plate skeleton morphology of the sand dollar (*Clypeasteroida*, Figure 5a), a subspecies of the sea urchin *(Echinoidea)*, became of particular interest and subsequently provided the basic principles of the biomimetic structure that was realized.

Since its main habitat is in shallow water near coastlines, the sea urchin's plate skeleton experiences varying external forces due to water currents and waves, which requires robust structures. In contrast to other echinoids, which grow roughly into a spherical shape, sand dollars develop a flat shape with a thin circular outline. Although their internal tethering—which has transformed into rigid mineralized, column-like structures (Figures 6a, 6b)—distinguishes them from globular sea urchins, their global plate arrangement can still be explained within the same structural model (Seilacher 1979). An in-depth biological investigation showed how the plate skeletons of sea urchins, in which the single plates are connected by finger joint–like stereom projections (Figure 5c), have evolved ways of taking maximum advantage of the structural capacity of such joints, which can withstand considerable shear forces but only limited compression and hardly any tension and bending forces (Figure 7).

3.3 Performance Catalog

In order to approach natural systems as role models for achieving goal-oriented research, a biomimetic process (Knippers and Speck 2012) in the form of a "technology pull" was employed. Predefined architectural and structural principles were set as points of departure for a so-called performance catalog, which was subsequently established in order to transfer parameterized biomimetic principles into architectural performance criteria. Through this investigation a number of biomimetic principles were abstracted and embedded as generative rules in a computational design tool, combining structural and manufacturing constraints as well as architectural and biological principles. Such principles include load bearing on a local level between two plates, as well as on a global level; principles for the plates' shape and arrangement, for achieving multilayered structures with higher structural efficiencies; as well as principles of perforation and light modulation. Besides these constructional and organizational principles, other fundamental properties of biological structures that can be found in many natural systems (Knippers and Speck 2012) are applied in the computational design process of the project.

Arrangement: The advantage of plate structures in comparison to folded structures like origami patterns lies in their topological rule of joining not more than three plates at one point (Nachtigall 2004; Wester 2002) (Figure 5b). This principle enables the transmission of normal and shear forces but no bending moments between the joints, thus resulting in a bending bearing but yet deformable structure, as can be observed in sea urchins.

Heterogeneity: As described above, biological systems are characterized by morphological differentiation of their elements. Through the developed digital fabrication process an architectural transfer of this principle is not only possible but allows for performative adaptation to local curvature and discontinuities (Figure 6c). In areas of small curvature the modules can be more than two meters tall, while at the edge they only reach half a meter (Figure 8b).

Anisotropy: Similar to many natural constructions, the developed plate system can become a directional structure due to its geometrical differentiation. Modules stretch and orient themselves according to mechanical stresses and load paths (Figure 1b).

figure 8

figure 8
The process of assembling the prototype. A: Each module is prefabricated inside the workshop; B: The modules are sanded and weatherproofed; C: The modules are assembled on site.

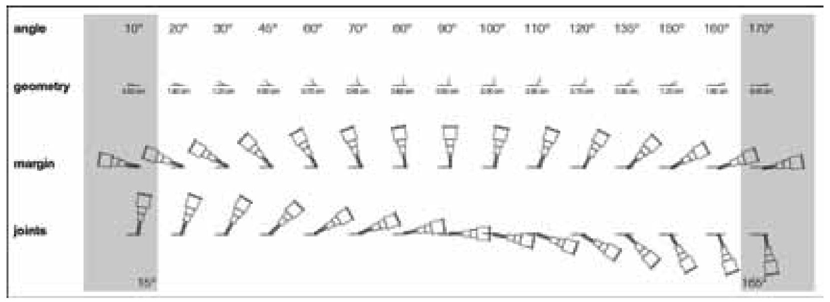


figure 9

Hierarchy: The plate system is organized as a two-level hierarchical structure. On the first level, the plywood sheets are joined at the edges through the finger joints and glued together to form a cellular module (Figure 8a). On the second hierarchical level, a simple bolt connection joins the cells together, allowing the assembling and disassembling of the whole structure (Figure 8c).

