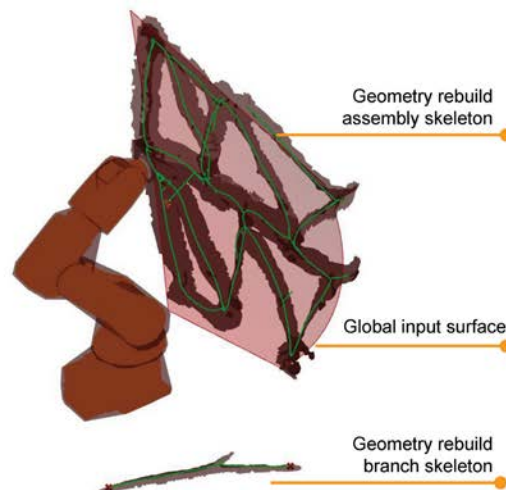
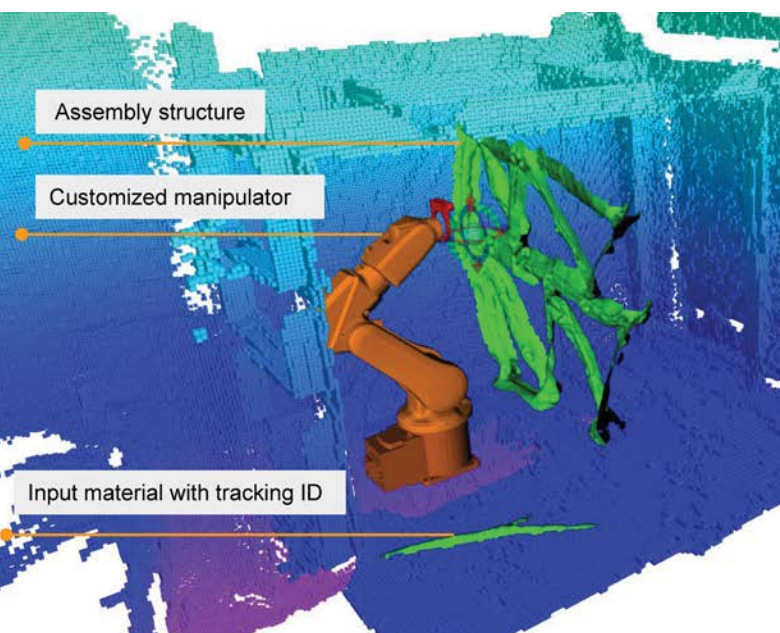


Responsive Robotic Assembly with Heterogeneous Materials

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A Case Study with Unprocessed Wood

