BRANCHING INVENTORY

Democratized Fabrication of Available Stock

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Abstract. Branching inventory is a construction methodology demonstrated through a full-scale structural prototype that reduces the waste inherent in milling lumber and celebrates natural variation by making complex form the efficient result of irregular material. The processing of wood into standardized components embeds waste and intensive energy consumption into timber construction. This work reimagines the utility of raw materials, using computational feedback to place natural form in dialogue with design intent – creating a dialogue between technology, material, and designer. A custom workflow synthesizes a network of branches into a specific, structural form, shaped by the thicknesses and curvatures of the stock material as well as design input. Building on work using machine visioning in fabricating non-standard timber by others – most of which relies on elaborate and cost-prohibitive 3D scanning and robotic fabrication systems – branching inventory demonstrates a low-fidelity, democratized version of such approaches, using standard wood and metal-working tools and in which the available material stock contributes to design possibilities.

Keywords. Digital Design; Digital Fabrication; 3D Scanning; Material Agency; Democratized Technology.

1. Introduction

During Industrialization, wood construction became standardized through the milling of logs into dimension lumber. Subtractive part reduction, repeated at forest, sawmill, and construction site, produces material and energy waste. Amid an escalating environmental crisis, dimension lumber faces new lifecycle questions and overextended supply chains. The potentials of computational imaging in fabricating non-standard timber have been both discussed (by Mario Carpo and others) and demonstrated in built projects (at AA Hooke Park, University of Michigan, Aarhus, and elsewhere) over the last several years (Carpo,

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2017; Devadass et al, 2016; Self and Vercruysse, 2017; Von Buelow, 2018; Larsen and Aagaard, 2019). Most of this work relies on elaborate and cost-prohibitive 3D scanning and robotic fabrication systems. This paper describes a democratized take on such approaches, developing a novel construction methodology which reimagines the utility of raw logs, using computational feedback to place natural form in dialogue with design intent. The workflow makes use of low-cost, consumer-grade and industry-standard software, and fabrication relies on simple welds and either a waterjet or jigsaw.

This methodology creates a dialogue between technology, material, and designer that reduces the waste inherent in milling lumber and celebrates natural variation by making complex form the efficient result of irregular material. A custom workflow synthesizes a network of branches into a specific, structural form, shaped by the thicknesses and curvatures of the stock material as well as design input. Because material eccentricity informs design geometry, minimal part reduction must be performed, in turn decreasing construction energy and waste during harvesting, production, and on-site construction.

The workflow is demonstrated through the construction of a full-scale structural prototype, a wall ten meters in length and three meters in height. Invasive plant species – specifically the bradford pear – are explored as a potential non-traditional, but rapidly-renewable natural material stream for construction. This effort attempts to incentivize the removal of such species (through harvesting) and in turn remediate the environment at a regional scale. The bradford pear, which was popularized in yards and parking lots due to its natural ornament and fast growth, is prone to losing branches due to its weak, acutely angled forks and numerous limbs originating from the same point. The built prototype collects and makes use of these fallen branches. Irregular branches are collected, scanned, inventoried, and sorted across a curved surface using a smartphone 3D scanning app and custom parametric workflow, matching natural curvature to the designed model and locating stronger branches near the base of the assembly. The parametric model outputs unique steel joint templates which program the overall geometry within each node.

This paper presents a built research investigation but describes a methodology that is globally transferrable – a democratized workflow between common tools that can be adapted to local material supplies and craftsmanship. The success of the prototype points to the possibility that imaging and computation, coupled with non-traditional material streams, can reconsider the default practice of standardization and part reduction in timber construction.

2. Methods

Branching inventory develops a hybrid analog/digital workflow from which many types of structures can be designed and built, which will vary in form according to material inputs and design intent. A system diagram illustrates the components and relationships in the process, which mediates designer, material, computation, and physical fabrication (Figure 1). The following project methodology is described in five main steps: collection and scanning, inventorying and analysis, branch and surface sorting, programmed joints, and physical assembly.