4 PARAMETER SPACE TRANSLATION

One of the stated goals of the project is to inform the design process through the parameters of fabrication. Therefore, in addition to the biomimetic principles, the specific parameter space of the machining setup has to be translated into the computational design tool as part of the generative rules. One of the main aspects of this translation is the mathematical description of geometric constraints, i.e., the specific spatial relation between work piece and milling effector through trigonometry and linear algebra.

4.1 Geometric Constraints

The fabrication angle of the joints is defined in a reciprocal parametric relation with the connection angle to the adjacent plate, constrained by structural properties such as load transfer capabilities and geometrical properties such as the depth of the indentation. For geometrical reasons, the depth of the joints decreases toward a connection angle of 90°, which provides less interlocking than a flatter or a sharper angle. On the other hand, approaching 0° or 180° results in an irrationally deep indentation and extremely sharp finger joints, which affect the precision of the fabrication and thus the connection's structural behavior.

In addition to these purely geometrical relations the particular machine constraints have to be taken into account. Therefore, in order to secure a collision-free processing of the material, the end-effector constraints, in the form of the spindle, chuck and milling tool geometries restrict the joint angles to a range of 15° to 165° (Figure 9).

The specifics of geometric plate relations, finger joint geometry, and the inherent logic of a subtractive fabrication process lead to the following sequence for the robotic fabrication of the finger joints: first, setting the general edge angle to be coplanar with the adjacent plate by milling the plate's edge with the tool shaft (Figure 10a); second, milling a mitered edge at the start and end segment of each edge by aligning the tool axis with the plate angle's bisector (Figure 10b); and finally, using the front end of the milling tool, indenting the finger joints into the plate's edge normal to the adjacent plate's construction plane (Figure 10c), producing accurately shaped force- and form-fitting joints as opposed to the rounded corners usually resulting from contour cutting with the tool shaft.

4.2 Fabrication Parameters

The second aspect influencing the parameter boundaries of the computational model is closely related to the logistics of the fabrication sequence based on raw plate dimensions, nesting of work objects, and tool path sequence, which are aimed at the reduction of post-production material waste, minimization of fabrication time and tolerances, as well as a just-in-time assembly sequence.

figure 9

The finger joint fabrication is geometrically constrained by the resultant geometry of the joints as well as by possible collisions between the machine and the stock piece.

In order to define an optimal strategy for the coverage of the given building area, a proper ratio between the plate units' size and their overall count is approximated. The tuning of these two parameters ensures suitable plate dimensions for comfortable transportation and turntable positioning, while matching the number of elements to the available resources and production time, yet also sufficient for the fulfillment of the global shape's geometrical flexibility.

Constraints relating to the facilitation of the assembly are also integrated in the computational model. The form and position of the structural elements have to allow manual accessibility to important connection details and have to avoid geometrical difficulties during the insertion of new elements in the structure (Figure 8c). The assembly logic embedded in the model takes into account the sequence of the construction, ensuring that the structure remains stable even in its unfinished state.

This way, factors such as connection angle and properties, tool and effector dimensions, workspace area, fastening possibilities, etc., are analyzed to outline the spatial domain of plate, finger joint, and module geometries. As embedded parameters in the custom computational design tool, these geometric aspects of fabrication directly influence the form-generation process such that the construction elements' geometry satisfies the production constraints.

5 ROBOTIC FABRICATION PROGRAMMING: INTEGRAL DIGITAL INFORMATION MODELING

The identified specific parametric and geometric relationships are translated into a generative model integral to the digital data processing chain from CAD to CAM to robotic fabrication. The abstraction into codified instructions as part of an automated programming strategy is the premise for the subsequent fabrication of geometrically unique building elements (Bechthold 2010). In addition to the parametric rule set outlined above, this requires a focus on aspects of scalability of the data model, integration of the generative model with existing industry-based data models, and ultimately the specifics of robotic fabrication with regard to robot kinematics.

