LOG KNOT: Robotically Fabricated Roundwood Timber Structure

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LOG KNOT is a robotically fabricated architectural installation which aims to expand and optimize the use of entire trees and irregular timber geometries in construction. LOG KNOT creates an infinite loop of roundwood, curving three-dimensionally along its length. The project borrows strategies from traditional wood building and manufacturing, while implementing contemporary technologies to achieve precision and mass customization. By utilizing robotic fabrication processes and 3D scanning, it is possible to create complex timber curvature that requires minimal formwork for assembly, thus reducing waste and optimizing the use of valuable timber resources. LOG KNOT's design is based on naturally existing timber geometries found in mature ash trees infested by the Emerald Ash Borer. Furthermore, the installation capitalizes on the idiosyncrasies of such irregular roundwood components. In a reciprocal design process, the project fosters synergies and feedback between material, fabrication, digital form, and full-scale construction.

RESEARCH AIMS AND OBJECTIVES

This paper will outline processes and methodologies for robotic fabrication, variable complex-curvature creation, joinery detailing, geometric and structural optimization, the reduction of moisture-related material failures, and on-site assembly. First, the research team developed a design method to create curvature from roundwood pieces, both regular and irregular. Components are computationally processed to form a spatially complex figure-eight knot (Savoy knot). Based on initial 3D models, a number of irregularly shaped trees and small roundwood members that cannot be processed by traditional sawmills are selected and harvested from a local forest. To complete the design process, the trees are 3D scanned and the digital model is adjusted to fit the available timber stock inventory, reciprocally shifting the form-to-log strategy towards log-to-form. Second, the structure is computationally optimized and fabrication protocols are developed for the available robotic system, a KUKA KR200/2 with a 5hp CNC spindle. Custom computational solvers locally optimize the structure for bending and moment forces at each tri-fold mortise and tenon joint. Custom fabrication protocols improve the positioning of a work piece in relation to the robotic end effector. Each wood component is treated with Pentacryl, a non-hygroscopic and non-toxic wood stabilizer, to prevent checking and shaking which can compromise connections. Third, a series of full-scale prototypes are constructed to develop connections and structural details, further improving the efficiency of design and fabrication protocols. Due to the unique joint design, LOG KNOT requires only minimal formwork for assembly and can be built without heavy machinery. The main research contributions of this architectural installation are in the area of minimal formwork assembly, bending and moment force optimization of mortise and tenon joints, as well as the creation of variable compound curvature utilizing both regular and irregular roundwood geometries.

RESEARCH CONTEXT

The invasive Emerald Ash Borer threatens to eradicate most of the 8.7 billion Ash trees in North America. Since its discovery in the United States in 2002, the Ash Borer killed tens of millions of ash trees and has drastically transformed entire forest ecosystems in the process (Herms and McCullough, 2014). In New York State, where ash trees constitute about 10% of the tree population, the Emerald Ash Borer was first discovered in 2009 and has since rapidly spread across the southern half of the state (USDA, 2019). Infested ash is often comprised of mature growth, including many trees with irregular trunk and fork geometries. While such trees could be used for construction, they are typically regarded as economically "invaluable" (worth about $ 0.25 per tree), as they cannot be processed by regular sawmills. As a result, most of the dead ash trees end up as firewood or perish without purpose while releasing carbon dioxide in the atmosphere. LOG KNOT borrows strategies from traditional wood building and manufacturing (Blondeau and Du Clairbois, 1783) and aims to increase the use of roundwood and irregular wood geometries in construction. Currently, only about 35% of the wood of a tree is estimated to be used in construction (Ramage, et al., 2017), focusing mainly on the straight tree trunk and generally omitting curved and forking timber altogether.

LOG KNOT expands on research projects such as the Wood Chip Barn (Mollica and Self, 2016) at Hooke Park (Self, 2016) and Limb at University of Michigan (Von Buelow, et al., 2018), as well as industry applications developed by companies such as WholeTrees Structures (WholeTrees LLC, 2019). The process

Figure 1. View of completed installation. In a reciprocal design process, the LOG KNOT fosters synergies and feedback between material, fabrication, digital form, and full-scale construction. Image by Jeremy Bilotti.

and design methodology shared by these projects constitutes a paradigm shift in the design and construction of wood structures: rather than first mass-standardizing an irregular product (a tree) to subsequently mass-customize a design from the standardized components (plywood, 2x4s, etc.), each project starts with the available natural timber geometry and capitalizes on its idiosyncrasies.