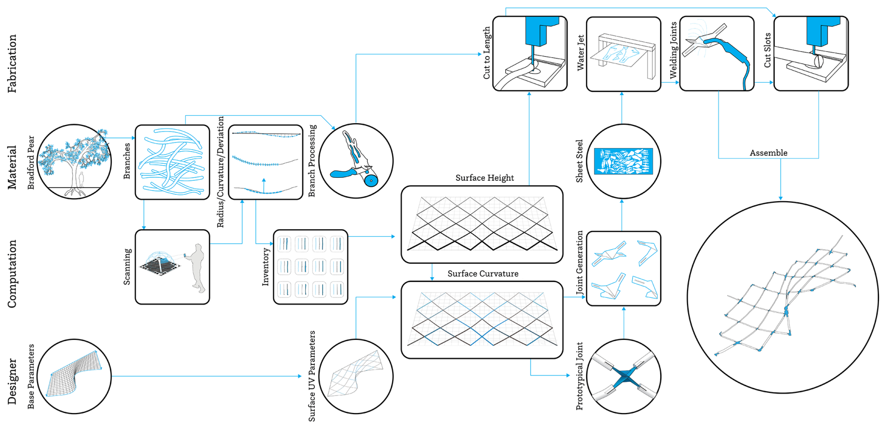

Figure 1. System Diagram.

2.1. COLLECTION AND SCANNING

The project aims to make use of material that is too irregular to be milled into traditional lumber. In this case, a desire to use material from invasive plant species led to the project team selecting the bradford pear, a tree with irregular branches and weak forks but otherwise quality wood that is popular for woodturning pens and other small objects. The team harvested all material for the project from a single bradford pear tree, resulting in a collection of sixty branches, each approximately one meter in length.

To extract physical qualities from the irregular material which can inform a design, a reliable 3D scanning method was required. Several 3D scanning methods were tested, from consumer-grade smartphone apps to high-end industrial 3D scanning hardware and software systems. These were assessed based on scan accuracy, usability, file size, and cleanliness of the digital model. Ultimately, a user-friendly smartphone app, Qlone, was selected. Qlone is a photogrammetry scanning software that uses a printed calibration grid as the surface on which an object is scanned. This surface can be printed at any scale and isolates the digital model from all background material, meaning that no post processing of the resulting digital mesh is required – this was a significant advantage over other smartphone scanning apps. An augmented half dome is viewable around the object as it is scanned to direct the user to views and angles yet to be photographed.

This method produced scans that were clean, immediately usable, and of high enough resolution to be processed using the project workflow. Since a joinery method (described below) was developed that does not require accurately machining the branches themselves, the selected scanning method was more than sufficient. This approach sets itself apart from other projects that rely on extremely accurate 3D scans to generate 3D toolpaths for intricate joinery. Additionally, the use of a smartphone app democratizes the approach, replacing 3D scanners which retail for tens of thousands of dollars with software that costs a few dollars. The resulting digital meshes are also significantly smaller in file size, making manipulating dozens at once within a single Rhinoceros file possible on a standard laptop. It is also worth noting that this method is limited by the resolution of the smartphone camera, and resolution does not scale with larger objects. This is due to the nature of the photogrammetry method used in the software, which requires the same number of photographs be taken of an object, regardless of scale.

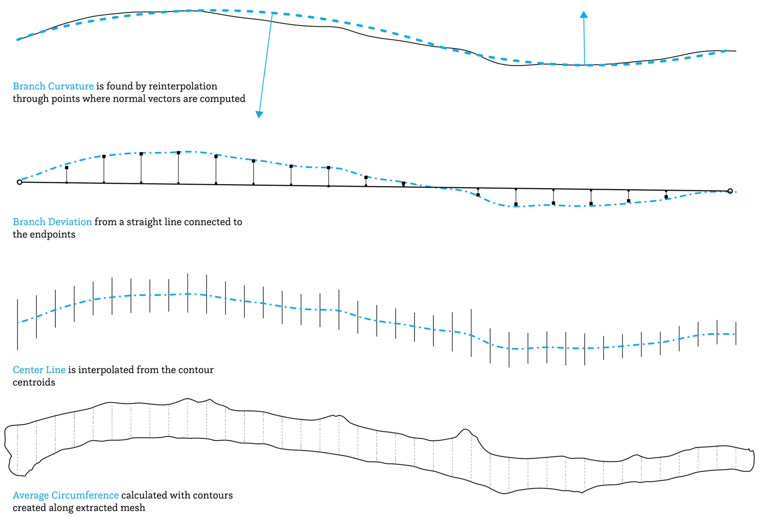

Figure 2. Branch Analysis.

2.2. INVENTORYING AND ANALYSIS

This step of the process functions as the digital link between designer and material. First, the inventory was prepared for analysis, with the goal of extracting specific understandings of the branches' inherent eccentricities, such that they can be used to the designer's advantage. Once all sixty branches were scanned, they were numbered to match their physical identity, compiled into an organized grid in a single Rhinoceros file, and oriented uniformly lengthwise. The data extracted (including values of curvature and average radius) is crucial to understand and determine how the irregular material can be used accurately in predictably modeling and fabricating a structure (Figure 2).

