Application of Robots to the Construction of Complex Structures using Standardized Timbers

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Abstract –
For thousands of years, the human construction process was mainly done by hand. In an era when automation technology is so mature, although some components of building components can be produced industrially, on-site construction and special component production still require a lot of manpower. But no matter how skilled the workers are, more or less mistakes will occur during the construction process, which wastes a lot of material waste and energy waste, especially when dealing with increasingly complex digital designs. Using a robot instead of manually completing the construction process will be the solution to these problems. Currently, most ideas for robot construction are dealing with non-standard components in the field, this will cause a lot of problems, first of all, it will extend the construction cycle, and secondly, it will generate a lot of waste. This article proposes a new construction workflow using standardized timbers. Spatial information for each piece of wood is communicated directly to a robot fabricator. The robot, equipped with various tools, can accurately position and assemble timbers. This workflow has the potential to improve the sustainability, time, cost, and quality of construction.

Keywords –
Robotic Fabrication; Parametric Design; Standardized Timber; Spatial Structure

1 Introduction

Fukuda Building Technology Lab and iSMART Qingdao were able to leverage their previous research into mass standardized timber and robotic fabrication, combining expertise across laboratory in two month effort. Fukuda Building Technology Lab and iSMART Qingdao fabricated a wooden arch in modules(using 840 pieces of timber and 3155 nails) at Qingdao University of Technology iSMART Robotic Center, used over 26 hours to fabricate 8 parts of the structure and were then shipped and assembled at the exhibition venue where it stole the show with its complex structure and huge volume, topping out at 2.25 meters tall and 4*4 meters wide.

The success of the wooden arch marks a major step forward for automation construction application and sustainable application of robotic fabrication. Because it shows the possibility of applying standardized timber to complex spatial structures, and the use of wood allows for a sustainable, renewable material to displace concrete or steel to reduce carbon footprint. The use of robotics simplifies the construction process, allows to constructed faster and precisely. Designed construction process and use of standardized timber simplifies the works of workers allows the undergraduates who have only received simple construction training and complete safety training to easily complete the construction work.

In the future, iSMART and Fukuda Lab seeks to optimize these workflows and implement into their projects, ensuring a better solution of robotic construction.

1.1 Problem Statement

Robotic is an old and new field in architecture industry. The importance of developing technology to increase the productivity of the construction industry has been proposed in the late of 20th century[1-3]. Over the decades, many studies have also emphasized the necessity of implementing robotic technology.[4] Whether in China or Japan the population aging and declining labor force have become a serious problem, the aging workforce and the increasing complexity of construction shows that traditional construction methods have gradually shown inadequacies [5]. Although many studies have been implemented and various of technologies have been developed but application of robotics still limited and behind other industries. High cost, unskilled worker and lack of research funding make robotic technology not widely used in the construction industry.

Considering application of Robotic Timber Construction(RTC)research is still in initial stage, and high cost and high construction difficulty is the main problem. Fukuda Lab and iSMART used uniform standardized timber to displace customized wood and optimized the man-machine collaboration workflow. Significantly reduced costs and the skill requirements of workforce.

2 Robot Setup

A 6-axis KUKA kr30/60/HA robot applied in this experiment. The robot is operated at a speed of 2 meters/s, vertical range of activity from +35° to -135° and large turning range of 185° in both directions.

2.1.1 Tool Setting

In order to optimize the construction process 3 tools are equipped, those tools are mounted to one shared base to allow for rapid positioning. These tools include(Fig 1):

- A customized pneumatic suction sucker for gripping wood with a maximum payload of 8kg.
- A customized laser emitter for locating the nailing point and glue area of each piece of wood.
- A customized pneumatic suction gripper for fixing the wood to allow the workers can finish the glue and nailing.

A pneumatic calibration table is set next to the reclaimer to recalibrate the position as each timber is processed.