Dead ash trees form an enormous and untapped material resource. This project proposes to take advantage of the Emerald Ash Borer's carnage and appropriate irregularly shaped ash trees for construction. By implementing high precision 3D scanning and robotic based fabrication technology, "waste wood" transforms into an abundantly available, affordable, and sustainable building material. No longer bound to the paradigm of industrial standardization, this project revisits bygone wood craft and design based on organic, found, and living materials.

RESEARCH QUESTIONS

LOG KNOT uses irregular and natural wood geometries for construction, leveraging roundwood and its superior structural capacity. The research team examined whether regular and irregular roundwood geometries can be processed to construct compound curvature assemblies. There exist a variety of techniques to create single curvature in wood structures – such as steam bending (Wright et al., 2013) or glue lamination (Issa and Kmeid, 2005) – but only few techniques to generate more complex curvature within a single structural element exist. In order to create complex curvature, the research team developed a simple method which can easily be replicated: first, the log is compartmentalized, establishing a series of discrete "parts" and second, the parts are re-configured into a complex curvature "whole" by carefully manipulating the assembly angles between the logs. Timber components reconfigured in such a manner can either follow single-curvature or double-curvature profiles.

Furthermore, LOG KNOT investigates the possibility to establish a minimal formwork assembly method for the connection of discrete log components. Due to a precise calibration of joinery, the research team arrived at a solution that enables stable connections during the construction process. Each joint is carefully and parametrically programmed to follow the global curvature geometry of the knot during assembly. The research team also considered the development and integration of localized structural optimization protocols for the project, following the assumption that custom mortise and tenon joints can be optimized for bending and moment forces. The LOG KNOT research team then explored various methods to achieve such a locally optimized and structurally intelligent construction system.

RESEARCH METHODS

Design Process: Geometric form finding and custom fabrication/assembly protocols between form-to-log and log-to-form were iteratively developed for this project. Starting with small-scale physical study models, geometries and curvature conditions of various knot configurations were first tested. The study model tests revealed the flexibility of the design logic and its ability to create complex curvature from roundwood log components.

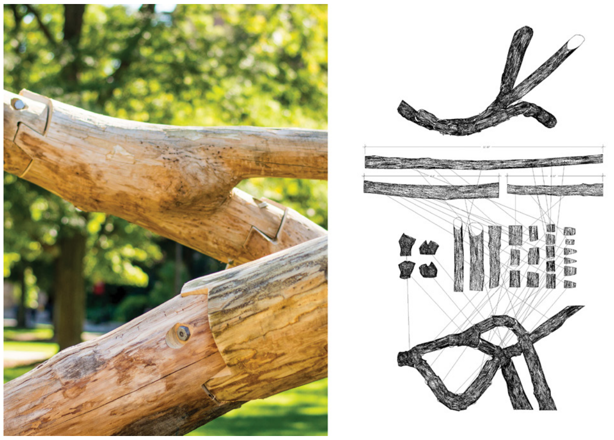

Figure 2. Detail view of completed installation and 3D scan of early prototype assembly. Image by Jeremy Bilotti. Drawing by Brian Havener.

Figure 3. LOG KNOT plan and section. View of robotically CNC milled tri-part mortise and tenon joinery studies. Image and drawing by Cornell RCL.

The research team tested a variety of knot conditions, settling on a spatially complex figure-eight knot (Savoy knot) for the installation. Study models were then translated into digital design protocols using Rhinoceros Grasshopper. Parameters were defined in order to control the relationship of roundwood components to the global curvature of the knot. Maintaining a fifteen-degree angle between components, the length of each roundwood component is dependent on the degree of global curvature. A tighter curvature radius results in shorter roundwood components, while a wider radius results in longer ones. The timber components' diameter significantly thickens as the curvature approaches the ground and becomes smaller towards the knot's apexes. A critical challenge of the design process is its reliance on information about the natural log geometries available. Oscillating between physical reality and digital model, the tree forks were only integrated into the digital model after harvesting, which required a flexible and parametric design model that can easily adapt to the available geometries.