The first operation performed on each 3D mesh was a simple contouring along the length of the branch, serving as a base for many other operations. Connecting the centroids of each contour curve results in an interpolated curve representing the centerline of the branch – a spatial delineation that can be further refined by interpolating circles over each of the contoured sections, in effect smoothing out branches with small protruding geometries. The generated centerlines are linked to each individual branch and stored in the corresponding place within the inventory. The interpolated circles also serve to measure and calculate the average circumference and radius of each branch – a set of values that are likewise added to the growing data inventory.

Using the new inventory of centerline curves, a set of curvature values are determined for each branch. First, the length of each branch curve is reparameterized from zero to one, and three points are positioned at 0.3, 0.5, and 0.7. A circle is then interpolated from these three points, representing the overall curvature of the branch. The radius of this circle is stored as the curvature value for each individual branch. The radius, also visualized as a vector, is used later on in determining the orientation of branches within the structure.

With these four components (average circumference, centerline curve, curvature value, and curvature vector) generated and saved, they are linked to their corresponding scanned meshes and constitute the complete inventory.

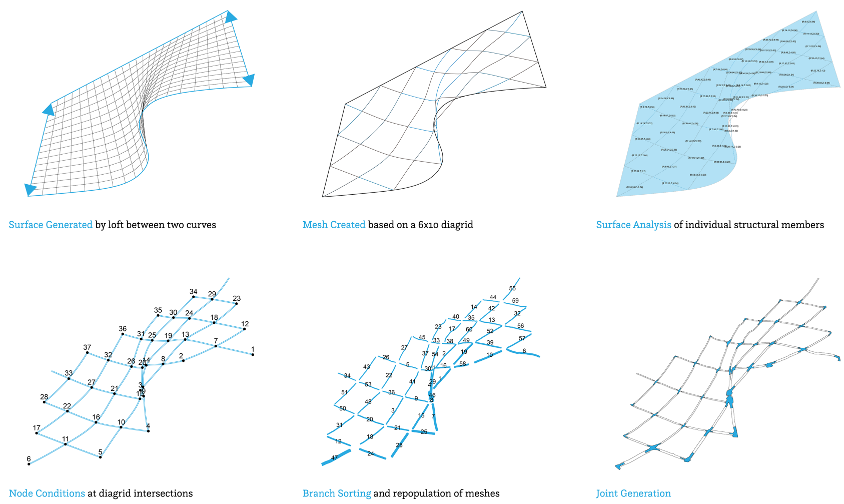

Figure 3. Surface Design and Analysis.

2.3. BRANCH AND SURFACE SORTING

Having scanned and analyzed an inventory of branches, the next step is to correlate this material inventory with a designed form. The form was designed as a lofted surface between a straight and an undulating curve, resulting in a vertical, wall-like structure that is serpentine at ground level and straight along the top.

With the form designed, branch sorting can begin. The designed mesh contains embedded information in each of its UV division curve edges that is similar to the information gathered in the branch inventory described previously. Each mesh edge has a particular associated curvature and has its own Z-height relative to the ground. These two values are evaluated and inventoried across the surface (as was done with the branches). These new mesh values are compared to the branch values in a best fit system as follows (Figure 3):

First, the branches are sorted by average circumference and assigned to an appropriate horizontal section of the mesh according to Z-Height values – heavier branches are kept toward the bottom of the structure and lighter branches are located toward the top. Next, beginning with the most extreme curvature values, branches are matched to the mesh edge with the most similar curvature value. After all branches have been located across the surface, the surface is reauthored based on the curvature values of the branches.

This reauthoring of the surface requires the designer to yield some degree of authorship to the eccentricities of the material. Each branch has its own texture and smaller scale surface variations – data not captured through the scanning process. These irregularities result in variability within the finished structure. If the process is performed again on a different set of physical branches, or branches from a different tree species, for example, the resulting geometry would be reshaped based on the peculiarities of the new inputs.

2.4. PROGRAMMED JOINTS

After the branches are located across the structure, a joinery method is implemented to physically fabricate the structure. Rather than relying on highly specific joints that must be machined into the ends of the branches (and therefore require high-fidelity 3D scans), a joint system was developed that could connect the ends of branches where they meet at the nodes on the surface. Joint design anticipated low skill fabrication methods and was aimed at expedient manufacturing and assembly. Finally, the joints were customized for each node by programming each with the overall geometry of the structure. The joint design made a large scaffolding or template unnecessary for assembly, since angles of intersection and positioning were inherent to joint geometry.