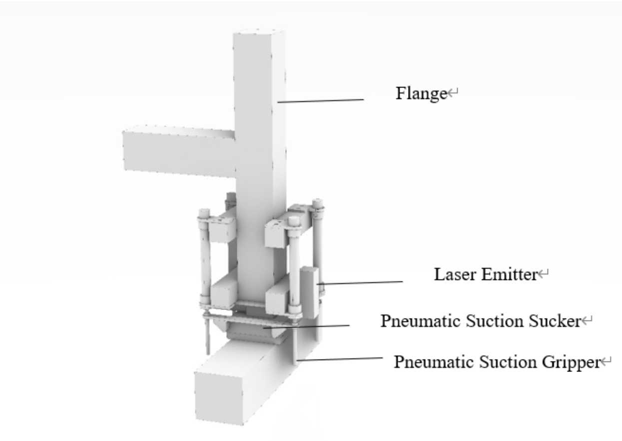


Figure 1. Customized Tools

2.1.2 The Robot Work Area

The work area measures 2.35 meters wide by 2.5 meters long and by 3.56 meters tall dictating the maximum construction area of robot. Laid out in a sector fashion, the area has two parts, the first being for material stacking and the other for construction. Each part is linked with safety control system of the robot and activates an emergency stop if limit or error occurs during robot operation. A safety operator is configured with the smart pad during each construction operation for collaborative operation(Fig 2). If an emergency occurs, the machine can be manually stopped. Positioned next to the material stacking area, a positioning frame is resting in a appropriate allows reposition each piece of wood to ensure that the center coordinates of them are accurate.

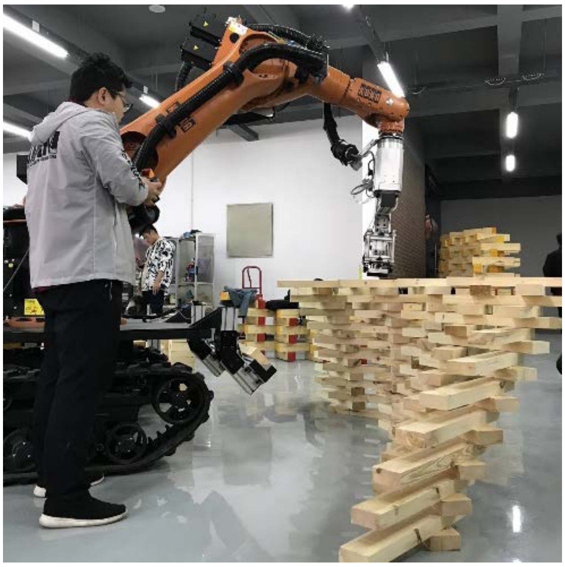


Figure 2. Safety Operator

2.1.3 Wood selection

A series of investigations in attempt to select suitable wood for RTC process. After comparing all kinds of the timber in Qingdao and Fukuoka lumberyards, our solution was to side on a low-cost approach using Japanese Hinoki as it is a popular construction material and it is reliable and easily machined. We use (50*100*650 mm) wooden bricks as construction material, the uniform size reduces processing costs and allows stacking without sorting, reducing construction difficulty.

2.2 Design program

A 4-sided symmetrical wooden arch were explored within the 5*5 meters area of the booth at the exhibition hall, with the basic theme of two sets of symmetrical construction units(Fig 3). Grasshopper was used to divide those 4 units into 8 construction team and divide the surfaces in to the center plane of timber, modeled in Rhinoceros 3d into its individual elements and generate.

