Rethinking Bamboo Roof-Based Architecture of Indonesian Traditional House Using Parametric Design and Automated Fabrication Techniques

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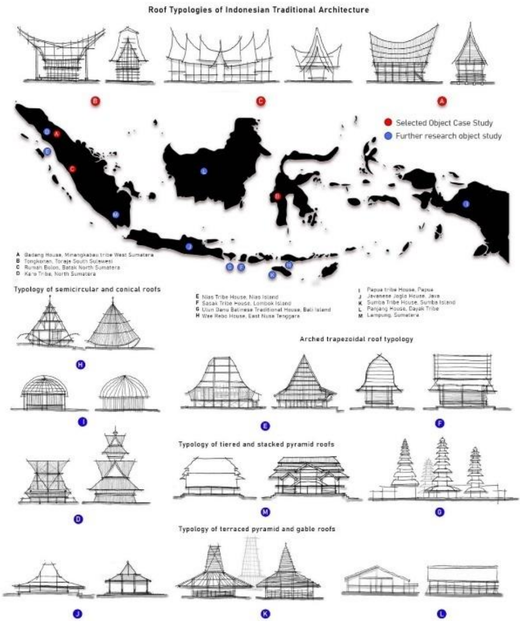
Indonesian traditional houses are well known as roof-based architecture due to the names of the houses given by the type of roof shape. The roof is the distinctive dominance of the house geometry in the overall size and body proportions, which aims to respond to the tropical climate and solar radiation. The roof structure is made of timber and bamboo with a non-rigid structure using traditional rope and palm fibre joints. Parametric design and digital fabrication have disruptively boosted the progress of complex emerging bamboo architecture design and structures over the past few years. However, it has remained challenging because bamboo construction relies heavily on manual fabrication and hand-operated assembly. Seeing this opportunity, we attempt to parametrically design and robotically fabricate the bamboo roof structure, automate the process, and move forward from the traditional method towards digital fabrication. Our verification design experiment object is a typical hyperbolic paraboloid bamboo roof scale prototype. Our findings highlight the advantages and challenges of bamboo-based structure design, robotic fabrication process, and novel opportunities for contemporary Indonesian bamboo architecture.

Keywords: *Bamboo Architecture, Indonesian Architecture, Robotic Bamboo, Parametric Design*

INTRODUCTION

Indonesian Traditional Architecture

Traditional Indonesian houses use bamboo and timber-frame structures as essential elements and showcase roofs as a prominent feature. It has been known terminologically that Indonesian traditional architecture is "roof-based architecture" because the house's name is inherently given based on the typological shape of the roof (Hardiman, 2005). The traditional houses have vital elements in ornamentation, symbiosis with external spaces, transitional, inner space, breathing walls, non-rigid structure, and protruding roof domination (Herwindo, 2019). Roof elements are recognized as the main head of the house, showcasing a dominant proportion compared to the body element of the house (stilt house), commonly using pilotis (ground-level supporting column or stilts) to show the impression of lightness on the heavy roof's proportions. Each tribe in Indonesia (figure 1) represents different forms and shapes of houses, conspicuously in the roof shape, and roof types are used in recognising and processing building figures. However, the diversity of the roof geometry shares a common thread in the roof steepness feature, which actualises local wisdom in adaptation to harsh weather, tropical climate, and intense solar radiation(Prasetyo et al., 2017)



Geometrically, the roof shape has a very sharp upper slope, causing the roof to buckle and resulting in a roof shape that can reduce solar absorption (figure 2). Climate consideration is pivotal to creating the roof geometry (Rajendra, 2021) and is embodied in the expression of the roof's steepness (Prasetyo et al., 2017) to drain rainwater quickly. For instance, with the hyperbolic paraboloid surface, Gadang House has a roof that tapers on both left and right sides, is curved inward on both sides and is lower in the middle of the shapes (Supriatna & Handayani, 2021). This similar geometry is also found in Bolon House, Bataknese, North Sumatera, Tongkonan House, Toraja House, and South Sulawesi. Traditional roof elements, bamboo, timber rods, and sheets are assembled manually with traditional joints such as rattan or palm fibre rope and a pin-a-hole joint system. Palm tree fibre (*ijuk*), shingle, reeds, straw, or coconut leaves are commonly used as the roof's outer layer, lowering thermal conditions and making it tropical climate-friendly.