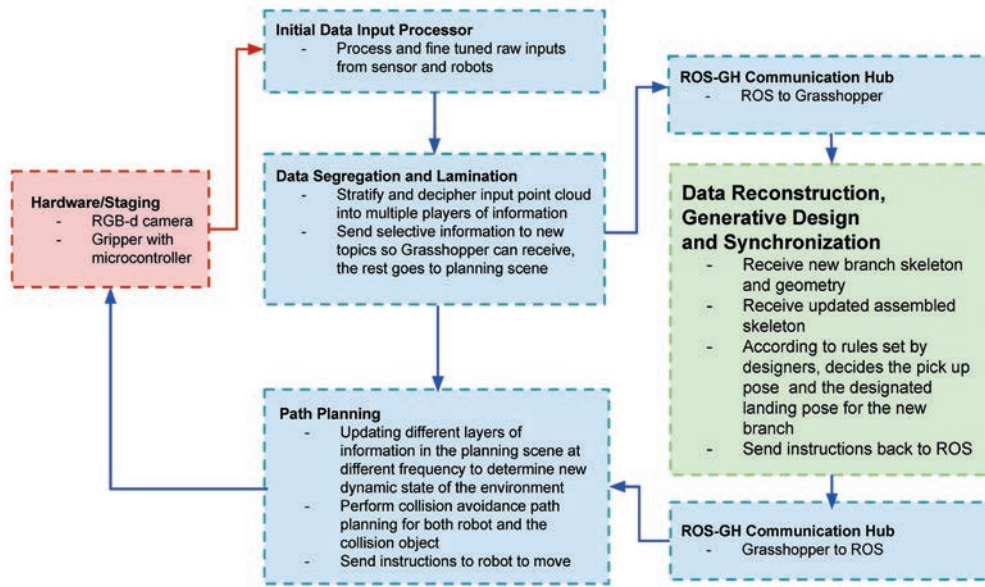


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ABSTRACT

This paper explores how robotic automated assembly can be adapted towards architectural materials, and develops a dual planning and design framework between ROS (Robot Operating System) and Grasshopper for responsive assembly with non-standardized tree branches. The framework synthesizes features of adaptive path planning, material analysis, and parametric design as an efficient and dynamic feedback system to adjust robot trajectory planning and design decision-making. It creates the potential for adaptive mass-customized fabrication with heterogeneous natural materials. The paper documents iterate research and testing leading to a series of prototypes using wood branches collected in local parks and forests as test materials. Approaching these through a bi-directional, real-time system, we bypass industrial standardization; confront geometric and tectonic challenges unique to irregular, biological forms; and evaluate the system's performance. The framework embodies techniques in 3D map generation and calibration through sensors, empirical design solver, and data efficiency organization. This distributed, resourceful approach to fabrication challenges the historical tendency of automation technologies towards increased mass standardization and capital concentration. The attention to direct employment of non-standardized raw wood not only supports biologically inspired computational designs, but also ecologically friendly fabrication practices that scavenge waste materials and save costs from material-standardization treatment. Responding to the global concerns of waste management and resource repurposing, the research seeks to contribute towards an equitable, ecological, architectural design practice with computation and semi-autonomous robots.

- 1 Two-part system in which ROS focuses on planning semantics, and Grasshopper focuses on design semantics.



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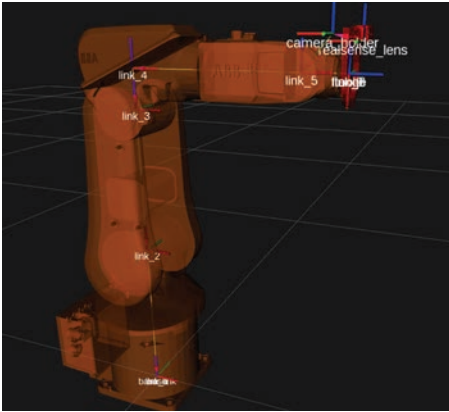
INTRODUCTION

With the development of automation and computation technologies, robotics are being adopted to support complex construction and fabrication for architectural parametric design. However, many transformative fabrication processes remain in offline programming, and do not assign generative design and adaptive planning during execution loops. While in the field of autonomous navigation and manipulators, sensor-based intelligence systems have shown the strength of point-cloud or vision-based, simultaneous localization and mapping (SLAM) algorithms to flexibly perform intelligent decision-making in real-time dynamic environments (Kerl, Sturm, and Cremers 2013). There is increased interest among the computational design community to incorporate unprocessed natural materials directly for fabrication, such as projects like Tangential Timber and Ashen Cabin (Schumann and MacDonald 2022; Lok and Zivkovic 2020). Besides appreciation for designs guided by biological traits and elements, this research and its projects also suggest wider application of these unvalued materials excluded by standardized manufacturing practices for waste minimization purposes. In addition, exploration in autonomous pipelines for different structural configurations is also increasing, such as unified sequence assembly path planning, distributed robotic timber construction, or collision-free pathfinding for raw wood logs with deep learning (Huang et al. 2021; Leder et al. 2019; Wu and Kilian 2019).