Timber Harvesting and Prototyping: The (anonymous research group) collaborates with (anonymous), a teaching and research forest of the university. Based on the environmental hazard caused by the Emerald Ash Borer, which reached the forests of (anonymous university) in 2018, the research team selected mature ash trees as the main wood to be used in the installation, with the goal to demonstrate that such trees can be used for structural architectural applications. However, initial fabrication studies were conducted using a number of wood species (ash, aspen, bass, beech, hemlock, maple) to explore the feasibility of robotic CNC milling in each species. Due to logistical reasons, the research team selected two types of wood for the installation: ash and hemlock. The two species proved to be the best suitable, due to both their successful processing by the research team's robotic setup and their local availability. Both wood species were available in suitable diameters as previously cut roundwood, seasoned for one year and stored on the grounds of (anonymous) forest. Both trunks and forks from twelve different trees were used for the installation. From those twelve trees, 72 log segments were cut, including four tree forks. To provide ample tolerances for the fabrication process, each of the segments was cut three inches long on each end. The logs were manually de-barked to achieve a consistency of color and texture.

Initial joinery studies were conducted using roundwood with a diameter of three to four inches. The research team tested conventional finger joints, mortise and tenon joints, dovetail joints, as well as custom steel dowel joints. Each of these methods exhibited severe shortcomings in either structural capacity, ease of assembly, or ease of robotic fabrication. Based on knowledge gained from the initial joinery testes, the research team developed a custom tri-fold mortise and tenon joint which is self-supportive during assembly and able to resist bending in multiple directions. Using the tri-fold mortise and tenon joint, a number of full-scale prototypes were created to test the structural capacity of the overall assembly. The prototypes exhibited high geometric accuracy, conforming to the designed global curvature geometry. When structurally loaded with 250 lbs, the twelve-inch diameter prototype assemblies exhibited no noticeable deformation.

Global Form Finding and Structural Optimization: Various structural optimization protocols are deployed in the LOG KNOT project. While the global knot form is derived from spatial considerations – albeit within the structurally sound framework of a closed-loop knot structure – the project is highly structurally optimized at a local level. To optimize load behavior, the radius of the roundwood reduces towards the apexes of the knot and thickens at ground level where moment forces and loads are highest. Additionally, the connections between components are structurally optimized: using the Rhinoceros Grasshopper plug-in Karamba, the research team extracted the direction of moment forces at each connection within the timber knot. The