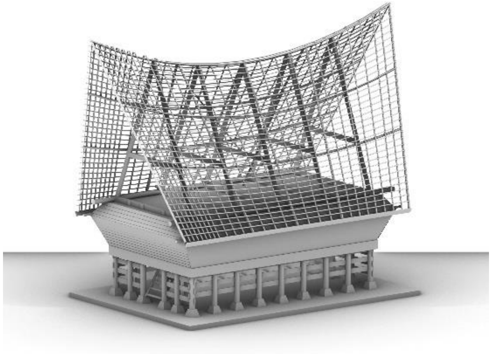


Figure 1 Typological grouping of traditional roof shapes in the Indonesian Archipelago

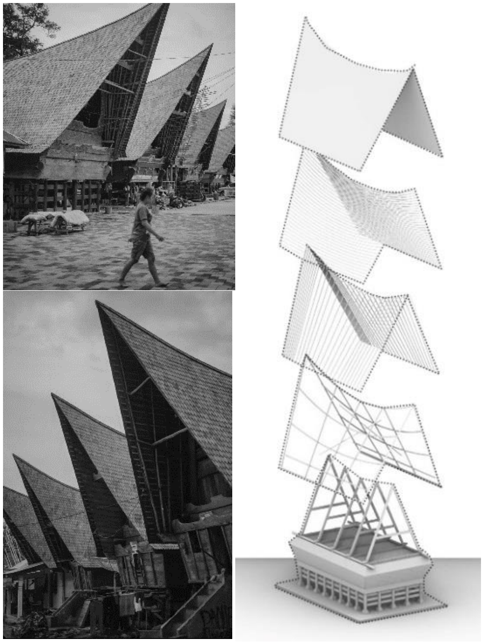
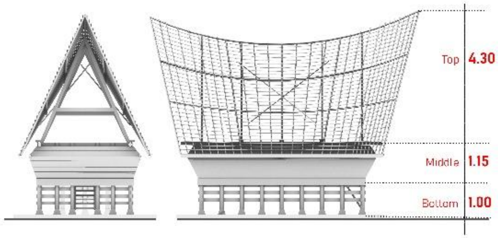


Figure 2 Axonometric Illustration of the structural component of Bolon House, Bataknese. North Sumatera, Indonesia

Figure 3
The proportional figure of the roof compared to the body and foot of the house



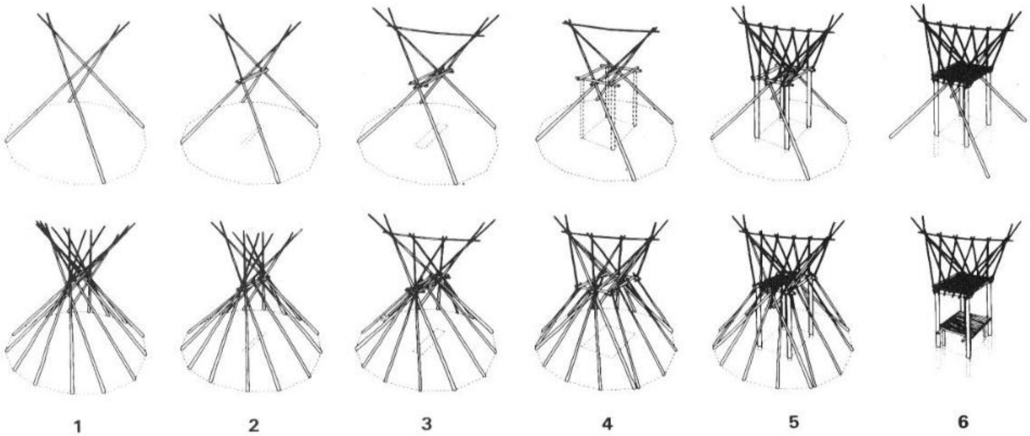
Anatomically, the roof represents the head of a traditional house that gives a larger dimension than the body (wall) and legs (stilt house) (Prasetyo et al., 2017). For this research, we choose the Bolon house typology as the case study object, which geometrically has a protruding shape, with a high-raised roof arch and curving at the top end of the roof (Figure 3).