Compared to previous work in the field, the majority of the test cases use dimension-specific materials and cohesive

dataset optimization to reduce uncertainty in the planning process. This framework looks specifically at non-standardized material with bottom-up decision-making in real time to dynamically adjust operations, in which material feeding, identification, and localization are also taken as a part of the planning process. We begin to question how sensor-informed stratified planning environments and calibration-free workflows inform interaction, design, and construction for architecture. If this adaptiveness is given to automated fabrication workflows, how can these systems inform design and fabrication with non-standardized materials in distributed format? In addition, how can automation enhance the potential for mass-customized parametric fabrication? With these questions, we seek to address the association between dynamic path planning and assembly workflow with non-standardized materials to investigate the design of such a framework.

To address the challenges in conforming non-standard material inputs to designed forms, this paper presents a real-time responsive robotic assembly framework with a ROS (Robot Operating System) and a Grasshopper-based bi-directional system, using COMPAS FAB as a communication portal (Quigley et al. 2009; Rutten. 2014; Romana et al. 2018). The framework orchestrates sensor-based material inputs, geometrical analysis, and dynamic path planning with a parametric design pipeline as a synthesized infrastructure to enable robotic automation with customizable forms by using non-standardized materials. This is accomplished through data segregation and lamination, by using RGB-D visual SLAM, sampling-based inverse kinematic

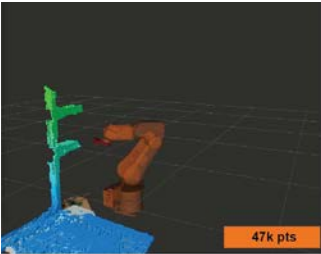


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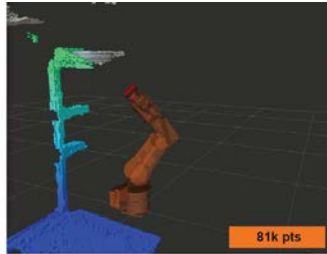


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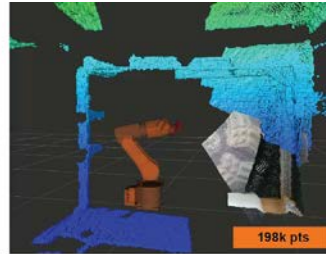
- 3 ROS urdf (TF tree) for robot eye-on-hand sensor setup where camera is linked to 5th axis.
- 4 Physical eye-on-hand sensor setup for robot.
- 5 Base map scanning with RTABmap at a resolution of 0.0025m.



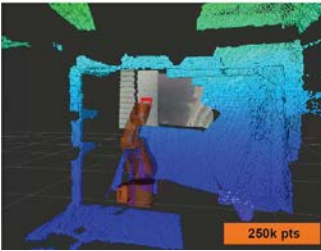
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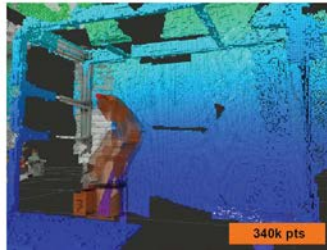
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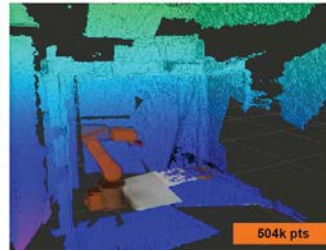
198k pts



250k pts



340k pts



504k pts

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path planning, OctoMap, clustering algorithms, Laplacian skeleton contraction with incomplete point clouds, and Poisson surface reconstruction (Hornung et al. 2013; Cao et al. 2010). By separating planning scenes into operation semantics in ROS and design semantics in Grasshopper, the framework demonstrates closed-loop distributed computing for real-time scene updates, material analysis, design generation, and collision avoidance trajectory planning (Figure 1).