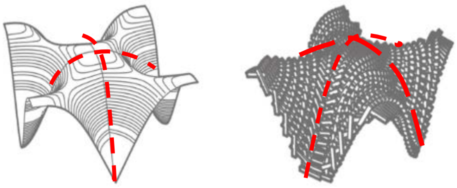


Figure 3. Model of the design

a nailing-gluing pattern needed to connect them. The positioning of nailing points and glued range of the digital model was automated using the custom script for Grasshopper. The nailing points and the glued area are mapped to the joints of the wooden blocks in the form of point coordinates. Primary parameters of divided surface geometry script, used to adjust the position of the nailing point and the size of the glue area:

- Timber Thickness
- Timber Length
- Timber Width
- Timber Rotation Angle

Using the custom script for Grasshopper, surfaces of the construction team are divided into polyline contours every timber thickness along the y axis (The default y direction in the software three-dimensional space.). Polylines are divided into lines based on timber length. According to the timber width and timber length, rectangular profiles are extruded along the resulting linear. Using KUKA|plc plugin for Grasshopper provide input data by design output subsequently by assembly. These input data include:

- Timber Thickness
- Timber Center Plane
- Timber Center Lines
- Nailing Points Plane
- Gluing Area Line
- Press Points Plane

Rotate the whole structure 90 degrees along the y-axis as the construction form. Timber geometry organized by construction order.

Using the Grasshopper Gluing area script, the overlapping area of the two layers of timber are offset inward by 15mm to generate the glued area. Primary parameters of Grasshopper Nailing points script, used to generate the nailing points planes:

- The Maximum Diameter of The Glue Range
- Nail Collision Radius
- Nail Length
- Glue Range Center Points

Using the Grasshopper gluing area script, glue range are showed visible, adjusting timber length and rotation angle to optimize the glue area to a suitable size and a suitable shape (quadrilateral), 4 terminal points of glue range are identified for primary rail and laser emitter, moved by the order of endpoints along the length from both endpoints. All endpoints are assigned to geometry and organized by construction order as glue range. Two nail points are selected by the maximum distance between the glue area minus the upper and lower nail collision range (to avoid conflicts) and assigned to each primary rail. All nails are assigned to geometry and organized by construction order as nail-points. The center points of two glue range center points which on the same timber are assigned to each primary rail as the press points (Fix the wood for nailing and gluing).

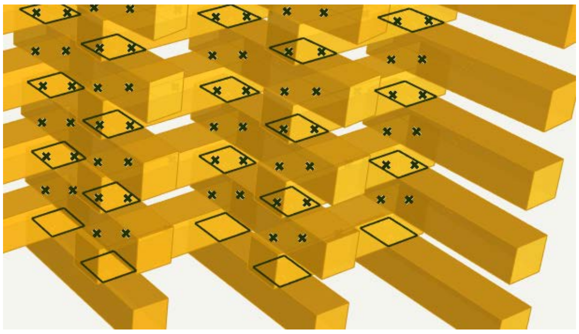


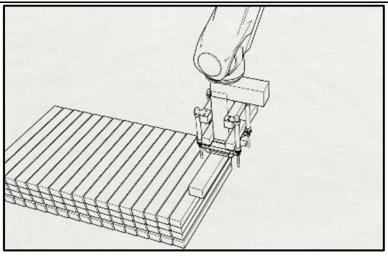
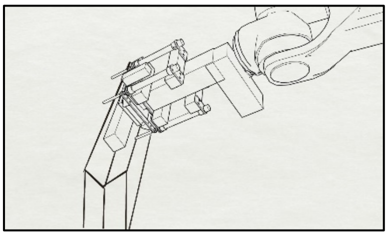
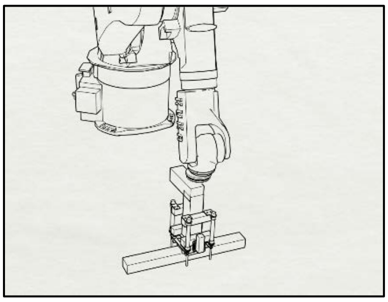
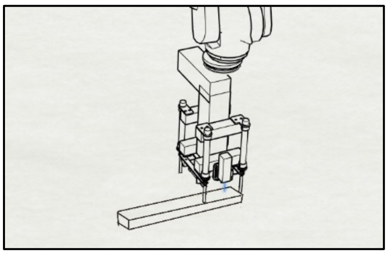
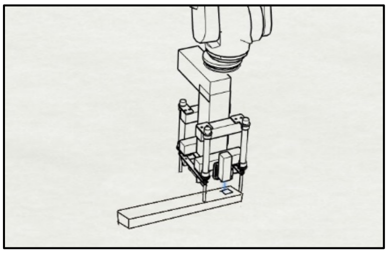
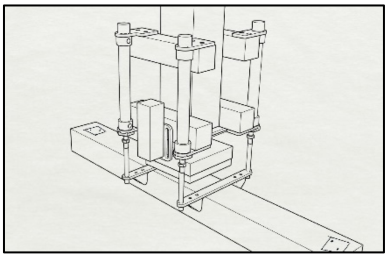
Figure 4. Geometry nailing points and gluing range