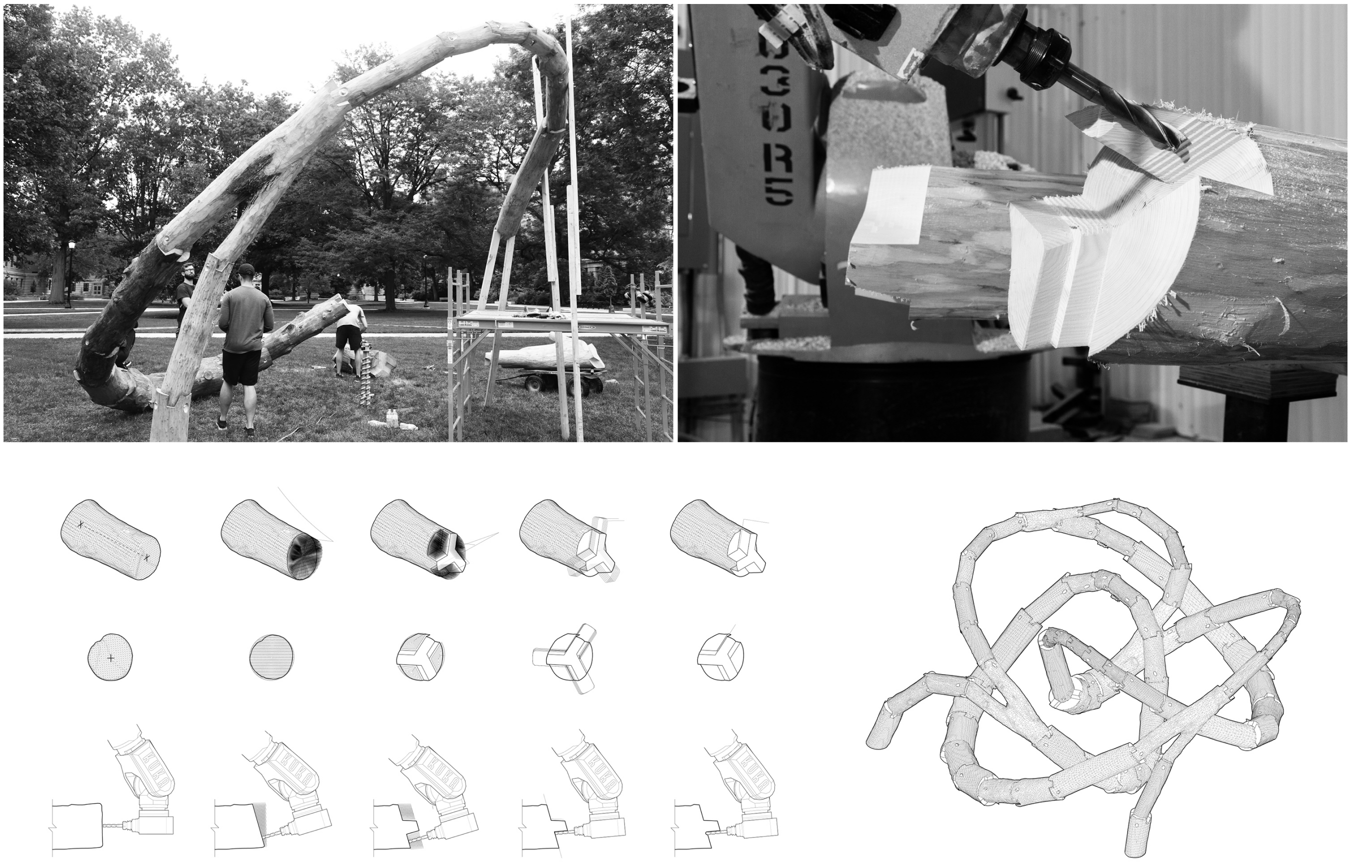

Figure 4. Minimal formwork assembly on site and details of the robotic fabrication process.. Image and photo by Cornell RCL.

analysis considers self-weight of the structure but omits a live load scenario.

The joints were designed with an "undercut" in one of the three flanges in each mortise and tenon connection, resulting in an assembly with a slight twisting-motion. The location of the undercut is determined by the force diagram derived from Karamba: the undercut is oriented to counter-act the joint's bending motion and positioned in the direction of potential structural failure. This particular joinery orientation and design prevents two components from disconnecting under various load scenarios.

Robotic Fabrication: The open-source robotic platform used for this project is a repurposed KUKA KR200/2 with a KRC2 control unit, a setup formerly deployed by GM as an automotive welding robot (Zivkovic and Battaglia 2017). The robot has a reach of 2400 mm and a repeatability of +-0.3mm. KRL code is generated in Rhinoceros Grasshopper using the KUKA|prc plugin (Braumann and Brell-Cokcan 2011) for custom CNC milling path generation. A Changsheng 220V 4.5KW Air Cooled ER32 spindle motor with a 4.5KW VFD driver inverter is used for CNC milling. The research team used two types of mill bits, an uncoated Carbide Square-End End Mill, 3 Flute, 3/4" Mill Diameter with an overall length of 6" and an uncoated Carbide Ball End Mill, 3 Flute, 3/4" Mill Diameter with an overall length of 6".

The research team constructed a flexible and variable log-mount system from locally available steel profiles. The hemlock and ash pieces were positioned in front of the robot using steel posts, each with a mounting plate. The posts can be attached to the log mounting frame via steel clamps and the logs are secured to the mounting plate via wood screws. Bypassing the time-consuming need to 3D scan each log in front of the robotic system to determine its position relative to the CNC mill, the research team developed a time-saving method to center each log and transfer its location to the digital model. Locating the log in physical space, the center of each round face of the blank log geometry was transferred into the computer. Since the LOG KNOT components rely on a center line in the computational generation of their design, aligning the center line of the blank log geometry through its two endpoints ensures that the joints are accurately calibrated despite irregularities of the round wood. After this calibration takes place, the robotic toolpath is generated for the log geometry as it appears in physical space. This greatly reduces the time needed to locate geometries compared to 3D scanning the log in place.