This paper mainly focuses on studying the Batak traditional house roof typology from North Sumatra in the form of two hyperbolic paraboloid surfaces. The similarity of its geometry with Tongkonan house and gadang house roof typology can also be potentially applied and investigated in different case studies with different typologies (Figure 1).

RESEARCH CONTEXT & LITERATURE
Traditional Construction Methods

Traditionally, Indonesian ancestors built houses by experimenting with trial and error strategies and understanding the building's structure and logical thinking principles (Sabono, 2022). The traditional structure's distinctive characteristic is the rocking construction form that allows the building to move stably when forces occur without experiencing collapse or damage (Joseph, 2018). The type of construction commonly used is the knock-down system, which allows the traditional community to assemble and dismantle the materials on site and can be reconstructed at another location (Amal et al., 2020). The construction process is started by moving and delivering the structural elements that are worked separately from and to the site location. Research on Asian and Indonesian traditional houses develops theories about how traditional communities constructed the construction of piled and gable roofs of traditional houses in the past (Schefold, Nas and Domenig, 2003) argued that both pile and column buildings were constructed simultaneously by developing primitive tepee-shaped piled structures set in the ground and overlapping each other at the top (Roxana, 2012).

Figure 4
The stage development of primitive pile buildings and roofs is based on Domenigs's theory (Schefold et al., 2003).



After the overlapping roof structure forms a complete geometry, the lower part that touches the ground surface is then cut, leaving the upper structure of the roof (figure 4).

Towards Digital Fabrication of Bamboo

A number of investigations have attempted to demonstrate the digital fabrication of natural non-standardized material with various approaches and techniques, such as ultralight bamboo structures with 3D printed joints and robotic marking in ETH Zurich (Kladeftira et al., n.d.), bending experiment bamboo strip with KUKA KR 120 R2500 via deep learning ((Yang & Xu, 2021), *Tie a Knot*: Hybrid Human-Robot Cooperation in Assembling wooden structures using UR10e Robot with rope joints (Mitterberger et al., 2022), *Robotic softness*: a robotic fabrication for woven structure using KUKA KR125/2 (Brugnaro et al., 2008), and *co-designing material robot construction* research of assembly lightweight bamboo bundle structures with mobile and movable gripping robot prototype (Lochnicki et al., 2021). These researches indicate predefined robotic systems with human interactive fabrications can be explored and implemented in robotically natural material fabrication, and drive us to rethink the design and evaluate robotic systems to experiment with the novel design-to-fabrication workflow for state-of-the-art robotic fabrication bamboo structures.

Research Questions

Traditional timber-bamboo frame structures are labour-intensive (Yor Maikol et al., 2020), and the disruptive modern construction demand from conventional methods has affected Indonesian traditional craftsmanship, which has gradually lost and is almost extinct. The hand-cutting woodworking methods with unique skills involve very high costs (Sharma et al., 2014). This paper aims to investigate the application of parametric tools and automated fabrication technologies for the design and fabrication of traditional Indonesian roof bamboo structures, shifting from traditional methods to digital fabrication techniques. We inquire the following questions:

1. How can we develop a framework to parametrically design and robotically fabricate a bamboo roof structure?
2. How feasible is the proposed digital design-to-robotic fabrication framework in comparison to conventional methods?

To answer these questions, we will develop and verify a workflow by conducting a design experiment. The workflow consists of the following phases: 1) utilizing suitable parametric tools for bamboo digital design, optimization, and structural analysis, and 2) defining materials and joint systems for suitable fabrication. 3) human-robot collaboration assembly incorporating tasks such as placing, holding, bending, and or buckling the bamboo material and immersive-assisted assembly and evaluation. Our verification design experiment includes designing and fabricating a typical hyperbolic paraboloid bamboo roof scale prototype.