2.3 RTC Process

The KUKA|plc plugin is applied to transform outputs from the design script into construction process and outputting robotic commands for execution. The Softwire used for RTC process are:

- Rhinoceros 3D (modelling)
- Grasshopper(scripting)
- KUKA|plc Plugin (robot communication and simulation)

An accurate simulation of RTC was created for a visual understanding of work process of the RTC, and adjust main parameters in time according to simulation results.

OBJECTIVE	ROBOT MOVEMENT	IMAGE
1. Get Timber From Stack	· Select Timber in Order · Turn on Air Pump · Get Timber from Stack	
2. Calibrate Timber	· Place Timber on Calibrator · Calibrate Timber · Pick up Timber	
3. Place Timber on Site	· Place Timber on Site · Release Air Pump · Move to Safe Distance	
4. Draw Gluing Range With Laser	· Move to Gluing Start Point · Turn on Laser · Transform Robot Speed to 0.2m/s · Move Along Endpoints · Turn off Laser	
5. Draw Nailing points With Laser	· Move to First Nailing Point · Turn on Laser · Move to Second Nailing Point · Turn off Laser · Transform Robot Speed to 2m/s	
6. Fixe Timber	· Move to Center Point · Turn on Gripper · Nail and Glue Timber · Turn off Gripper	

The script generates whole process of RTC. Standardized Timber allows the stacks don't need order, using the calibration device also allows the wood place unprecise, reduced the difficulty of placing stacks. Output construction data is oriented and centered to build site, that gives the designer a visual understanding of the structure which will be built. A series of subroutines are programmed outlining the overall construction process.

2.4 On-site Assembly

Limitation of robot arm length, manual handling, transportation and assembly logistics were factored which limited the size of each construction part could be. The constraints are that every part should be its longest length not greater than 2 meters and its height not greater the 1.5 meters. That ensured that every part fabricated by the robot could be lifted and moved by 6 people into a moving truck and erected on site. Every part was drawn a crossover line with neighbouring part, that aided in precisely aligning modules together. This simple modular technique was designed to allow for non-skilled worker to easily assemble complex structure with basic tools.

3 Result

Using the parametric workflow was necessary to managing the mass data of 840 individual timber with 3155 nails. The relation of the digital model allowed for this big data to be flexible, changing as the tests affirmed or rejected our initial setting. After completing the construction work, 4 construction units (Fig 5) were moved and assembled in the exhibition hall (Fig 6). The overall appearance is a smooth arch, consistent with expectations. The strong visual impact made by the huge volume. Using standardized timber placed along a hyperbola allowed audiences to visually obtain surface information.