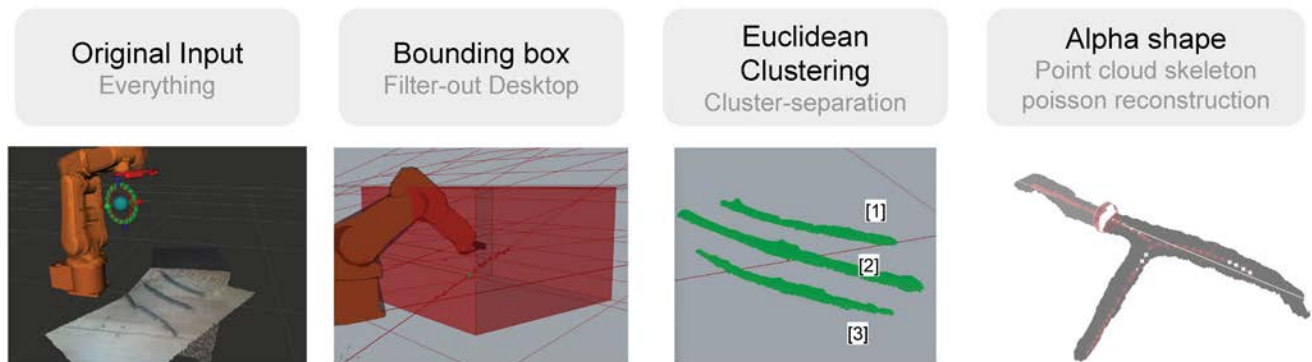
This framework is developed specifically to handle non-standardized raw wood from tree limbs. Each branch instance will be taken in as units to automatically generate a larger structure through means of a rule-based system or agent-based optimization. The framework we developed bridges the parametric design domain with sensor-based feedback path planning so that robots can adapt to a dynamic working environment and organize non-standardized input data. The framework is partially human-supported by requiring a human builder to manually create connections between the new input positioned by the robot and the entire work-in-progress structure. The successful implementation of the framework

illustrates how sensor-based, autonomous robotic systems provide the broad potential for natural raw material in architectural construction without the detour of standardization. Given the challenges identified, we defined the following objectives for the system: 1) accurately identify and extract the characteristics of non-standardized material and the work-in-progress structure for digital analysis and representation; 2) efficiently distribute computing data for either operation or design planning; 3) maximize planning success rate in a complex, evolving working environment by identifying the constraint of both the system and the material; and 4) create openness for the implementation of various fabrication rule sets.

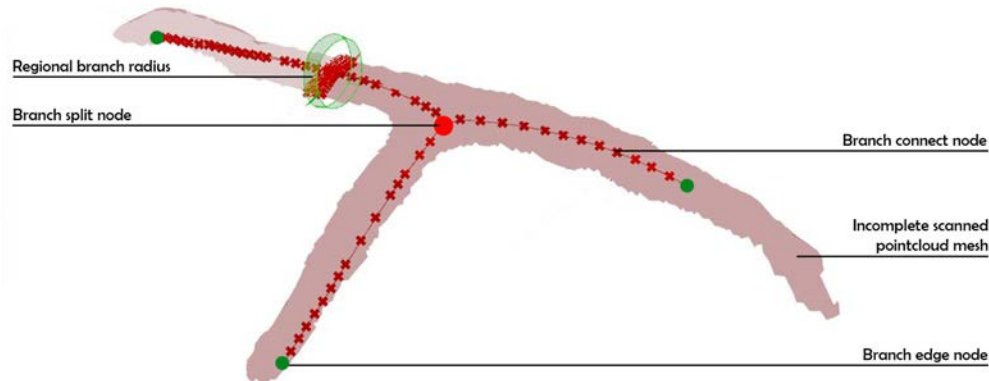
METHODS

System Overview and Hardware Setup

The system is composed of six main modules belonging to the section of hardware, ROS, and grasshopper (Figure 2). The following graph narrates how modules are organized and communicated. The physical setup for the system experiment consists of an ABB IRB120 robot with an Intel real-sense camera 435i fixed at its fifth axis, and an



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- 6 Sequential branch analysis through three layers of filter.
- 7 Branch data organization with three types of nodes and local radius.