Methodology

Based on our analysis of bamboo digital design tools and exploring various fabrication techniques in our previous literature review research (Mansuri et al., 2023), we introduce a new methodology (figure 5), which are: **1) Parametric Design Stages**: The study of fundamental design principles of the traditional roof in parametric modelling tools geometry script or model as a database digital bamboo geometry. Defined parameters are then applied to bamboo structural analysis and tested through structural simulation "*Karamba3D*" plugin in Grasshopper, and design optimisation using Kangaroo Physics. **2) Prototyping Stages**: including defining, processing, and selecting applicable materials for scaled prototypes and joint system consideration on digital and physical models. The model-making process of a scaled model is an integral part of fabrication to see how the material

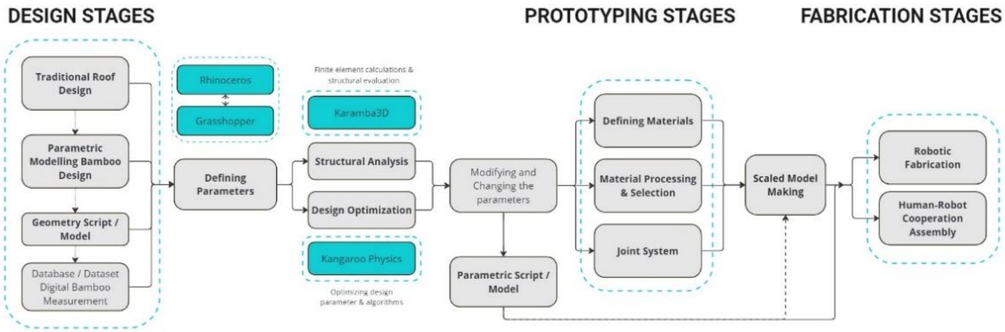


Figure 5
The design-to-fabrication framework.

and geometry work during manual and hand operation assembly **3) Robotic Fabrication Stages**: we develop a computational parametric script that can work with Robotic Fabrication UR10 with custom 3D-printed grippers and incorporate the assembly process with human-robot cooperative workflow. The research explores the Batak House roof, a hyperbolic paraboloid typology, as an object study in which our framework will be tested and applied.

Phase one: Parametric Design Stage

The significance of parametric design in bamboo architecture digital design is the ability to modify certain parameters to create an intricate, adaptable, flexible, and organic design process. Understanding the basic principles of the Batak House roof structure, we interpret and translate the structural layer into six different layers (figure 6). The 1st layer: *song-song boltok* and *tali pengurat layer* is the main frame of the structure, the second layer, *tali jabat* is the 2nd supporting layer and *urur* element is the 3rd layer. *Alo angin kayu* is then placed vertically as the 4th layer, and *Alo angin rotan* is attached to the 5th layer. The density of this last element and the distance are divided and adjusted to the size of the roof covering as the sixth layer. The original Batak House roof structure traditionally has more intricate and complex detailed components for structural and ornamental purposes. However, our prototype models simplify the Batak House roof element to achieve identical roof geometry. Materials such as timber, bamboo, tree poles, and branches are commonly used. However, in this research, we utilize bamboo as the material due to its versatile behaviour characteristics and sustainability. We calculate the performance of structural analysis and apply design optimization during the early stages of the design process.

Structural Analysis

The initial workflow of our study calculates bamboo structures using structural simulation using *Karamba3D*. It facilitates the structural decision-making process based on parameters by modifying the less material usage to reduce deformation but optimise the structural strength. *Karamba3D* provides visualisation graphics to help observe structural behaviour such as displacement, stress, and deflection using legend or visual information. Figure 7 shows that the edge of the surface, both left and right sides, is the main area where the displacement happens; meanwhile, the surface in the middle area experiences stress load, both in horizontal and vertical gravity load. Our future research will focus on the details of the performance structural design based on changing and modifying the parameters supporting the requested loads to achieve optimal structural strength.

