The hexEnvelope system

*a cross-platform embedding of material and software logic into descriptive geometry*

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Abstract

This paper follows the technical problematic of the hexEnvelope, a novel system for building complex geometric objects. Operating as a scripted system of parametric operations, and running through multiple 2D, 3D, and fabrication software packages, the hexEnvelope system allows for a highly tectonic assemblage of cellular units. Specific issues addressed within the system include the realization of curved surfaces through flat material, the embedding of fabrication logic and material performance within descriptive geometry, and multiple scales of deployment in terms of their tectonic and material consequence.

Introduction

This paper documents the production of the hexEnvelope (figure 1), a system that consists of a series of scripted plugins that moderate a constellation of graphic software. The project was initiated at the Avery Fabrication and Conservation Lab, at the Graduate School of Architecture, Columbia University. The recent acquisition of a Flow Corporation Waterjet allowed for the consideration of architectural scale fabrication projects. Given the utilization of a waterjet cutting machine, the hexEnvelope begins as a simple problem of constructing a curvaceous, topologically complex shape.

Figure 1. hexEnvelope installation
with rigid material, cut through numerically controlled equipment and assembled with unskilled labor. The product it ultimately describes is a folded metal structure which operates as a network of cellular elements (aluminum or steel), joined together through the tectonic strategies of fastening and folding. The hexEnvelope utilizes the MEL scripting environment within Alias Wavefront Maya, as well as other strategically employed software, to automate each stage of the production of the artifact—in terms of its geometric description, its tectonic realization, and the production of fabrication drawings and assembly documents. The ultimate goal is to produce an object that is able to negotiate seamlessly with curvaceous and rectilinear form, multiple scales of articulation, and multiple tectonic strategies. To this end, the hexEnvelope, in its first stage, uses polygonal geometry to describe a form, leveraging the potential of a system of description that accommodates arbitrary topology as well as using a faceted approach to curvature. The second stage utilizes vector line-work to translate an abstracted geometric figure into highly articulated documents that are tailored to the machine language of the fabrication equipment.

In order to understand the hexEnvelope as a system, rather than a product, we will describe it in the following way:

- As a sequence of operations, choreographed with a system of software platforms
- As a sequence of deployments at different scales, both in the context of industrial design and architectural design

Development Timeline and Credits

The hexEnvelope developed over a series of projects, scales, and venues.

The formal vocabulary of arbitrary minimal surfaces was explored within individual projects and group work of Karl Chu’s Fall 2005 studio at the Columbia GSAPP. This dialogue occurred around attempts to realize smooth form through different means of tessellation, which followed the problems of computation-based form production in the studio, as well as material experiments carried out by Toru Hasegawa within Vincent Lee’s concurrent Material and Methods seminar and third-party software research employed by Roland Snooks within his firm, Kokkugia (http://www.kokkugia.com).

The experimentation with cutting flattened tessellations of complex form was initiated within the Avery Fabrication and Conservation Lab, under the direction of Phillip Anzalone, within the Digital Assembly seminar taught in the Spring of 2006 at the Columbia GSAPP.

The hexEnvelope was tested in the context of (un)Natural Selection, an independent study conducted at the Columbia GSAPP on genetic algorithms and their use in the determination of form and fabrication. The project team included Ezio Blasetti, Dave Prigram, Roland Snooks, and the authors Mark Collins and Toru Hasegawa, who carried out the project under the supervision of faculty member Hernan Diaz Alonso.

The hexEnvelope continues to be explored within proxy, the studio formed by Mark Collins and Toru Hasegawa (http://www.proxyarch.com). Here, it is being tested as a means to realize a diverse array
of objects. Also under development is the deployment of the hexEnvelope as a web-based design engine.

**Sequence**

In this section, we will reverse engineer the production of the hexEnvelope. The hexEnvelope is produced by moving information through a series of software platforms. In order to maintain the integrity of the object through this process (which goes in and out of both 3-D and 2-D packages), one is forced to embed the logic of one software into the software that precedes it in the sequence. In other words, Maya, a 3D package, must anticipate Adobe Illustrator’s limitations as a 2D package, and allow for a description of the object that will survive the translation between radically different platforms. It is this embedding that defines the process of the hexEnvelope.