5.1 Scalability

Due to their geometrically intricate nature, any accurate three-dimensional representation of the finger joints will put considerable load on the data model. However, further investigation made it clear that the fabrication information can be generated independently from the geometric representation or visualization of the model. In other words the geometric representation of finger joints is not the basis for fabrication, contrary to commercial CAM packages that require a detailed model of the final geometry; rather, both the fabrication model and the visualization model are derived from the same data source. Consequently, the data structure of the digital information model favors aspects of scalability as opposed to representation: rather than containing the exact digital representation of each building element—which would be computationally expensive—the digital information model consists of, computationally speaking, "lightweight" proxy data objects each consisting of a polygonal planar NURBS patch, material type and thickness in alphanumerical form, and its specific fabrication information as a three-dimensional point cloud with an associated fabrication data file. A scalable data structure enables the integral generative definition of the more than 100,000 individual finger joints.

5.2 Topology Analysis and Tool Path Generation

A topological map of edge-plate connectivity becomes the basis for generating fabrication information. Each polygonal plate consists of exactly one planar face and its specific number of edges. In the geometry model, adjacent plates share one edge. With each plate and related edge being uniquely identified, a connectivity database can be automatically generated and maintained (Figure 11a).

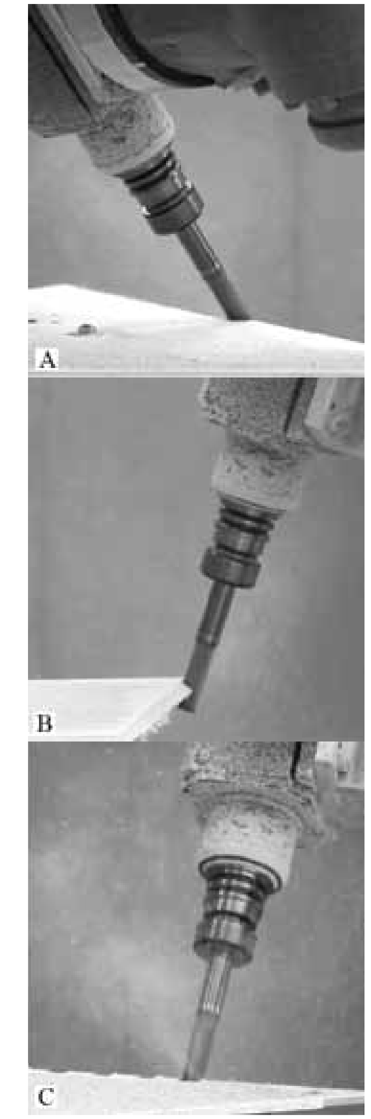


figure 10

figure 10

Three steps of the finger joint fabrication process. A: Milling the plate's outline; B: Milling the edge's miters; C: Spot facing the finger joints.

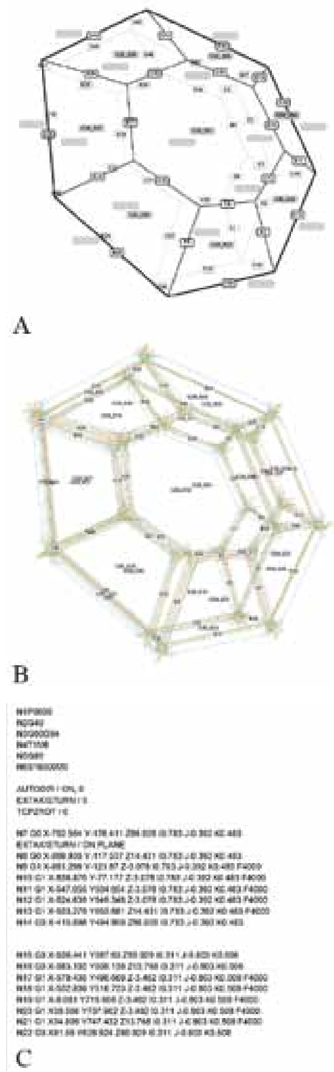


figure 11

figure 11

Tool path generation. A: A module's topological map; B: Geometric representation of the generated tool paths; C: Translation of the tool path to CNC code for machine simulation.

figure 12

A: Geometric representation of the three different tool paths; B: Close-up of the finger joint milling process.