Multiple joint iterations were developed and tested, ranging in scale and complexity. Initially, joints anticipated the overlapping and capturing of branch ends, but this was deemed too visually clunky and complex. Instead, the final joint design required the branches terminate just short of intersection, slotting into a node made of two intersecting pieces of steel sheet and forming a thin joint that does not distract visually from the legibility of the best fit system.

To model and fabricate the joints, two planar surfaces were generated using the points of intersection between four branches, intersecting with each other at the center of the joint. Two triangles were created to hold the surfaces together for welding accurate angles and to reinforce the joint. Once the joints were adapted to the geometry of each node in the structure, they were cut from a 14-gauge steel sheet and welded manually using triangular alignment pieces. Cutting the joints can be performed by either a CNC water jet or plasma cutter in a typical digital fabrication workflow or, in a more low-tech, democratized approach, by hand using printed paper templates and a metal bandsaw or jigsaw. Joints at the edges of the assembly are generated with the same process with slight variation: the bottom joints connected to the ground are made with the two metal planes folded and welded back-to-back, while the elbow joints on the ends and top edges are simply bent to the correct angle to hold the edge pieces in place.

Figure 4. Assembled Structure.

2.5. PHYSICAL ASSEMBLY

With the branch and joint inventory complete, the joints were fabricated, and the branches were trimmed to length. To attach the metal joints to the wood branches, six centimeter kerf cuts were made in the ends of each branch to accept the joint. With the metal joint inserted, two holes were drilled through both the branch and joint through which bolts hold the assembly together and prevent rotation.

The digital model was referenced to guide the correct orientation of the branches during kerf cutting. The photographic data gathered during 3D scanning aided in this alignment process, but it proved to be the most tedious part of fabricating the structure. Future work should consider the use of augmented reality systems to aid in proper and precise alignment of end slots.

All joints and branches were assembled sequentially working in rows from the bottom to top of the structure. The bottom joints were anchored to the ground with a foundation of cement pavers. Once fastened, the programmed geometry of the joints accurately positioned the branches in the correct orientation within the overall assembly, meaning that assembly was easily completed in its correct upright orientation by a team of two individuals without the use of scaffolding or any large scale alignment templates (Figure 4).

3. Results

The 3D scanning method proved accurate enough to complete the project and was affordable and data efficient compared to more advanced systems. Some discrepancies were experienced in the process that could be designed around in future work. Since the object being scanned sits on top of a flat registration image, the underside of the object is obscured from view and thus interpolated. This reduced accuracy of the scan for the bottom side of each branch and produced some geometrical discrepancies during branch analysis. Future work should explore mounting of the branch within a simple armature for scanning, such that it is elevated, and the bottom is more visible. Finally, Qlone produces scans with no measurable scale, meaning that scans were manually resized. Future work can use of a physical scaling object to calibrate the resultant digital model.

Orienting the branches for slot incision presented challenges. Methods exist and have been proven by others to accomplish this step by robotically locating the branches in space. Such techniques, while effective, would dilute the democratized approach of this project. Alternatively, consumer-grade augmented reality headsets may provide better guidance in the future to match branch orientation more accurately to the digital model.

Several challenges arose during fabrication of the metal joints. In particular, the CNC water jet that was planned for fabrication suffered an unrelated technical problem and was unavailable for use. As a result, the team successfully implemented the low-tech joint fabrication option, using full-scale printed paper templates to cut joints manually with a metal bandsaw and jigsaw. The incorporation of triangular templates for accurate welding of angles was effective. The 14-gauge steel that was selected for the joints, while enabling a freestanding installation, resulted in some flexibility in the structure. Future versions would benefit from thicker steel and further stiffening of the metal joints by permanently integrating the triangular angle templates.

4. Discussion

This research contributes to a body of work that advances applications of irregular, non-standard materials in the production of architectural structures, in particular projects using the irregularities of raw material to impact the form of an assembly (MacDonald et al, 2019). Ideas around material agency and minimization of waste in digital fabrication processes resonate with Bandsawn Bands, a project in which the natural form of a tree flitch generated a three-dimensional topographic surface, while ideas about scanning and building with logs offer alternative approaches to the process developed for making use of tree forks in Tree Fork Truss (Johns and Foley, 2014; Devadass et al, 2016). Techniques aimed at minimizing part reduction build on the approach developed to make use of concrete debris in Cyclopean Cannibalism (Clifford and McGee, 2018). Branching Inventory contributes to this area of scholarship by proposing and demonstrating the transformation of such methods to readily available democratized technologies – no prohibitively expensive scanning or robotic fabrication equipment is necessary. The approach is globally transferrable, usable by anyone with a smartphone, laptop, Rhinoceros/Grasshopper, and a few basic manual tools.