7

Arduino-driven gripper on its sixth axis, reducing extra rotation for the camera's mapping accuracy (Figure 3 and 4). This eye-in-hand camera installation provides more flexibility for scanning large structures and the surrounding scene. The controller is connected to the ROS system running on a Linux system, and Grasshopper on a Windows system is connected to ROS through a Wi-Fi server.

Data Segregation, Analysis, and Lamination

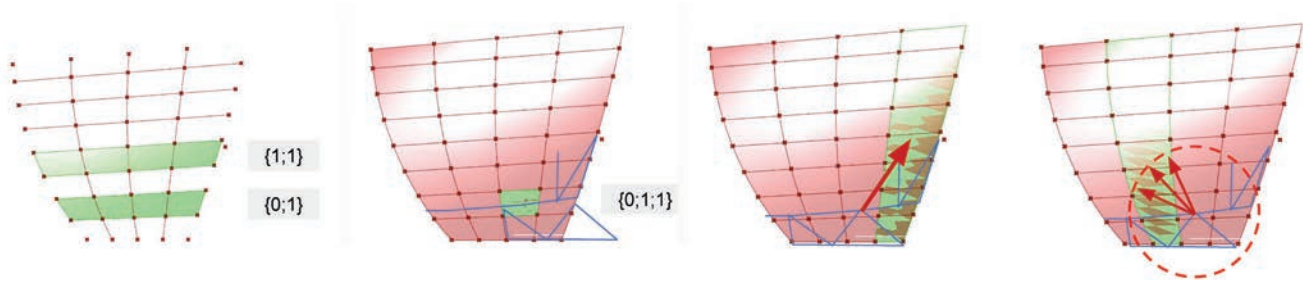
An important feature of the system is clear-stratified layers of the planning scene constituted by a process of segregation, analysis, and lamination, where the environment, material, operation tracking, and product updates are at different frequencies. The base environment 3D map (Figure 5), processed by RTABMap, with colored pointcloud and constructed into Octomap, is pre-scanned in jogging motion before the start of every work session (Labbé and Michaud 2019). Three layers of data decomposition are applied to identify and analyze branch input or working assembly: 1) a bounding box that filters non-related point cloud in the scene, 2) Euclidean clustering if multiple inputs are given, and 3) Laplacian point cloud contraction to read nodes and lines that constitute a skeleton of the object (Figure. 6). In Grasshopper, the nodes are further divided into different types to indicate bifurcation and edges for design interpretation (Figure. 7).

Planning Scene and Design Scene Synchronization

The synchronized trajectory planning scene and design scene take separate concentration upon operation and design semantics by gating non-affiliated data for visual clarity and computing efficiency. The robotic operating system preserves the raw data, and channels selective information to Grasshopper: 1) robot configuration, visualization, and movement; 2) branch point cloud and skeleton; and 3) assembly point cloud and skeleton.

After a design decision is made according to the input, the assembly status, and the tracked steps, Grasshopper sends the following to ROS:

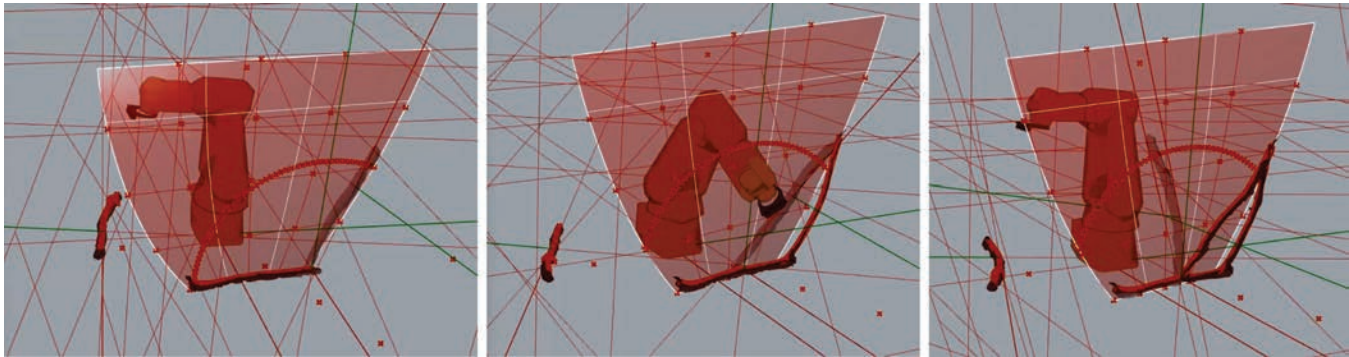
- Goal position and gripper information: The command sent to ROS can be serial or singular, where the ROS planning scene can plan and execute a single trajectory or consecutive trajectories. Gripper information, and an attachment status, are associated with every goal position, which the gripper will change or maintain in its opening angle after the manipulator has completed its trajectory and has attached/detached a specific collision object accordingly.
- Assembly mesh: The assembly does not track different versions in the planning scene. The new input will overwrite the previous one to ensure that the working



8 Visualization of UV-guided design logic.



9 Evolution of assembly structure through multiple cycles.



10 Real-time visualizations in Grasshopper during Assembly.

environment will always contain a work-in-progress assembly.

- Branch mesh with assigned ID number: In the iterative process with singular input, a tracking number is not necessary; however, when dealing with batch inputs, the planning scene will associate each branch with a number ID to keep track of when to import into the planning scene, attach or detach the item to the tool center point (TCP), and remove the item from the scene. Before attaching the branch item to the planning scene, the planner ensures that the item exists.
- Topics publish messages that remain in Grasshopper for iterative updates: 1) the UV grid indexes the target surface where the last branch's end edge was; and 2) the UV grid indexes the target surface for the Grasshopper to search for the next branch's start edge.

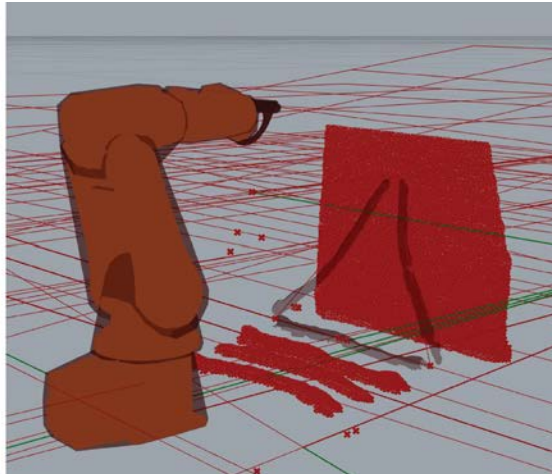
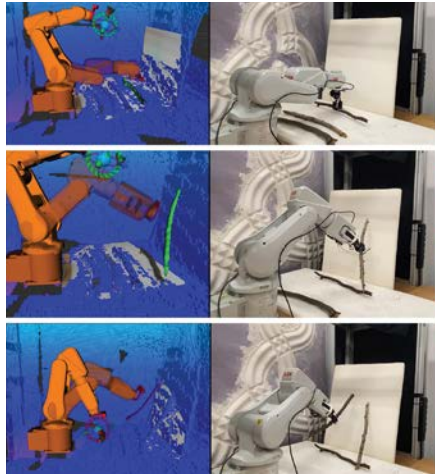
Planning Optimizer

The Open Motion Planning Library (OMPL), a default sampling-based trajectory planner in ROS Moveit, works

as a mature library for singular-path trajectory planning (Coleman et al. 2014). However, to consider picking and placing a branch as an integrated operation, an intermediate optimizer is developed to perform two filters of search and planning to enhance the success rate in a highly constrained environment. This empirical approach targets complex working environments and reach-limit expansion by optimizing the two-goal pose of pick and place regarding the difficulty of moving the branch to its ideal location. By eliminating most of the error samples in the first filter without collision checking, this optimizer significantly increases the success rate of planning with minor tolerance adjustments in the trajectory planning scene.