Each plate thus being "aware of its neighbors" allows for various checks on producibility, including containment of neighboring plate angles in the defined interval, number of plates meeting at one point, etc. At this point the validity of the generative design model is confirmed.

The angle between the edge's parent plate and its neighbor plate, including concave vs. convex relationships and material thicknesses, are arguments for functions that ultimately generate the ordered point clouds for trimming, mitering, and finger joint cutting tool paths while respecting the order in which these are robotically actuated (Figure 12a).

5.3 CNC-Code Extraction

With all the tool paths being identified and associated with their parent plates (Figure 11b), the extraction of the tool path information in the right manufacturing order into an ISO-based CNC format (ISO 6983) becomes logistically feasible. Exactly one fabrication file is generated per plate, thereby greatly facilitating the logistics of fabrication. The fabrication file itself contains the tool path information as structured data in Cartesian coordinates for linearly interpolated point-to-point movements in the sequence that they are robotically actuated and their corresponding tool vectors. The point data is augmented by fabricational information specific to material and milling tool such as machining speed (feed) and the spindle's rotational speed (Figure 11c).

At this point the main challenge becomes the transformation of the global coordinates of each plate and its associated tool paths in world space to the local coordinate system of the base on which the raw plate will be machined. Coincident constraints between plate centroids and base origin, parallelism between normal vector and base z-axis, as well as parallelism between each plate's longest edge and the base's x-axis permit the unambiguous positioning of each plate in the base coordinate system without having to physically unroll and reposition each individual plate in the 3D model.

5.4 Robotic Simulation and Robot Code Generation

The CNC code extraction represents an intermediate step in the processing of the fabrication data. Much of the aforementioned information about Cartesian coordinates and point-to-point movement could theoretically and practically be translated directly into the robotic language that drives the machine, in our case Kuka Robotic Language (KRL). However, there are primarily two reasons why CNC code extraction prior to robotic actuation becomes necessary or desirable.

First, the complexity of the seven-axis fabrication process necessitates the prior simulation of the robot's kinematics as opposed to relying on the subsequent automatic calculation by the robot control unit (Brell-Çokcan and Braumann 2010). The kinematic simulation of the robot movements is achieved by reverse transformation of Cartesian coordinates to the angular coordinates of the machine's revolute joint space. At this point dedicated algorithms are used to resolve the ambiguity of a robot with seven DOF being able to reach the same point in space in an infinite number of ways. The approaches to solving these ambiguities such that there is exactly one meaningful configuration of the robot's revolute joints are either numerical, geometric, or iterative, e.g., by introducing targets

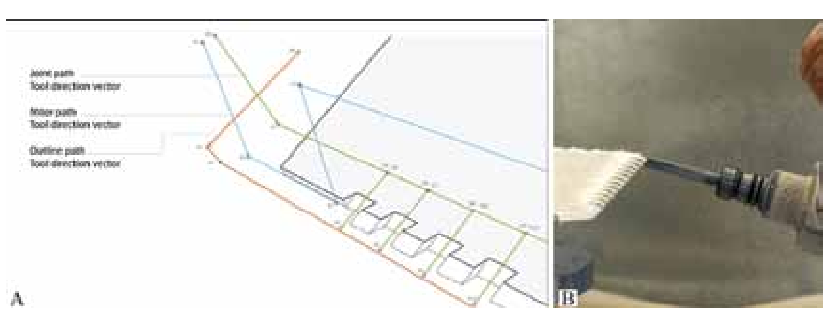


figure 12

and trade-offs. Implementing an operational workflow that does not rely on the outsourcing of the simulation of the robot's kinematics to a post-processor requires not only embedded parameters and constraints of tool and effector in the design tool as outlined above; it also requires the solving and optimizing of the inverse robot kinematics inside the design environment.

