Robotic Rod-bending
DIGITAL DRAWING IN PHYSICAL SPACE

Parke MacDowell
Macdowell, Tomova

Diana Tomova
Macdowell, Tomova

ABSTRACT
This paper details preliminary project-based design research that emphasizes the development of tools and processes in tandem with the development of ideas and forms. Amid increasingly mechanized fabrication processes, this project injects the human as code-writer and tool-builder, asserting authorship within the modes of production themselves.

The initial output from this foray, wavePavilion is an architectural installation generated by computer algorithms and built using custom digital fabrication technology. Completed in June 2010, the project is located on the grounds of the University of Michigan Taubman College of Architecture and Urban Planning. wavePavilion has a footprint of 20x30 feet and stands 14 feet tall, containing over a kilometer of 1/4-inch diameter steel rod.
1 Concept

Since the Renaissance, traditions of drawing have remained central to the discipline of architecture, contingent on a belief in the ability of the architectural line to represent space. In recent decades, however, computer modeling has largely supplanted the power of line with that of surface. The trend towards increasingly complex three-dimensional form-making highlights the centrality of surface modeling as both initiator and response within the feedback loop between software and design. While the ramifications of this shift are widespread, expressed in everything from the drafting table to the skyscraper, the dominance of surface is especially apparent in the still-nascent domain of digital fabrication. Digital fabrication has emerged as a way to build complex virtual forms, using computer-controlled machines to accurately produce highly-variable parts. Prevailing digital fabrication practices break down virtual surfaces into these discrete parts through mediating strategies like sectioning and paneling. wavePavilion bucks this trend, discarding contemporary strategies of mediation and instead harnessing the potential of algorithmic computing to re-empower the line as a driver of architectural form.

Surface-derived projects demand an intermediate step between design and fabrication to rationalize calculus-dependent shapes into parts that can be built with manufactured sheet-goods such as plywood, metals, and plastics. wavePavilion supports an alternative way of thinking about complex form, one that embeds material and fabrication constraints within the initial logics of formation. In wavePavilion, there is a resonance between the linear character of extruded steel rod and design algorithms rooted in linear geometry. The directness of this relationship propels the line from what is now a comprised role within architectural representation to a critical role as an agent of built form. Here, the crude but variable base unit of the line, deployed within an assembly through complex relational logics, evokes qualities of surface and atmosphere. In so doing, the line challenges the ubiquity of the “blob” within scripted/parametric form-making—geometric composition supplying all the complexity and nuance for which we have become enamored of calculus-dependent surface modeling.

Digital fabrication has the potential to collapse the long-standing divide that separates ideation and representation from construction. As the relationship between design and built form becomes more fluid, the scope of architectural practice might be expanded and strengthened as the designer acquires greater control over the means of production. The increasing reliance on digital fabrication precipitated by complex architectural form foregrounds the significance of tools, processes, and the biases and tendencies they embed. Investing an ethic of design within the modes of production themselves capitalizes
on opportunities latent within this trend. To this end, \textit{wavePavilion} (Figures 1-3) emphasizes the development of tools and processes, in tandem with the development of ideas and form, as a means of winning authorship for the designer amid increasingly mechanized fabrication practices.

2 Computational Design

The structure and aesthetic of \textit{wavePavilion} was developed through a scripted strategy of geometric evolution. This Rhinoscript code combined programmatic influences with intrinsic formal tendencies to produce an architectural object that manifests its logics of formation with respect to a specific set of spatial demands. This computational process can be described in a series of phases, as seen in the adjacent diagrams.

The virtual environment in which the pavilion form-script operates is established in Rhinoceros. This meta-site is seeded with critical nodes (Figure 4), which embed information tied to real-world spatial and programmatic requirements. This process generates a field of vector impulses, influencing the innate tendencies of the form-script. The script then tracks a course within the data-environment of the established vector field, demarcating a curve of primary structure that describes two zones, each with distinct views and orientation (Figure 5).

The resultant spaces are simultaneously connected and autonomous, a perception reinforced by the modulating density of the developing pavilion form. A secondary array of geometry acknowledges the primary curve but follows its own logic (Figure 6).
In the specific instance of wavePavilion, this new layer delaminates from the primary form at the end of its trajectory. This expression highlights the internal variation invested within a single form-making strategy.

A network of three-dimensional polylines grows from the preparatory geometry on the ground plane (Figure 7).

The length and orientation of each segment of these polylines is dependent on its proximity to the critical nodes and the logic of the form-script. Within a certain range of the critical zones, seating elements develop. Beyond this range, echoes of the same geometric tendency are retained as merely vestigial forms. Collectively, these forms read as a single undulating gesture that runs the length of the pavilion. As a kind of ancestor geometry for the final pavilion form, the three-dimensional polylines are the simple progenitors of a lineage from which more complex descendants evolve. The ancestor geometry establishes the broad morphological characteristics of the pavilion (Figure 8), but lacks the sophistication to address issues of structural integrity and user occupation.

Figure 13. A custom CNC rod-bending device operates in tandem with a multi-use 7-axis robotic arm to shape the steel components. The behavior of this toolset is driven by a communication script which translates 3D computer geometry into robot/bender choreography.