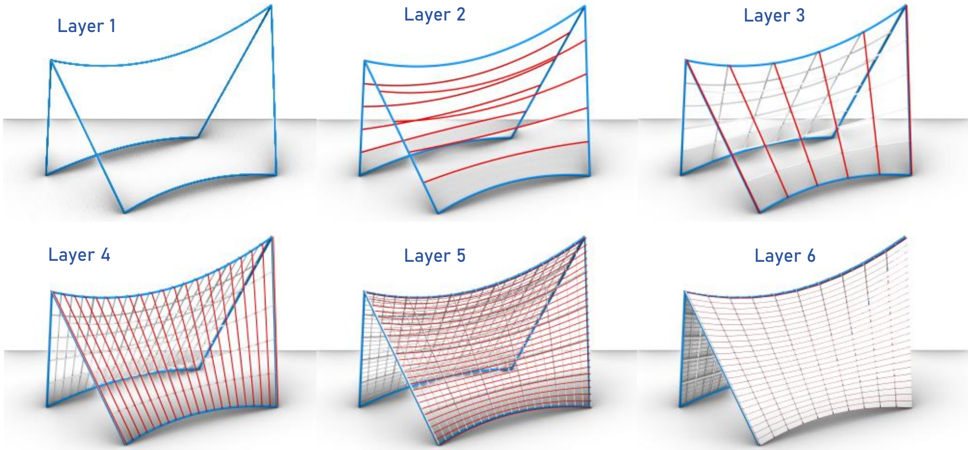


Figure 6
The basic structural layer of the *Batak House* roof for fabrication.

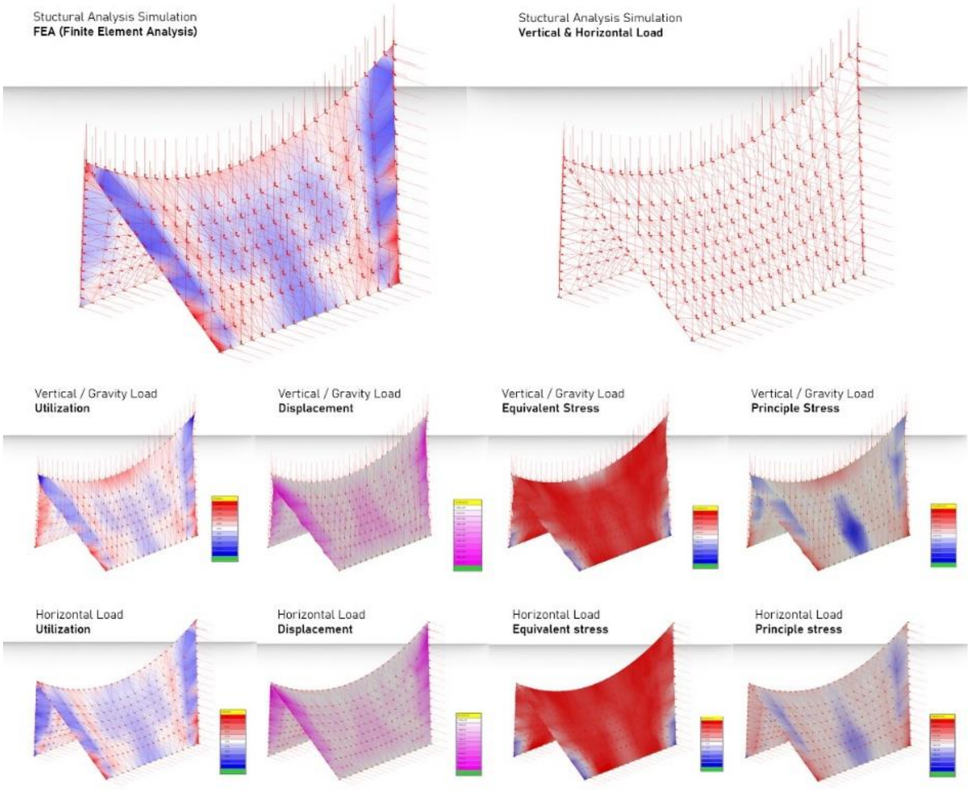


Figure 7
Structural Analysis FEA, Karamba 3D.