The second reason for generating open and neutral CNC code is the possibility of sharing that code with contractors that use either different robots or specific machining configuration. By utilizing CNC code as a vehicle, the fabrication does not necessarily become indifferent to robotic fabrication; rather, it becomes independent of a specific robot brand.

5.5 Built Prototype: Research Pavilion

The final pavilion consists of more than 850 geometrically unique, robotically fabricated birch plywood plates joined at the edges by more than 100,000 individual finger joints. The high potential of the combined design principles is demonstrated by the fact that the entire pavilion could be built out of 6.5 mm (1/4 inch) thin sheets of plywood only, despite its considerable size: 200 cubic meters (7050 cubic feet) of gross volume were built using only 2 m³ (70.5 cft) of wood. The pavilion consists of two interior spaces that emphasize the experience of the constructional logic: the main space is characterized by the differentiated openings in the double layer modules as well as by its prominent relation to the park; an interstitial space is framed by the gradual separation of the double-layered structure into two single layers. Together the two interior spaces exemplify the capacity of the system to enable differentiated spatial and programmatic experiences (Figure 13).

6 SCAN DATA VALIDATION

Over the life of a project a variety of dedicated data models are produced. However, data models that relate the built result to the models that were used for design, analysis, and fabrication as a means for validation are usually absent from the design and construction process. Recent developments in surveying technology now make it possible to perform detailed 3D laser scan measurements.

6.1 Tolerances

The design, fabrication, and construction of a full-scale case-study project not only provided the possibility of investigating aspects of design methodology, computational design, and fabrication strategy, but also an opportunity for validation of the various data models (design model, finite-element model, fabrication model), related computational processes, and the evaluation of material behavior over time by utilizing state-of-the-art 3D laser scan technology.

Tolerances and discrepancies measured between the digital geometry model and the built prototype are expected and can be attributed to different origins ranging from inherent tolerances in surveying of the site, to fabrication and construction tolerances, to the material behavior of 6.5 mm birch plywood, and ultimately to the 3D laser scan. Fabrication tolerances can be inflicted by the fabrication setup: attachment to base <0.5 mm), deflection of cantilevering work pieces <1 mm), tolerances of the robot <0.2 mm). Construction variables are attributed to levelness of the site, accuracy of base/foundation and compound tolerances during assembly. Additionally, differences between the built prototype and the geometry model due to deflection were predicted through FE analysis: up to 5.95 mm nodal displacement under dead load. With all tolerances added up, an accumulative tolerance of up to ±2.5 cm (±1 inch) was to be expected.

6.2 Scan Reference Points, Sequence, and Interval

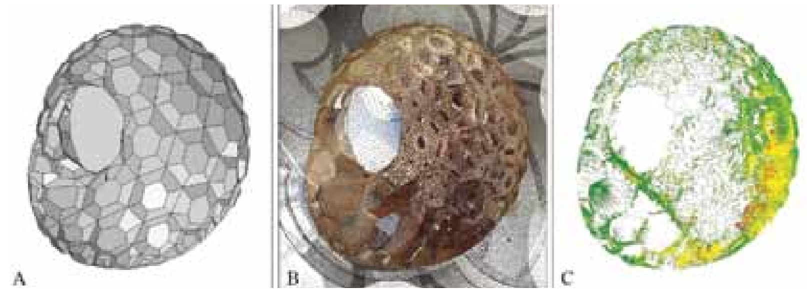
Two complete 3D laser scans were performed within a three-month interval—the first scan just after completion of the project, the second scan just before the disassembly—using a Faro Focus3D Scanner with a horizontal and vertical resolution of 0.009° (40.960 3D-pixel per 360°) and a distance noise (unfiltered) of 0.6 mm at 10 m. While the horizontal field of vision allows full 360° horizontal

figure 13

figure 13

Full-scale prototype. A: The double-layer structure responds to both structural and architectural requirements; B: The spatial experience changes remarkably at night when the interior lighting emphasizes the individual character of the spaces and the double layer's depth.