A custom milling code protocol was created in Rhinoceros Grasshopper, using the plugin Clipper to generate continuous polyline offsets. Four types of tool path were generated to be executed by the robotic system. First, using the ¾" square end mill bit, the rough pass protocol creates an even surface, angled at fifteen degrees from the faces' normal. Second, once the angled surface is created, the mortise and tenon rough pass is cut, at four inches deep. Third, the finishing cut is executed, using the side of the bit instead of its tip, thus further taking advantage of the robot's six-axis flexibility. This significantly reduces the time it takes to execute the finishing pass while also increasing the accuracy of fabrication. The fourth and final tool path finishes the undercut detail. While the first three steps use the square end mill bit, the fourth changes to the ball end mill bit. Doing so demarcates the undercut flange with an easily identifiable round profile cut, which signifies the correct orientation of flanges between two components (i.e. undercut flange to undercut flange).

Depending on log diameters, the rough pass takes anywhere between 20 minutes and 90 minutes to execute (per side), whereas the finishing pass takes about 10 minutes on average. The robot moves at a milling speed of approximately 90 millimeters per second. Milling speeds were manually adjusted if the robot encountered knots or other defects in the grain of the wood. The 72 individual timber components were fabricated over a span of 15 days, averaging 4-5 logs per day.

Material Parameters: In order to prevent checking (ash) and shaking (hemlock), the research team coated the log ends with Pentacryl, a fast-acting, non-toxic, non-hygroscopic, and non-oxidizing wood stabilizer. Pentacryl penetrates green, wet wood with a high moisture content and draws out the moisture without the need to fully submerge the entire log. Other wood stabilization methods such as kiln-drying were considered but proved to be too costly, too energy consuming, and too slow for the purposes of the project. After harvesting, the moisture content of the ash logs was 20 – 25%, close to the ideal moisture content of 10 – 15%. The moisture content of the hemlock logs was 45 – 55%. Both, the ash and the hemlock logs significantly profited from the daily brush coating with Pentacryl. Compared to untreated control samples, checking and shaking were significantly reduced after treatment with the wood stabilizer. A total of 10 gallons of Pentacryl was used for the project and its prototype tests.

Connection Details: LOG KNOT is a fully permitted temporary installation which had to undergo a thorough review at the municipal and university level. In order to prove the structural feasibility of LOG KNOT and prevent fencing in the installation during the six-month exhibition period, the research team worked with (anonymous) structural engineers. The structural engineering team analyzed the installation under live-load scenarios, suggesting a strengthening of lag bolts to ensure that the structure can be climbed upon safely. Besides the wooden mortise and tenon connection with the structurally optimized undercut, the log-to-log connections are secured with 3/4" diameter hot-dipped galvanized steel lag bolts of varying lengths. Each joint is secured by three lag bolts. LOG KNOT is designed for disassembly, therefore relying upon the use of steel lag bolts instead of wooden dowels. The mortise and tenon ratio was carefully calibrated to be as close to 50%-50% as possible to ensure an even distribution of forces and prevent breaking of joinery components.

Due to the temporary nature of the installation, the research team was not permitted to create concrete foundations to fasten the project to the ground. Instead, eight removable 36" Penetrator Aluminum Screw Anchors with a 2" hex head, manufactured by American Earth Anchors, were used to prevent lateral shifting of the structure. The earth anchors were attached to the foundation logs via a ¼" steel plate which was bolted to the log with ¾" lag bolts. The earth anchors were driven into the ground using a compact size impact wrench and a large manual wrench.

Assembly: LOG KNOT was assembled by a dedicated team over the course of three days. The self-supportive joinery detail affords an assembly without the use of heavy machinery. First, one of the major anchor points of the installation was installed and securely fastened to the ground with the aluminum earth anchors. Subsequent pieces were then attached to the foundation log whereas lag bolt holes were always drilled and installed in place. After each completed knot "arch" segment, the structure was attached to the ground using the earth anchors. Periodically, individual 2x4s were used as temporary prop-up scaffolding, attached to the emerging LOG KNOT installation with wood screws. The custom milled joinery geometry at connections ensures that global curvatures were met and accurate. Over the course of the six-month installation period, the de-barked logs aged from a light-brown color to gray and black hues, due to weathering. This effect was predicted and desired, resulting in a subtle material transformation of the installation over the course of the exhibition.

