Robotic Fabrication of Nail Laminated Timber

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Abstract –
Robotics, mass timber, and parametric design are all key technologies that are underutilized in construction. To fully take advantage of these new technologies requires a rethinking of the entire process from design to construction. The Greenbuild Pavilion represents a new construction workflow, in which a digital parametric model is communicated directly to a robot fabricator. The robot, equipped with various tools, can manipulate dimensional lumber into complex geometries with industrial precision. This workflow has the potential to drastically improve the sustainability, quality, cost, and time of construction.

Keywords –
Robotic Fabrication; Nail Laminated Timber; Mass Timber; Automated Construction; Digital Fabrication; Architectural Robotics; Advanced Timber Structures, Sustainable Structures.

1 Introduction

Perkins + Will's Building Technology Lab was able to leverage its previous research into mass timber and robotic fabrication, combining expertise across offices in a year-long effort. Hakim Hasan, from Perkins+Will Boston, and Anish Reddy, from the Los Angeles office, fabricated a pavilion in modules (using 2,451 individual pieces of wood and 10,828 nails) over 54 hours at Autodesk's Technology Center in Boston. It was then shipped to Chicago and assembled at the Greenbuild Expo, where it stole the show with its curved geometry and massive scale, topping out at 4.26 meters tall and 6 meters wide.
The success of the pavilion marks a major step forward for sustainable applications of robotics. Because it is a post-and-beam mass timber structure, the pavilion's workflow could be applied to a structure as tall as 18 stories. The use of wood allows for a renewable, widely-available material to displace steel or concrete and reduce a building's carbon footprint. The use of robotics allows for buildings to be delivered faster and more precisely. Moving forward, Perkins + Will seeks to implement these workflows into its projects, ensuring a better final product for its customers.

1.1.1 Problem Statement:

Robotics, mass timber, and parametric design are all key technologies that are underutilized in construction. To fully take advantage of these new technologies requires a rethinking of the entire process from design to construction.

Cross-laminated timber (CLT) has become more popular in recent years, with most innovation (led by companies like Katerra[1]) centering around providing orthogonal modules that can be prefabricated off-site and quickly assembled on-site. The International Code Council recently adopted new language for 2020 that would permit high-rise construction with CLT (and other related mass timber assemblies) up to 18 stories. These developments feed into a burgeoning demand for sustainable, efficient, and dense structures in the current real estate market.

Robotic fabrication has the potential to allow more complex assemblies with mass timber than are typically produced in a factory. Recent research into robotic fabrication with wood has focused on dome structures (ICDE/ITKE Research Pavilion 2015[2]) or typical balloon framing (DFAB House[3]), which do not translate easily the high-rise industry. For robotics to become economically viable in construction, it must take advantage of economies of scale and be able to produce mass timber assemblies.

2 The Robotic Setup

The robotic setup is a 6-axis ABB IRB 4600-40/2.55 mounted on an ABB IRBT 4004 external linear track yielding 7 degrees of freedom. The robot is operated at a speed of 2 metres per second and has a Maximum reach of 2.55m from the base of the robot, and when mounted on the external linear axis, the range is extended across 9 meters with a position repeatability RP of 0.06 mm and a path repeatability of 0.28mm.

2.1.1 The Tools

5 tools are equipped with ATI automatic tool changers allowing for the robot to quickly switch from one to the other. The changeable tools are mounted to a shared base to allow for easy repositioning. These tools include:

- A custom-made spring-actuated suction gripper for gripping wood with a max payload of 20kg.
- A Modified Fasco Lignoloc Coil Nailer shooting a magazine of 150 wooden nails. (Tool Not Used throughout the entire Process)
- A Modified Dewalt Pneumatic Nail gun with a 300-nail magazine shooting 63.5mm nails
- An Air-cooled milling spindle equipped with a 12.7mm end mill with a max rpm of 24000.
- A Modified Dewalt Circular Saw with 177.8mm Diameter Blade

An alignment slide constructed to serve as a constant reference obtaining the physical gripping center of each piece of lumber. A Schunk pneumatic gripper with stepped grips was floor mounted to function as a work holding as each Lumber is processed. Using the suction gripper, there were limitations to the weight and imprecisions for vertical placing of members as there is a 1.5 mm of movement due to the spring actuation. The circular saw was limited in the max perpendicular cutting depth of 63.5mm. When using the pneumatic nail gun, in order to have a successful fire meant that the nozzle has to be fully pressed up against and perpendicular to the lumber.