figure 14



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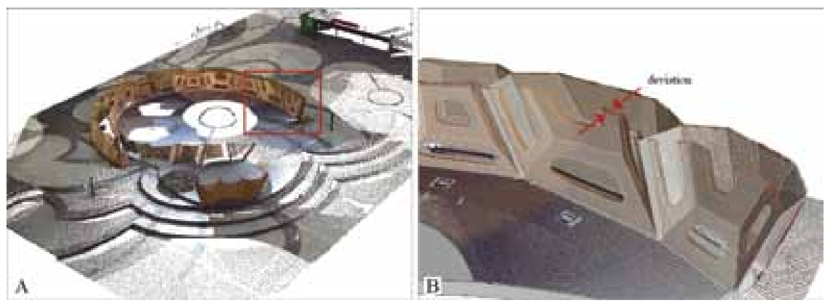


figure 16

figure 14

A: View from northeast showing the two main spaces of the pavilion; B: 3D laser scan model consisting of 1.2 million points built from every 250th available scan data point.

figure 15

A: Geometry model as the basis of fabrication; B: 3D laser scan model as the basis for vector-based deviation analysis; C: Vector-based deviation analysis.

figure 16

A: Horizontal section through the scan data model facilitates the interpretation of the data. B: A zone of particularly high deviation identified in Figure 15c.

scans, the vertical field of vision is limited to 305° which produces circular areas where the scanner is located during measurements that contain no data (Figure 16a).

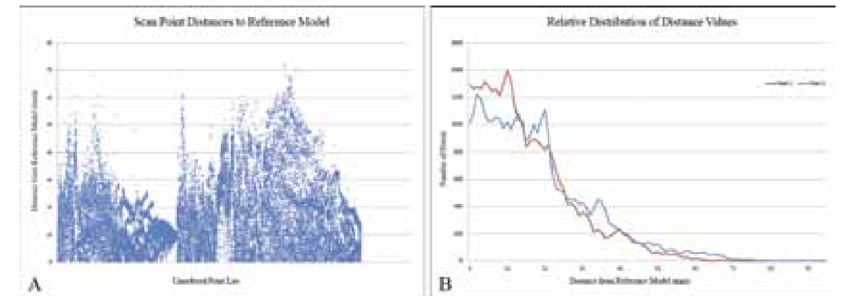
In a first step, the locations of 12 individual scans are identified such that the entire prototype including interior and exterior surfaces can be captured; second, reference points are defined on site, which are used to connect the individual scans and to align the geometry model with the scan model.

The two full scans consist of 24 individual scans that yield an unordered point cloud of more than 500 million discrete data points. In addition to the Cartesian coordinates of each measured point, the data include RGB values of the color of the measured surface (Figure 14b). The gathered raw data forms the necessary basis for the subsequent analysis.

6.3 Data Visualization

Due to the large quantity of available data, a scaled approach to its visualization has been chosen to achieve a manageable data overlay with the existing geometry reference model: to create an overview of the entire model every 250th point within the bounding box of the pavilion is visualized yielding roughly 1,200,000 points (Figure 15b). For the overall displacement analysis every 2,500th data point is visualized and analyzed with respect to its closest distance to the reference model, which allows for the identification of zones of varying measurement deltas. Display vectors between reference points and measured points are scaled exponentially and color-coded such that zones of higher deviation are emphasized (Figure 15c).