**Flow-Jet cutting and the Flow software**

The Flow Co. WaterJet, a 2-dimensional cutting mechanism that utilizes a high pressure stream of water and aggregate to cut through dense material, was chosen as a means to work with folded metal as both a structuring system and skin. The opportunity afforded by the machine was to envision a structure of completely unique parts, where the logic of systematic repetition and economies of scale would be muted. Upon using the machine, its limitations became manifest, as the cutting process, though automated by the computer, is both slow and prone to failure. While allowing for the production of novel parts, the system would clearly need to economize as much as possible with the cutting time. Roughly, this translated to:

- minimizing the total number of cuts into the material, as each new cut requires the machine to puncture through the material at much slower speeds than simply extending a pre-existing cut
- minimizing the size of any constituent piece of the system, as the machine bed is limited to a maximum of 2’-0” x 4’-0” sheet material
- calibrating the material selection and thickness to gain the maximum amount of tectonic possibilities (fastening, folding, corrugating, gluing, etc) while allowing for an efficient cutting speed per part

These parameters suggest an assemblage of small, hard pieces—essentially a cellular packing. Limited to two-dimensions by the cutting mechanism, we chose metal as a means to bring about depth and overlap through folding. After considering different folding strategies, we decided on an industrial fold cut (figure 3) as an ideal way to use two-dimensional stitch patterns to create fold edges within the sheet metal.

Another important consideration was the relative efficiency of figure packing as it related to available sheet material (figure 4). The constraints of small sheet sizes made packing efficiency a top priority, as wasted material could not be recovered. Not only was the size of each cell made smaller to fit on a sheet, but a diversity of cell sizes was preferred to provide the packing algorithm with a wide array of
sizes. Larger cells would be complemented with extremely small cells that could be “packed” into the margins created by the large cells. In this sense, the efficacy of packing algorithms would drive a sensibility of un-equal tessellation of the surface.

**Drawing machine – automation production of tab tectonic**

The hexEnvelope figures the term “tectonic” as an intensification of information at the point of meeting between surfaces. As the geometry that is fed into the system is “arbitrary,” in the sense that it can take any tessellated form, the tectonic phase is the moment when that arbitrary surface is understood as material that will be assembled, and is articulated according to the consequences that flow from that.

Always using two tabbed surfaces to join cells together, the system actively decides which system of connection to use on this surface. At this stage of development, we have used the length of the tab as a driver of tectonic choice. Thus, if a tab is extremely small, it can be merely folded onto the adjacent cell. This folded-arm connection is shown in Figure 6. Logically, if the tab is extremely long, it must be describing a more robust element, and therefore a more robust connection is “selected” from the gallery “and drawn” onto the tab. This process of selecting and drawing occurs per figure and is actually
a process of mapping a more detailed drawing of a tab onto a simplified line-work. This allows for the geometry, as it is manipulated in 3D to be abstract, and only takes on the appropriate level of detail at the moment before it is packed and sent to the water jet.

As the information that is mapped to the tab can be of any complexity, we are free to imbed information into the tab that will be used later for labeling and manipulating and to instantiate this line work in a way that will minimize cutting time. A close examination of a detail tab reveals certain techniques used to minimize punctures at the cutting stage; the outline of each figure is folded onto itself to produce seam lines, bolt slots, and the perimeter of tabs. By creating a continuous line that defines the final cut piece almost completely, we create a condition in which only a few punctures of the material are needed to cut each piece. This can result in shrinking the cut time by a factor of 3, a considerable benefit.

The process through which this mapping occurs is a combination of Maya deformation tools and MEL scripting. A script parses through the rudimentary line-work that describes each figure, identifying each tab and choosing an appropriate detail tab from the gallery (a combination of a user identified string and the tab length inform the choice of tabs, i.e. the script chooses the “large” version of the tab family “fold_tabs,” which was specified by the user.) Using a simple 2x2 lattice, the detailed tab is literally applied to the outline of the place-holder tab, which is subsequently deleted.
Vectorizing Geometry

As we are using a cellular agglomeration strategy to realize the structure, a fundamental step in moving from form to fabrication is the atomization of a continuous surface into smaller pieces (figure 7), while at the same time providing some means to rejoin them. In this process, each face of a polygonal figure is treated as an individual “cell.” It is detached from the surface, at which point small tabs are extruded from its edges. These tabs, when later folded up perpendicular to the figure, will allow for a shared surface of connection to be further articulated as a surface for fastening or as a fold-arm. Additionally, a seam is introduced into a segment of the figure, producing a break in its continuity. By breaking the figure along this seam and unrolling all the constituent angles of the cell to 180 degrees, the 2-D cut pattern that defines the shape is created. Each shape is cataloged and reduced to line-work, which will form the base onto which detailed fold lines and tab connections will be drawn.