Figure 5. One construction unit

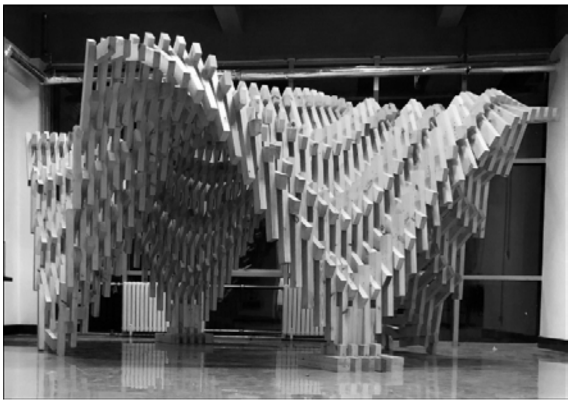


Figure 6. Construction Result

3.1 Speed of Construction

Every steps of the construction were gradually sped up to maximum capabilities without affecting performance and quality. Each step of pick up the timber to nailing it in place would take per 1 minutes 42 seconds. For the total of 840 members, total construction time amounted to 24 hours, and it takes 2 hours to assemble.

3.2 Human-Robot Coordination

Despite the automated nature of the RTC process, there were a few manual processes involved during fabrication and post fabrication. 840 standardized timber supplied from the lumber yard came in size of 50*100*650 millimeter stacked on site. 3115 nails nailed by non-skilled labour. with the nail-points and glue-range marked by robot, the work of nailing and gluing were very easy and non-skilled labour can finish the work with simple training.

3.3 Calibration

Every tool was carefully measured in and calibrated of optimal performance to untilize the high precision of the robot. Integration tool's TCP (Tool Center Point) was measured in with an accuracy of 0.01mm-0.05mm. The sucker went through a series of optimizations, gripping vacuum pressure and crawl speed reached the expected value. As for the Laser, adjusted the distance from the timber surface to 5mm which is the best focal distance to burning wood surface for mark the nail-points and glue-range. The speed of laser process was running to 0.2m/s, provided clear marking (Fig 7).

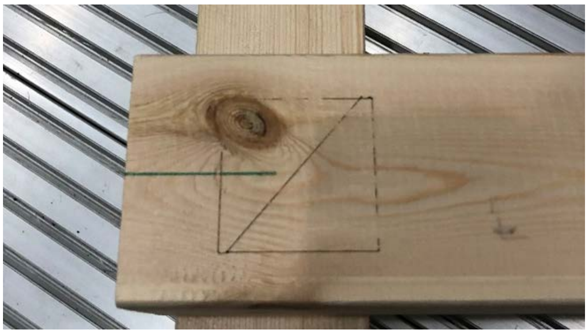


Figure 7. Mark of glue-range and nail-points

4 Conclusion

The success of the wooden arch marks a major step forward for application of robotics. Because it used the standardized timber to construct a complex hyperbolic structure. The use of standardized timber allows for a widely available, renewable material to displace steel and concrete to reduce a building carbon footprint, in the same time, allowed to reduce the material cost and processing cost. The use of robot allows the resulting optimized with millimeter precision. Human-Robot coordination allows non-skill labour involved in construction, alleviated the social problem of shortage of experienced workers. The communication between the digital model and the robot allows for a seamless translation from design to constructed on-site.

5 Future Research

Fukuda Lab and iSMART will seek ways to implement this workflow into real projects. Due to time and technology limitations, nailing and gluing process have not been automated in this experiment, the project used generous tolerances to finish within the deadline. Future research will optimize workflow, automate and integrate the nailing and gluing process into the current process.

In the future, iSMART and Fukuda Lab seeks to optimize these workflows and implement into their projects, ensuring a better solution of robotic construction.

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References

[1] T. Bock and T. Linner. *Construction Robots*, ISBN: 9781107075993. Cambridge University Press, New York, USA, 2016.

[2] T. Bock and T. Linner. *Site Automation*, ISBN: 9781107075979. Cambridge University Press, New York, USA, 2016.

[3] J. Paulson and C. Boyd. Automatation and robotics for construction. *Constr.Eng.Manage*, 111(2):190–207, 1985.

[4] T. Bock. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. *Autom. Constr*, 59(7):113–121, 2015.

[5] H. Hasan and A. Reddy and A. TsayJacobs. Robotic Fabrication of Nail Laminated Timber. In *36th International Symposium on Automation and Robotics in Construction*, 1210–1216, Banff, Alberta, Canada, 2019.