Following the generation of the overview model and the identification of zones of higher deviation in step one, reference boxes allow the independent high-resolution analysis of selected quadrants of the model: Figure 16b shows a volume of 2.5 x 4.0 x 1.5 m (15 m³ or 530 cu ft) with a point number



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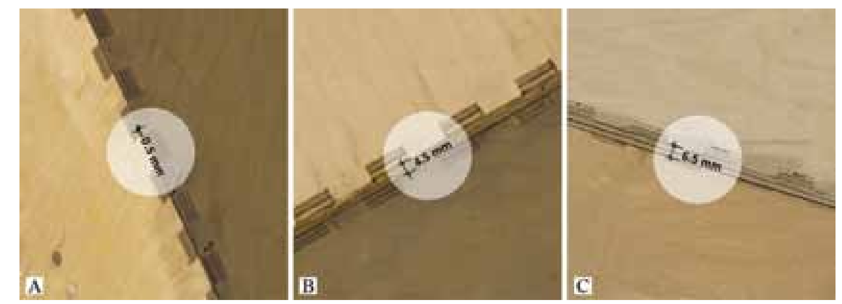

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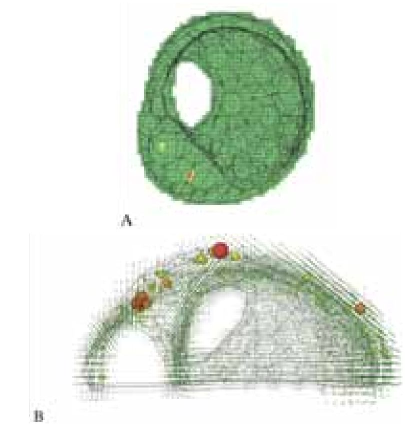

figure 19

of roughly 600,000. At this scale detailed features of the prototype are visible and deviations from the reference model become obvious.

The analysis of the distance values between measured points and reference geometry for scan 1 shows a distribution of values ranging from 0 to about 70 mm (Figure 17a). However, the average deviation is only 15.76 mm, and more than 80 percent of the values lie within a range of ±25 mm. It is important to note that this refers to the compound deviation of the global geometry. The actual tolerances between the modules averaged around 6 mm, with the measured maximum being 14 mm (Figure 18).

This confirmed the relative precision experienced during the construction process, where most modules could be aligned and assembled without major tolerances or gaps. The analysis of scan 2 shows a distribution of values ranging from 0 to 80 mm, the average deviation being 18.63 mm. It also shows that the number of points with little deviation decreased in scan 2, i.e., that deviation increased over time (Figure 17b).

Comparing the two scans with respect to their relative deviation identifies the few zones where deformation occurred over the lifespan of the project: minor deformation in the single-layer structural zone and at the highpoint of the arch of up to 3 mm (Figure 19). The prototype therefore proved to be extraordinarily stable.

7 CONCLUSION

In this paper the authors present a methodology for exploring and filtering emerging machinic morphospaces of multi-axis robotic fabrication technology through biological principles that act as role models for performative morphological differentiation. Through the built case study project,

figure 17

Scan data analysis. A: Chart showing the distribution of closest distance values for scan 1. B: The relative distributions of deviation values show that the number of points with a deviation larger than 60 mm approaches zero.

figure 18

The distribution of distance values measured between modules ranges from 4 to 8 mm.

figure 19

Comparison of scans 1 and 2. A: Areas of relative deviation between scans indicate where deformation occurred (green areas: no deviation, red areas: up to 3 mm). B: Voxel-based comparison of the two scans.

they show how this methodology can be applied successfully to form-adaptive and geometrically complex modular construction. The performative capacities of the fabrication based, bio-informed material system are derived from the integration of biomimetic, fabricational, structural, and architectural principles in one digital design environment. The project illustrates how generation, management, and control of increasingly complex datasets require adequate, efficient, and very often custom data structures that support design exploration. While the evaluation of the built prototype through 3D laser scanning showed that the resultant tolerances and deviations slightly exceeded the prediction, it also showed that the structural system showed almost no deformation over the lifespan of the project and proved to be extraordinarily stable. Further research will be directed to more accurately reflect fabrication and construction tolerances, as well as material behavior within the design environment to be able to make better predictions on the physical result of robotic fabrication processes.

In this sense, the project attempts to computationally synthesize not only the physicality of robotic fabrication and the focused exploration of the design space, but also that of material behavior within the computational domain.