The extrusion process, as well as the splitting of each figure and tab extrusion, is carried out via MEL scripting in Maya. At the moment, the script uses the facing direction of each hexagon to determine how open/deep it should be. After it has run through each piece of geometry, the file is exported as an OBJ file and imported into Pepakura. Pepakura, a software for making paper-cutting templates from simple polygon models, is used simply as a surface un-roller. Unlike many plug-ins that perform similar operations in order to facilitate texture mapping, Pepakura leaves the geometry intact, merely flattening the angles between faces, and not introducing any stretching into the planes. Outputting to vector line work, Pepakura will strip out all the 3D information from our model.

Creating the Conditions for flatness

The hexagon as well as a number of other n-gon shapes are, for us, interesting as a surface articulation in their ability to inscribe movement onto a form. As opposed to the stability of a quad or triangular mesh, the hexagonal pattern actively “marches” across the form, producing a running pattern that builds relationships across diagonal cells as well as the cardinal directions. The process of moving from a triangulated mesh to a hexagonal mesh is simply an inversion (see figure 8)—each triangle is subdivided into three new triangles. By removing the original mesh, the hexagonal mesh is leftover; and is effectively an “averaged” version of the previous form—this averaging is preferable as we are working
in the formal language of minimal surfaces.

Due to this averaging, however, the faces produced are more complex and often curve in space. This issue of non-planarity needs to be addressed considering the fabrication technique employs flat material that is folded into shape. Here, extrusion is used as a means to effectively re-triangulate the hexagonal figures. This is taken as an opportunity to introduce depth and aperture in the system. Later versions of the hexEnvelope will use the depth produced in the service of structural integrity—all versions of the hexEnvelope use a differentiated depth and aperture in each cell to promote a formal condition of opening up and closing off. This extruding process can be taken to extreme, iteratively applied to achieve a “flowering” of the surface. The ability of the extrusion to move slowly over multiple cells between the condition of a frame and the condition of a skin follows from the sensibility of an intensive operation; moving away from black and white conditions toward a logic of intensities, gradients, field conditions and pixilation is paramount to the hexEnvelope’s exchange with current digital design practices.

Applications

Thus far, two applications have been explored for the hexEnvelope system: as a product and as a piece of interior architecture.

hexEnvelope @ product scale

Developed as a user-assembled product, the Happy Family Lamp (coined from its tectonic closeness to the Chinese take-out box) is an example of how the hexEnvelope system can be deployed as a lowest-common-denominator fabrication strategy. By exclusively utilizing folded-tab connections, the lamp can be assembled without tools or fastening hardware by unskilled labor, which allows it to be sold as a kit of parts rather than as an assemblage. Besides affording the efficiencies of flat packing, this fabrication strategy allows the act of putting
The lamp forecasts a web-based retail model, in which manipulations could be made to the base topology in order to personalize the object. By establishing the size of each ring of cells, its corresponding aperture size, and the depth of each extrusion, each user could design a unique version of the lamp to be custom fabricated.

hexEnvelope @ installation scale

In parallel, the hexEnvelope was developed to confront larger-scale interior applications. Deployed as a constituent of the (un)Natural Selection installation at the GSAPP 2006 Year End Exhibit, it was theorized as both a structured space partition and a parasitic surface modulator. Due to the large size and increased skilled labor in assembly, the structure was allowed to become more complicated, in both its tectonic and its formal development.