Phase two: **Prototyping Stages**. For digital fabrication and scaled model-making purposes, in the initial stages of our research, we selected bamboo stick poles as our material, whose behaviour and characteristics have similar versatility to the actual raw bamboo, such as the capability to bend or buckle. As we use UR10 for this initial current research, we need to observe and see how feasible and visible the robotic fabrication could be incorporated into such material behaviour. As our research progresses, we will continue to work with the actual bamboo sticks, poles, or strips, and the dimensions or the material will be adjusted to our suitable tools on a scalable size based on the same principle of its robotic fabrication. The joint system of the bamboo element is traditionally paired and tied with rope (straw, palm fibre, rattan, or synthetic polyester). However, for this research, we use plastic locking Joint ties to allow flexible adjustment for a non-fixed bamboo structural arrangement. Before initiating the robotic fabrication process, we created a smaller-scaled prototype of model-making to observe how the assembly process can work manually understand how the roof geometry works with hand-assisted assembly, and then apply the same behaviour principle to the robotic fabrication scenario (figure 8).

Phase 3: Robotic Fabrication Stages. This research presents the robotic fabrication system capable of partially assembling bamboo roof structures with cooperation and interaction with human intervention. This Human-robot cooperative research mainly focuses on task allocation when humans assist robots while assembling and fabricating the structures. We partially automate the process with robotic assembly and human intervention and assistance in joining & tracking the elements of bamboo structures.

The system consists of bamboo sticks and the UR10 robot with custom 3D-printed grippers that assemble the bamboo sticks into the bamboo architectural structure. The robot performs several assembly tasks, such as picking, placing, holding, stabilizing the structure, bending and buckling the elements, and dealing with mechanical properties inherent in bamboo behaviour to achieve geometric configurations specified by the architects. By performing this task, we can see the feasibility of assembling the bamboo design. To achieve the traditional roof typology, the bamboo structural construction system consists of 5 different layer arrangements of bamboo, tied with plastic zip-tie joints, the base is reinforced with steel anchors.

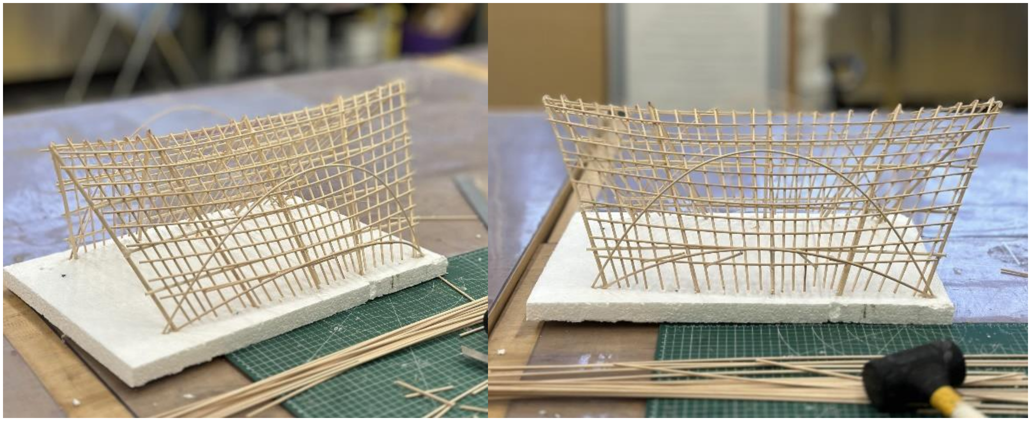


Figure 8
Scaled model-making, assembled manually.

Robotic Task Distribution

The first layer of the main structure (figure 6) is initially placed and attached to the base steel anchor. The second layer of bamboo carries out task 1 (T1) by robotically holding and stabilizing the element and manually bent and joined by humans. Furthermore, the third layer of the structure performed task 2 (T2), by robotically picking, rotating, and placing the pre-cut bamboo stick. Subsequently, the final task is executed by completing the last layer by performing task 1 (T1) similarly, but with a smaller and denser bamboo arrangement. We commence the robotic task by carrying out simple tasks such as gripping, picking, and placing the bamboo element and see how the gripper can robotically hold and stabilize the structure while performing manual bending tasks (figure 9) .