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REFERENCES

Bechthold, M. (2010). The Return of the Future: A Second Go at Robotic Construction. Architectural Design 80(4): 116–21.

Brell-Çokcan, S., and J. Braumann. (2010). A New Parametric Design Tool for Robot Milling. Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA), 357–63.

Eble, G. J. (1999). Developmental and Non-Developmental Morphospaces in Evolutionary Biology. Morphospace Concepts and Applications.

Hoadley, R. B. (2000). Understanding Wood: A Craftsman's Guide to Wood Technology. Newtown: Taunton Press.

Knippers, J., and T. Speck. (2012). Design and Construction Principles in Nature and Architecture. Bioinspiration & Biomimetics 7(1).

Menges, A. (2012). Biomimetic Design Processes in Architecture: Morphogenetic and Evolutionary Computational Design. Bioinspiration & Biomimetics 7(1).

Menges, A., and T. Schwinn. (2012). Manufacturing Reciprocities. Architectural Design 82(2): 118–25.

Nachtigall, W. (2004). Bau-bionik: Natur, Analogien, Technik, 8–13. Berlin: Springer-Verlag.

Kirby, I. (1999). The Complete Dovetail: Handmade Furniture's Signature Joint. Plano: Cambium Press.

Krieg, O. D., K. Dierichs, S. Reichert, T. Schwinn, and A. Menges. (2011). Performative Architectural Morphology. Respecting Fragile Places—29th eCAADe Conference Proceedings, 573–80.

La Magna, R., F. Waimer, and J. Knippers. (2012). Nature-Inspired Generation Scheme for Shell Structures. Proceedings of the 24th Symposium of the International Association for Shell and Spatial Structures, Seoul 2012.

Schindler, C. (2007). Information-Tool-Technology: Contemporary Digital Fabrication as Part of a Continuous Development of Process Technology as Illustrated with the Example of Timber Construction. ACADIA Conference 2007 Expanding Bodies. Proceedings of the International Conference, Halifax.

Schindler, C. (2009). Ein Architektonisches Periodisierungsmodell anhand Fertigungstechnischer Kriterien, Dargestellt am Beispiel des Holzbaus, 163. Eidgenössische Technische Hochschule Zürich.

Seilacher, A. (1979). Constructional Morphology of Sand Dollars. Paleobiology 5(3): 191–221.

Vincent, J. (2009). Biomimetic Patterns in Architectural Design. Architectural Design 79(6): 74–81.

Wester, T. (2002). Nature Teaching Structures. International Journal of Space Structures 17(2): 135–47.

IN-SITU ROBOTIC CONSTRUCTION: EXTENDING THE DIGITAL FABRICATION CHAIN IN ARCHITECTURE

ABSTRACT

In this paper, viable applications are explored for mobile robotic units on construction sites. While elucidating potential aims and requirements for in situ fabrication in the construction sector, the aim of this work is to build upon innovative paradigms of human-machine interaction in order to be able to handle the imprecision and large tolerances commonly faced on construction sites. By combining the precision of machines with human cognitive skills, a simple yet effective mobile fabrication system is experimentally developed for the construction of algorithmically designed additive assemblies that would otherwise be impossible to build using conventional manual methods, because of the sheer number of individual building blocks and the scale of the structure. This new approach for the collaboration of humans and machines—aiming at a fuller integration of human abilities and the advantages and capabilities of digitally controlled machines—will result in advances in the construction industry, opening up new fields of application for architects and designers in the design and realization of buildings.

Volker Helm
Architecture and Digital Fabrication (DFAB)
Swiss Federal Institute of Technology (ETHZ), Zurich

Selen Ercan
Architecture and Digital Fabrication (DFAB)
Swiss Federal Institute of Technology (ETHZ), Zurich

Fabio Gramazio
Architecture and Digital Fabrication (DFAB)
Swiss Federal Institute of Technology (ETHZ), Zurich

Matthias Kohler
Architecture and Digital Fabrication (DFAB)
Swiss Federal Institute of Technology (ETHZ), Zurich