RESEARCH EVALUATION

LOG KNOT was successfully installed by the research team and showed no evident structural deterioration after enduring six months of harsh exterior weather conditions from mid-August 2018 to mid-March 2019. In order to test the geometric accuracy of the overall assembly, the research team used a FARO Focus 3D S120 laser scanner with a resolution of up to 1/32" (0.79 mm) and a range of up to 120 meters to 3D-scan the completed installation. The scans were compiled and processed using the FARO Scene software and were subsequently exported to Rhinoceros as point clouds. This process reveals that the curvature of the installation closely matches the predicted curvature of the 3D model. Minor deviations were found at the locations where the knot structure meets the ground. Overall, deviations of up to 10 inches were found

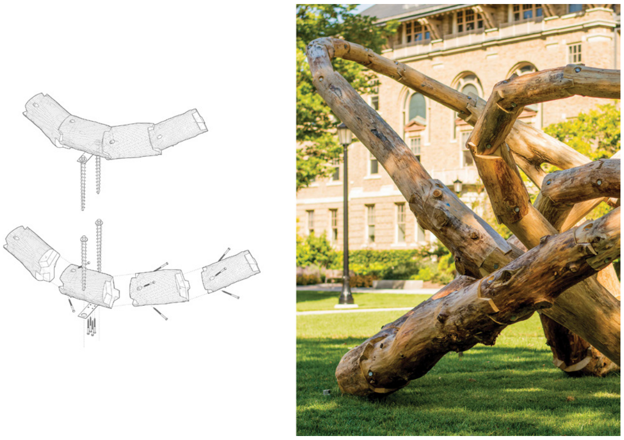

Figure 5. Axonometric with detail connections. Comparison of 3D scanned geometry with digital model. Detail of final installation and cantilevered knot “arches”.. Image by Jeremy Bilotti. Drawing by Cornell RCL.

in some parts of the structure. Those deviations likely resulted from human error during the construction process and are not a product of accumulative curvature errors in the joinery detail.

To improve the construction method, future investigations will focus on the development of an all-wood joinery connection detail, close coordination between the research team and an accredited engineer, the optimization of fabrication protocols, the optimization of wood usage within full trees, and four-point bending flexural tests of components and prototypes in a structural engineering laboratory. Additionally, the research team is eager to increase the scale of future building prototypes and structures, aiming to build large scale roof structures. For this purpose, the research team will collaborate with (anonymous company), a leading glulam manufacturer in the United States.

CONCLUSION

Unfamiliar notions of craftsmanship and precision, both digital and analog, emerge from LOG KNOT’s conceptual design practice and characteristic construction technique. New technological paradigms such as robotic based fabrication radically challenge our understanding of wood as a building material but have yet to take better advantage of wood as a sustainable and smart material for construction. Small roundwood members or tree forks are usually not utilized for construction purposes because today’s sawmills are not equipped to process irregular tree geometries. By making use of robotic fabrication technology, structural mass-customization, and advanced 3D scanning technology, this project aims to better adopt available forest resources. The robotic platform enables the processing of highly irregular tree geometries – such as mature ash trees infested by the Emerald Ash Borer – which are normally discarded or used as firewood.

LOG KNOT was exhibited as part of (anonymous university’s) 2018 Biennial called “Duration: Passage, Persistence, Survival” and addresses this theme on multiple levels. Environmental cycles, birth, growth, and decay are intrinsic to complex forest ecosystems and processes: conceptually and spatially, the LOG KNOT project references these eternal cycles and reciprocal relationships between systems, both natural and technical. The infinitely looping structure is an interplay between archaic natural geometry, advanced computation, and state-of-the art digital fabrication. By questioning how forests are used as a resource, LOG KNOT provides a critical commentary on various perpetual wood cycles: economic, environmental, and cultural in nature.

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