To summarise the tasks, we feed the bamboo stick, picking and placing it robotically, and we see how our workflow can work together with bending and buckling capabilities using robotic technology. For constraints limitations of the robot to do such task, in another case, the robot's role in holding and stabilizing the bamboo element structure will also be tested, simultaneously involving humans to bend and buckle the bamboo manually with the hand-operated method and fix the joint system in the collaborative process with the robot. In our Human-robot assembly scenario, we provide pre-cut bamboo stick material that has been coded, measured, and sized to specific dimensions beforehand. The automated dimension is translated from the digital data obtained from the script's list. In task 1 (T1), where bamboo sticks are placed horizontally, the role of the architects is to determine the centre point of bamboo sticks based on the coordinate calculation scripted in the Grasshopper and then bend the bamboo sticks on both sides of the bamboo tip while fixing and tying the joint attached to the structure in the underlying layer. Robots constantly and continuously place, hold, and stabilize the bamboo stick from the middle point coordinate. At the same time, humans work together to interact for complementary tasks in bending and fixing the joint to achieve the predefined curvature of the desired design.

After completing the first layer assembly, task 2 (T2) is performed with robotic placement of the second layer of vertical bamboo sticks. As the array configuration of bamboo sticks is arranged based on the shapes' surface distribution, the robot will pick, place, and rotate the bamboo sticks following the design rules and assembly scenario (Figure 10). The human connects the sticks with the underlying layer with the plastic zip-tie joint, and the robot always stays in position to hold and stabilize the structure.