Figure 14. Prototype tooling was developed over multiple iterations to deliver the high precision required in the custom CNC bending process: Clockwise from top left: waterjet-cutting parts, bender_v1.1, gripper_v1.0, bender_v1.3, bender_v2.0, bending die fabrication, welded gripper mandibles.

Figure 15. A custom communication script evaluates 3D virtual geometry and outputs a command file for the robot/bender toolset.
The descendant geometry (Figure 9) takes the crude form of the ancestor geometry and augments it with a more nuanced understanding of proximity and spatial relationships.

New behaviors manifest, wherein individual components engage in physical exchange with their neighbors, forming aesthetic and structural alliances toward the development of a cohesive society of form. The late stage form-society displays broad networks of structural affiliation while maintaining a high degree of local diversity (Figure 10).

Behavioral gradients read across the breadth of the pavilion, but moments of eccentricity—phase shifts (Figure 11), vestigial phenotypes, dormant features—reveal the complex relational processes of the underlying system. Through this process of formal evolution, the wavePavilion manifests an index of its own phylogeny, physically expressing its internal logics while satisfying the pragmatic requirements of built, occupiable form.

3 Robotic Fabrication and Assembly

To support the conceptual aims of the project, a multi-use 7-axis robotic arm was paired with a bespoke CNC rod-bending device (Figure 12) to bend ¼ inch steel rod into unique (non-repeating) three-dimensional shapes. This precision toolset (Figure 13) and the communication codes that control its behavior were designed and built coded by the authors to resolve highly specific fabrication requirements beyond the capacities of conventional CNC tools.

A custom script was developed to analyze the digital geometry of the wavePavilion and translate that information into a series of operations for the bender and robot. This code breaks input geometry into lines and arcs and records data such as length and orientation for each element (Figure 14).

The data is exported as a series of commands in kukaCode (for the robot) and hex-base machine code (for the bender). These commands choreograph the actions of the robot and bender in order to reconstruct the original digital geometry out of steel rod (Figure 15).

The bent components were organized with a simple indexing system (Figure 16) and transported to the site, where they were manually assembled and welded (Figures 17, 18).

The multi-planarity of each component is critical to this assembly process, eliminating the need for positioning jigs because each component can only align with its neighbors in a single, specific orientation. As part of this self-indexing assembly, each element fits precisely against the previous pieces while guiding the positioning of the subsequent. Once positioned, the rods were manually welded in place.

4 Conclusion and Projection

wavePavilion was a quick, two-month investigation that has initiated an ongoing trajectory of research. Both scripting and customized robotic fabrication embed a sometimes daunting learning curve that inhibits the potential of these tools and processes within an academic setting. With this in mind, the physical and computational tools developed for wavePavilion have been shared with designers both at the University of Michigan and other institutions in hope of accelerating the research through increased accessibility and open-source participation. Experimentation by the authors and others continues in 1/4-inch and 3/8-inch metal rod. Refinements to the toolset are also ongoing (Figure 19), and the next-generation bending device currently in development will expand this experimentation to larger diameter materials. Computational improvements, such as visualization software to better predict fabrication challenges, expands both the operability of these processes and their capacity for broader application.

As a pedagogical device, wavePavilion has served as launching-pad for student projects at the University of Michigan within the context of fabrication and computation seminars. Likewise, the scripts and tools from the project were the focus of Robotic
Fig. 17. Individual components are CNC precision-bent and indexed prior to transportation and manual onsite assembly.

Fig. 18. Carefully placed welds reinforce the structural pattern and allow the entire pavilion to act as a single moment frame.

Fig. 19. Bender_v3.0, fabricated by Wes McGee, is a more robust version of the toolset used for the wavePavilion. This bender can be easily dismounted from its frame, and can be replaced with a hydraulic bender (currently in fabrication) for bending larger diameter metal rods and pipes.

Fig. 20. The prototype bentSteel_chair02, by macdowell tomova, employs an alternative attachment strategy. The bundled 3/8-inch steel rods are welded within waterjet-cut fasteners to deliver a cleaner aesthetic.

Constructs, an intensive design workshop involving students and faculty at Princeton University and instructors from the University of Michigan. In February 2011, Michigan’s FABLab played host to students and professors from the Architectural Association and London Metropolitan University who traveled to Ann Arbor for a week-long visiting studio organized around robotic rod-bending. This expanding repertoire of projects foregrounds a design ideology in which tectonics and generative logics are intimately linked through the medium of the line.

The viability of these processes, as evinced by wavePavilion, suggests the potential for more refined architectural applications: Mechanical attachments might replace welded connections to increase assembly speed. Secondary membrane systems may be developed to provide enveloping capacities. The bent steel of wavePavilion may even be paired with wire mesh and shotcrete to produce highly customizable structural forms (Figure 20). Critically, wavePavilion opens the domain of digital fabrication to a host of non-conventional practices in which concept and instantiation are linked without the need for rationalizing strategies to mediate design intent and fabrication constraints. The expansion of this preliminary exercise through knowledge-sharing between multiple designers will channel this potential toward new modes of spatial description and tectonic opportunity.

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