2.1.2 The Robot Work Cell

The work envelope measures 4.26 meters wide by 12.22 meters long and is enclosed by 2.43 meters tall polycarbonate walls seen in Figure 2. Laid out in a linear fashion, the cell has two doors positioned at opposite ends, the first being for material loading and unloading to and from the cell and the other for general access. Each door is tied into a safety control system of the robot and activates an emergency stop if faults during robot operation. Inside of the cell starting from the loading door on the right, is a pallet positioning marker located on the floor to indicate the approximate placement of the pallet of boards. This allows the operator to quickly and accurately position the pallet in place. Next to the pallet is the lumber alignment slide where every piece of lumber picked by the robot is dropped on the slide and re-picked from its centre. Positioned next to the slide, all the robot end effectors are resting in their appropriate holders and all mounted to a shared base. The work holding is fastened to the floor next to the tools with a transparent Plexiglas wall acting as a barrier to protect the tools from dust and other objects during the milling and mitering process. Next to the work holding is the build platform where the pieces of lumber are placed and the build-up process occurs. The platform measures 1.5 meters by 4.5 meters dictating the maximum building area of the robot. At the end and outside of the cell is the operator viewing and control desk.

Figure 2

2.1.3 Selecting the Wood Grade

There were a series of investigations in attempt to select the right species and grade for the robotic process. Out of all the various species available at the local Boston lumberyards, Douglas fir was the preferred choice in terms of surface finish and density but it was prohibitive due to its relatively high cost. Our solution was to side on a low cost approach using the lowest grade Spruce-Pine-Fir (SPF) framing lumber as it is readily available and is a popular construction material. Our robotic setup was constructed to tend both 2x4 (38.1 x 88.9mm) and 2x6 (38.1 x 139.7mm) dimensional lumber at a maximum length of 1.21 meters, however we limited the design to using only 2x4 (38.1 x 88.9mm) Lumbers with a maximum length of 1.21 meters and a minimum of 0.3 meters.

2.2 Design Scripting

Various surface-based forms were explored within the 10’x20’ envelope of the booth at the exposition, with the basic theme of a Core (two Columns and a Beam) and Shell (Ground Floor, Upper Floor, Exterior Wall, Interior Surface). Grasshopper was used to divide the surfaces, modeled in Rhinoceros 3d into its individual elements and generate.

Figure 1
Rendering of Design

A nailing pattern needed to connect them. The application of textures to the digital model was also automated using the Human plugin for Grasshopper. Wood textures were mapped to each individual piece along its length (slightly shifted each time to maintain a natural feel. Primary parameters of Grasshopper Shell geometry script, used to divide the surface into its individual elements:

- Board Thickness
- Board Width
- Maximum Board Length
- Minimum Board Length

Using the Grasshopper Core geometry script, surfaces of Core are divided into curve Contours every Board Thickness along the y axis. Contours are divided into point Nodes (limited to Maximum Board Length). Nodes are connected by lines of Primary Rails. Rectangular profiles matching the Board Thickness and Board Width are extruded along the resulting linear Input data provided by the design outputs are sorted by type and subsequently by assembly. These inputs are:

- Lumber Geometry (Optional)
- Lumber Center Plane
- Lumber Center Lines
- Lumber Left and Right Miter Lines
- Dowel Points
- Lumber Lengths
- Nail Points

geometry and mitered at intersections. Lumber Geometry is organized by build order.

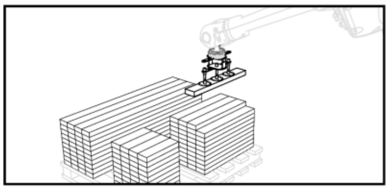
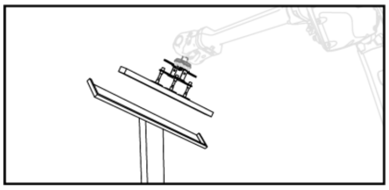
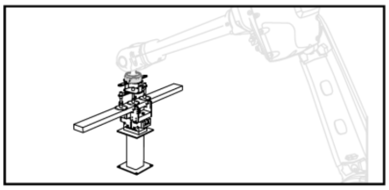
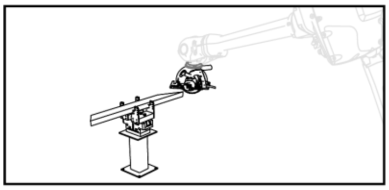
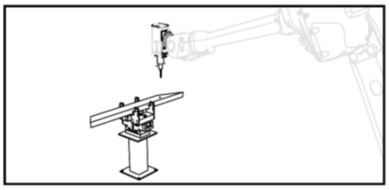
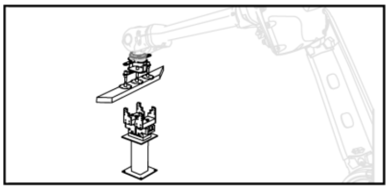
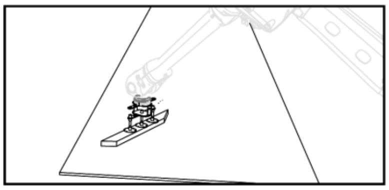
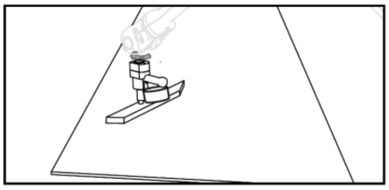
Primary parameters of Grasshopper Core nail script, used to generate a nailing pattern:

- Nail Offset from Ends
- Nail Offset from Center
- Nail Spacing

Using the Grasshopper Shell nailing script, two Nail Endpoints are identified for every Primary Rail, moved by the Nail Offset from Ends along the length from both endpoints. Two nails are offset by the Nail Spacing diagonally from the Nail Endpoint and assigned to each Primary Rail. Two nails are offset at the opposite diagonal (to avoid conflicts between layers) from the Nail Endpoint and assigned to the Primary Rails in the next layer. Two Nail CenterPoint are identified for every Primary Rail, moved by the Nail Offset from center both ways along the length from the CenterPoint. Two nails are offset by the Nail Spacing diagonally from the Nail CenterPoint and assigned to each Primary Rail. Two nails are offset at the opposite diagonal (to avoid conflicts between layers) from the Nail CenterPoint and assigned to the Primary Rails in the next layer finally, all nails are assigned to geometry and organized by build order as NailPoints.

2.3 Robotic Process

A program script was developed that converts outputs from the design script into a fabrication process and outputting robot-readable commands for its execution. The Software used for these processes are; Rhinoceros 3d (modelling), Grasshopper (scripting), Machina Plugin (robot communication), and ABB Robot Studio (simulation). An accurate 3d model of the robot cell was created for a visual understanding of the workspace of the robot.

OBJECTIVE:	ROBOT SUBROUTINE:	IMAGE:
1. Get Lumber From Pallet	- Pick Up Suction Gripper - Turn On Vacuum - Pick Lumber from Pallet*	
2. Align Lumber	- Place Lumber on Slide - Release Vacuum - Apply Vacuum - Pick Lumber from Slide*	
3. Clamp Lumber	- Open Work Holding - Place Lumber in Work Holding - Close Work Holding - Release Vacuum - Return Suction Gripper	
4. Miter Lumber	- Pick Up Circular Saw - Turn On Circular Saw - Miter Left and Right Ends* - Turn Off Circular Saw - Return Circular Saw	
5. Mill Dowel Hole	- Pick Up Milling Spindle - Turn On Milling Spindle - Mill Dowel Hole* - Turn Off Milling Spindle - Return Milling Spindle	
6. Get Lumber from Clamp	- Pick Up Suction Gripper - Turn On Vacuum - Move to Work Holding - Open Work Holding	
7. Place Lumber on Platform	- Place Lumber on Platform* - Release Vacuum - Return Suction Gripper	
8. Nail Lumber	- Pick Up Nail Gun - Nail Lumber* - Return Nail Gun	

* Subroutines with variable target parameters

The first part of the script generates 3 stacks of lumber on a pallet. The stacks are 1 foot, 2 feet, and 4 feet in length from which the robot will pick each piece of lumber from. The output design data is then oriented and centered to build platform, this gives the viewer a visual understanding of the geometry which will be built. A series of sub routines were programmed outlining the overall fabrication process. This is depicted in Figure 2.

2.4 Manual Assembly

Apart from the maximum 1.5m x 4.5m x 1.4m build volume on the platform, transportation, manual handling, and assembly logistics were factored which limited the size of what each module could be. These constraints are that no module should be heavier than 200 lbs., its two smallest dimension not exceed 4 feet and 7 feet, and its longest length not greater than 16ft. This ensured that every module fabricated by the robot could be lifted by two people onto flat dollies loaded into a moving truck and erected on site without any heavy machinery involved. Every module was fabricated with ½ inch dowel holes that corresponded with its neighbouring module this aided in precisely aligning modules together and then subsequently fastened with screws for additional security. This simple modular technique was created to allow for non-skilled labour to easily assemble complex components with basic hand tools.

2.5 Results

The parametric workflow was critical to managing the complex data of the 2,154 individual pieces. The relational nature of the digital model allowed for this large amount of data to be flexible, changing as real-world tests affirmed or rejected our initial assumptions. In the robotic script, Machina was a useful tool to seamlessly compile fabrication instructions from Grasshopper into robot-readable code, simulate robot movement in ABB Robot Studio and subsequently sending that data in real time to the robot for execution. This allowed for real-time modifications to the design as changes arise.