Figure 5. Variability of branches produces visual distortions in assembly.

The project also advances an ecological narrative through the use of material that is essentially landscape waste and would not otherwise be usable in architectural applications. Specifically, the use of material harvested from invasive species, whose existence is typically a nuisance, demonstrates the utilization of such material and incentivizes their removal and the subsequent remediation of native ecosystems.

The bradford pear was selected for the demonstration of this workflow due to its tendency of breaking at joints during storms and losing branches that are otherwise hardy lumber. The project methodology is established in such a way that in future work, other invasive or non-invasive tree species can be used by simply substituting these new materials as the scanned inputs. Since the formal qualities of the scanned material influences the final form of the structure, each species will yield a different geometry (Figure 5). The process mediates authorship in the realization of architectural form: it grants agency to the material and requires the designer to relinquish some degree of formal control. Technology is used to span the gap presented by eccentric material qualities that are typically avoided altogether, with a cohesive process of 3D scanning, digital inventorying and analysis, and form found optimization through a best fit system.

Finally, scaling the system from a pavilion-scale installation toward a more traditional architectural scale with building enclosure is conceivable. Projects using similar scanning strategies have demonstrated that building-scale structures are possible (Mollica and Self, 2016). In this case, the reliance on low-tech, accessible technologies must be considered in scaling the work, possibly drawing upon the inherent knowledge within vernacular building traditions (Watson, 2020). Barriers to widespread use (codification, permitting, etc.) remain, but as recent developments in public policy enabling mass timber construction in the American northwest show, such changes are possible if technologies and material systems can be adequately demonstrated and tested at scale. Structural testing of input materials would be a first step in developing a precise understanding of the material's capacities, such that digital simulations could prove the performance of structural assemblies. This work intends to question the role of standardized materials in architectural production, presenting an accessible workflow to bring irregular natural materials into contemporary building.

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References

Von Buelow, P., Torghabehi, O.O., Mankouche, S. and Vliet, K.: 2018, Combining parametric form generation and design exploration to produce a wooden reticulated shell using natural tree crotches, *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2018: Creativity in Structural Design*, Cambridge.

Carpo, M.: 2017, *The Second Digital Turn: Design Beyond Intelligence*, MIT Press, Cambridge.

Clifford, B. and McGee, W.: 2018, Cyclopean Cannibalism: A Method for Recycling Rubble, *ACADIA 18: On Imprecision and Infidelity, Proceedings of the 38th Annual Conference of the Association for Computer Aided Design in Architecture*, Mexico City, 404-413.

Devadass, P., Dailami, F., Mollica, Z. and Self, M.: 2016, Robotic Fabrication of Non-Standard Material, *ACADIA 2016: Posthuman Frontiers: Data, Designers, and Cognitive Machines; Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*, Ann Arbor, 206-213.

Johns, R.L. and Foley, N.: 2014, Bandsawn Bands: Feature-Based Design and Fabrication of Nested Freeform Surfaces in Wood, *Robotic Fabrication in Architecture, Art and Design*, Ann Arbor, 17-32.

Larsen, N.M. and Aagaard, A.K.: 2019, Exploring Natural Wood: A workflow for using non-uniform sawlogs in digital design and fabrication, *ACADIA 19: Ubiquity and Autonomy, Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture*, Austin, 500-509.

MacDonald, K., Schumann, K. and Hauptman, J.: 2019, Digital Fabrication of Standardless Materials, *ACADIA 2019: Ubiquity and Autonomy, Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture*, Austin, 266-275.

Mollica, Z. and Self, M.: 2016, Tree Fork Truss: Geometric Strategies for Exploiting Inherent Material Form, *Advances in Architectural Geometry 2016*, Zurich, 138-153.

Self, M. and Vercruysse, E.: 2017, Infinite Variations, Radical Strategies, *Fabricate: Rethinking Design and Construction*, Stuttgart, 30-35.

Watson, J.: 2020, *Lo-TEK: Design by Radical Indigenism*, Taschen, Cologne.