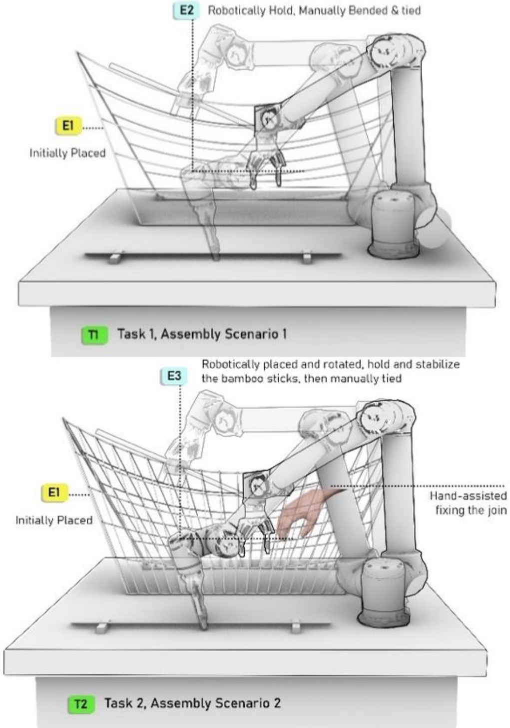


Figure 9
Assembly logic plan

Figure 10
Assembly scenario and Layer of bamboo structure

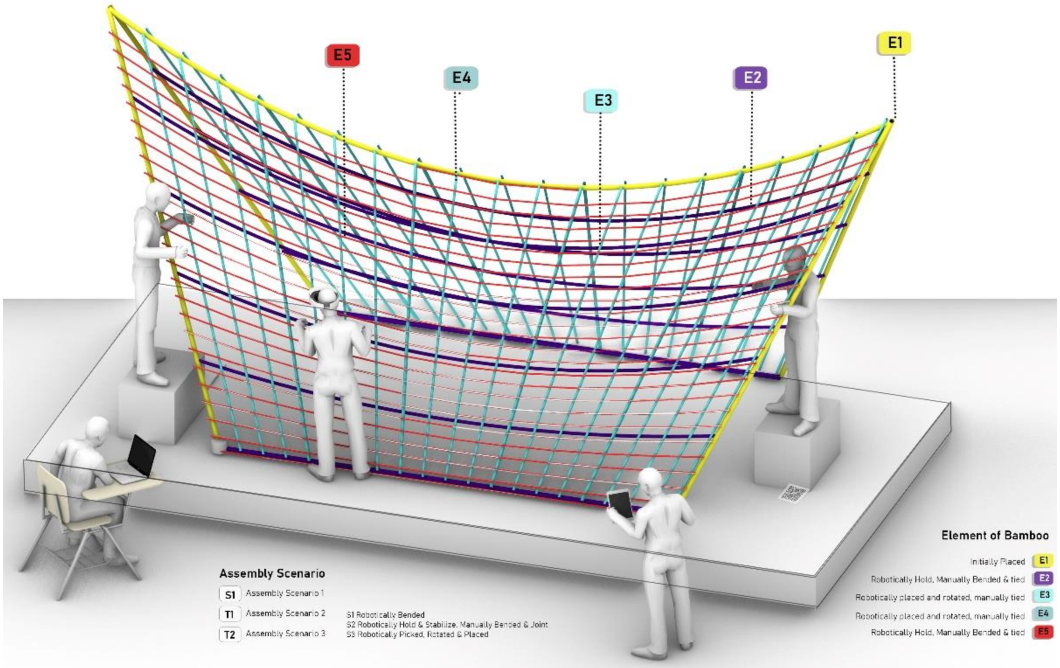
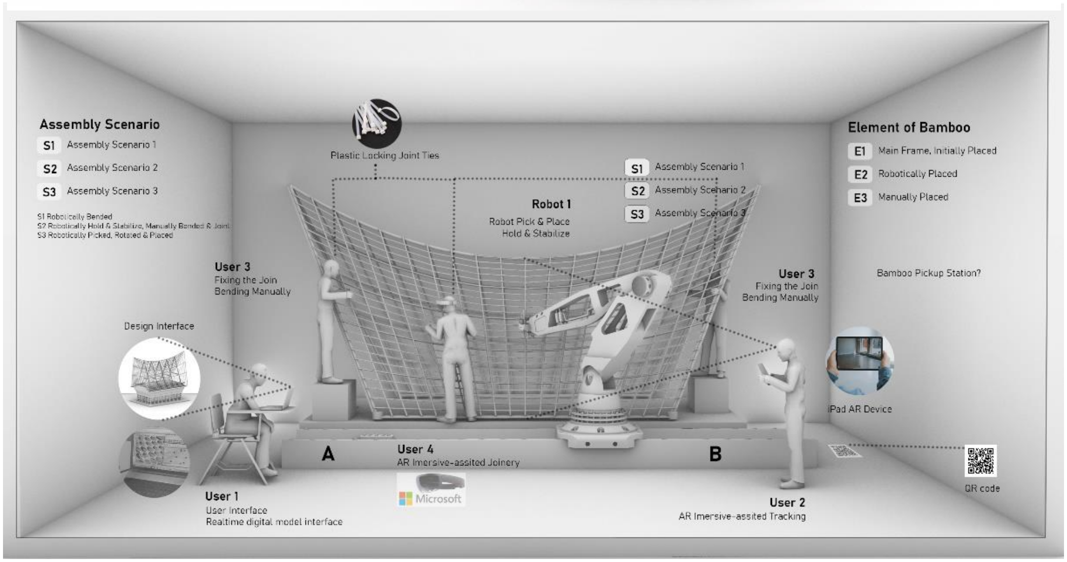


Figure 11
Assembly scenario and Layer of bamboo structure



CONCLUSIONS & FUTURE WORKS

Our proposed research demonstrated the potential for human-robot collaboration which is tied to the mutual relationship of bamboo and robotic capabilities. We intend to challenge the bamboo natural materials characteristic as a driving force to be robotically integrated during the assembly process.

To verify our proposed framework is workable and doable, we need to conduct the fabrication simulation plan with design experiments by performing our proposed new robotic fabrication task, such as gripping the bamboo with a specified diameter, placing, rotating, bending, buckling, holding, and stabilizing, and releasing the pre-ready bamboo material for fabrication. The feasibility of our proposed framework is validated through small-scaled model-making that is fabricated manually. From this process, we learn how the geometry of the bamboo roofs works during manual assembly and gather information on the same principle of assembly logic that we can potentially implement into robotic assembly. Accordingly, we illustrate the fabrication logic and strategy by showcasing the initial fabrication simulation plan, understanding the fabrication setup, grouping the distribution task between humans and robots, categorizing the assembly scenario, and outlining cooperative assembly logic (Figure 11).

Expanding the robotically assembly natural material, such as bamboo, into a large-scale structure will benefit the novel opportunity of emerging sustainable architecture and how we build bamboo architecture. Our future work will focus on verifying our proposed framework through design experiments. We will also explore different contemporary bamboo parametric designs and continually improve our human-robotic fabrication process by evaluating our framework through design model experiments and case studies.

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