As a system that works with an arbitrary topology, intense topological mutation was preferred as a means to express the ductility of the system; the final installation contains complex topological features of funnels, negative and positive curvature surfaces, open-ended cylindrical projections (i.e. holes), and two-axis oppositional funneling. Derived from point-cloud data in Rhino 3, the generative approach was to encourage as much topological intensity within a compressed area through the densification of points. By creating a bulbous shell with an entangled center, a basic circulation diagram around a central point of focus was created. The polygonal mesh created through the process was used only as a placeholder for future operations.

The tessellation of the topological form was driven by the demands of fabrication and cost. In this scenario, two water-jet machines were to be utilized, one of limited size (2’x3’ max. material size) and the other of commercial grade (4’x8’ max. material size). The problem of tessellation invoked a constellation of concerns; by increasing the size of each...
face, a more faceted formal vocabulary could be developed. However, the increasing size of each piece would displace its production onto larger equipment, causing the cost to go up (as assembly time decreased, as it is easy to put three large pieces together rather than several smaller pieces). Table 2 shows this balance, as the weighting toward small or large figures has inverse consequences in terms of material and time. By using tessellation strategically, we were able to intensify the resolution of the more complex center of the installation, and let the perimeter be more expansive and simplified. The hexagonal treatments of the final surface smoothes out inequalities.
within the tessellation and produces a diffused marching figuration that translates between different conditions.

**hexEnvelope @ structural resolution**

Structurally, the system performs best operating as a cellular network, each piece contributing to the fixity of its neighbors through interlocking. The latest development in the system is a means to ensure that all angles are locked and that provision is made for the correct assembly of any two pieces. A variation on stiffening members that were originally laced through the network of the (un)natural selection installation (figure 10), custom reinforcement bars were developed as a means not only to insure a structural integrity (providing the truss action that the depth of the cells afford) but also to aid in the building of the cells. A parametric stiffener is fed the relative angles between cells and builds the line work for every angle to be reinforced. By embedding a small circular cut in the center of each cell face, a perpendicular can be folded away.

*Figure 12. hexEnvelope installation, photo.*
from the cell to allow for the connection of the stiffening bar. Through labeling, faces can be matched to their appropriate members, which provides a template for the folding of one cell relative to another.

Conclusions

At this time, we would like to argue for the increasing interest in a tectonic realization of complex forms, as opposed to the aspirations of seamlessness that has embodied much of digital production to date. The hexEnvelope, in its unqualified embrace of material strategies of connection, is intended as a display not only of a means to build complex geometry, but also of a means of displacing that production onto alternative machinery to milled formwork.

Through the introduction of a tectonic assembly, not only are efficiencies of production afforded but there is also a potential for articulation of its affect condition, which adds value to any abstracted system of form (figure 8). Rather than being viewed as an incidental means to an end or an unwelcome by-product of fabrication, the detailing process should be used to articulate a finer grain of information, both in terms of describing a more complex object, as well as revealing the processes that informed the shaping of that object.

Another important aspect to this work is the use of multiple software programs and multiple geometric paradigms. By exploiting existing tools as well as “piggy-backing” (as opposed to “bootstrapping”) by writing custom scripts that run over or alongside these tools, and by incorporating a workflow that advantages as many software methodologies as possible, the architect can open up a world of exploration not limited to any one platform. Common to all software tools is a logic of procedure and recursion—to develop a truly productive relationship with our tools, we must ask them to speak a language that is closer to ours, even as our language bends to concepts embodied in the computer. This means that we must take a more active interest in the development of tools, systems and interfaces that prioritize design intelligence and flexibility.

The hexEnvelope attempts to be one such system, in which a designer can incorporate a series of tessellations, a series of forms, and a series of connection strategies to address the issue at hand. The automation features most prominently in the ability to handle complex form and large numbers of unique pieces, displacing the work of the designer from production to exploration.

Figure 13. Happy Family Lamp, detail showing tectonic resolution.
References


Appendix: Alternative Description

The hexEnvelope is designed as a universal system that conflates issues of design value, previously stratified within a domain of scaled documentation. Acting only in intensities, whether they be intensities of aperture, structure, topological intricacy, or tectonic expression, the hexEnvelope is an attempt to describe a multi-modal means of operating with material. The hexEnvelope is a series of defined tectonic strategies that may be assumed (depending on factors of labor and material), a series of geometric figures that may be recognized, and a series of operations conducted upon that geometry to bring about qualities of texture and aperture.