2.5.1 Fabrication with Robots

Despite the automated nature of this process, there were a few manual processes involved prior to fabrication and post fabrication. The 800 boards supplied from the lumber yard came in 2.43 meter lengths and required cutting them down to 1.2, 0.6, and 0.3 meter lengths using a standard chop saw. With two people involved, the time to process all 800 boards was approximately 7.5 hours. These lumber pieces had to be stacked in a pile on pallets and place in the robot cell for retrieval by the robot.

2.5.2 Jointing and Planing

In initial testing, the lumber was jointed and face planed to ensure a squared rectangular profile and a smooth surface finish. This made all boards, regardless of their natural inconsistencies, uniform and guaranteed proper suction when being gripped by the suction gripper. The jointing and face planing of all 800 boards would have been time consuming and labour intensive, taking over 42 hours to complete. This approach was abandoned and instead the focus was to engineer a more robust gripping system to accommodate for the natural inconsistencies of the unprocessed wood. Special webbed suction cups from Schmalz were used that would then compartmentalize the suction over the surface of the Lumber for better adhesion. In tandem an air ejection system had to be integrated to release the boards when being placed due to the high suction (101 kPa) generated by the vacuum pump.

Figure 4

2.5.3 Quality Control

A visual inspection of the Lumbers were done when stacking them on pallets. Features that would disqualify a Lumber from being placed on the stack are significant warping, large splits, and loose knots. Splits and knots that run through or around the centre top face of the Lumber tends to create a leak in the vacuum cups and is likely to fall when being handled by the robot. Warped Lumbers however can be used in the process by cutting them down to 1 foot lengths, but unless factored in, it can affect the consistent aggregation of Lumbers. After quality controlling all 800 boards the unusable percentage was a surprising 2.25 percent, less than anticipated.

2.5.4 Calibration

In order to utilize the high precision of the industrial robot, every tool was carefully measured in and calibrated of optimal performance. Each tool's TCP (Tool Center Point) was measured in with an accuracy of 0.01mm-0.03mm. Starting with the suction gripper, it went through a series of iterations varying the suction cup types, gripping vacuum pressure, and quick release mechanisms. As for the Fasco Lignoloc nailer, it was working normally when running at a reduced robot speed of 250mm/s but stopped working when attempting to run at 700mm/s. This was mainly because the air flow rate we were supplying was too low for the speed we were moving. This cause a rupture inside the tool rendering it unsuitable to continue use in the process. Pressed with time, we had to resort to using the standard Dewalt nailer with steel nails. The initial approach to cutting the ends of each lumber was using a milling spindle. This was to allow the flexibility of cutting beyond straight miters. The process was too slow and there was no need to cut the ends other than straight miters. The milling spindle however was appropriately used to position the dowel holes. Mitering the ends of the boards was done with a ripping blade on the circular saw. The maximum speed of cut was 90mm/s while still have a good cut finish.

2.5.5 Speed of Fabrication

Every portion of the fabrication was gradually sped up to its maximum capabilities without affecting performance or quality. On average the processing of each board takes 1 minute 20 seconds from the point of picking up the board to nailing it in place. For a total of 2,154 members, total fabrication time amounted to 54 hours.

2.5.6 Assembly Evaluation

Laser scanning was used to verify the constructed geometry against the design model. The robotically-constructed modules were accurate to 1mm precision, while the completed assembly, done by hand, were accurate to within 75mm. This further advances the notion that robotic fabrication should extend into the assembly process, allowing its inherent precision to carry through to the constructed building. Figure 3

Figure 3

Comparison of laser scan of constructed pavilion (wood texture) and digital design model (in red). All geometry was verified to be within a 75mm tolerance.

2.6 Conclusions

The success of the pavilion marks a major step forward for sustainable applications of robotics. Because it is a post-and-beam mass timber structure, the pavilion's workflow could be applied to a structure as tall as 18 stories.

The use of wood allows for a renewable, widely-available material to displace steel or concrete and reduce a building's carbon footprint. The use of robotics allows the resulting assemblies to be infinitely varied and optimized with millimetre precision. The direct nature of communication between a digital model and a robot allows for a seamless translation from an imagined design to constructed reality. Moving forward, Perkins + Will seeks to implement these workflows into its projects, ensuring a better final product for its clients.

2.7 Future Research

Future research will seek to build on this workflow and seek ways to implement them into real projects. Because of the experimental nature of the project, the workflow was somewhat imprecise. Wood is a natural material and no two pieces of lumber are alike. The project used generous tolerances to finish within the deadline.

There are two ways this research can continue: non-structural elements and structural elements. Non-structural elements would generally use the same workflow, with adaptations for specific forms and connection types. Structural elements, however, must be built to more exacting standards, and will most likely require sensors feeding data back to the digital model, allowing the model to adapt to the shape of the actual lumber given. Machine learning could be used to optimize nailing patterns by understanding and analyzing the grain of the wood.

2.8 Acknowledgements

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