UV-Guided Design Rule System

The system opens to various construction logics, which only requires the sequentially grouped outputs of a picking goal position and the placing goal position. In the experiment for modular customization, the design logic



- 11 Non-planar arrangement of batch input. The robot scanned three branches simultaneously, sequentially placing them in triangular form leaning against a wall.
- 12 An iteration in the assembly process.

11

utilized was the UV-guided rule system that iteratively maps the branch inputs to fit a global surface. At this point, Grasshopper would continuously memorize the grid, where the last branch starts, and mark down both the start edge and the end edge. This would allow the new input to potentially be attached to its previous member (Figures 8, 9, and 10). Depending on the physical setup, the UV grid is searched from left to right, bottom to top.

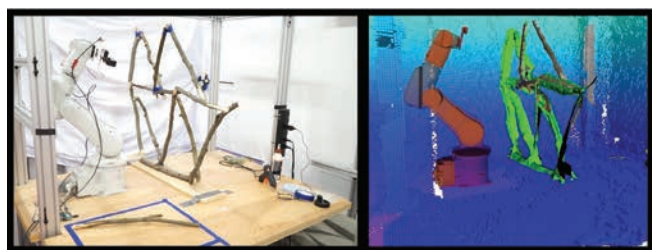
Iterative Assembly Process

The iterative assembly process can be categorized into two types of input: batch input and single input. Batch input presents multiple branches at the same time, and makes a top-down execution according to the design rule set and all available information. In this testing example, three branches are organized into a batch input, where the design system asks for an enclosed triangle that leans on a vertical surface (Figure. 11). In comparison, iterative input with a single piece of the branch does not embody

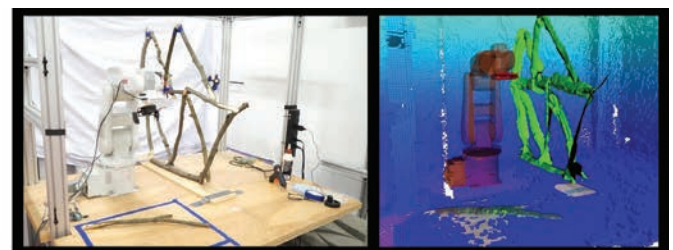
any top-down approach, and does not need Euclidean clustering to separate the branches into different groups of point clouds. However, the bottom-up approach requires the robot to re-scan the working structure every iteration to update the discrepancy between the physical structure and the simulated configuration, for performing local rectification described in the UV-guided surface fitting design. A complete cycle of assembly scanning, input scanning, data processing, and operation to human-support connection (including curing time), takes approximately 12 to 18 minutes for each branch. This iterative process takes advantage of the robot's precision in positioning to hold the material until it attaches firmly to the assembly while adapting human flexibility in connection management to support the assembly process (Figure 12).

RESULTS

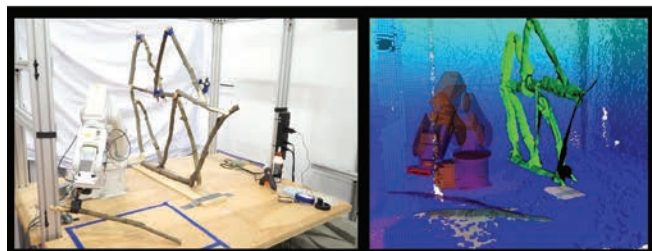
Multiple prototypes constructed by this sensor-based assembly framework demonstrate the effectiveness of



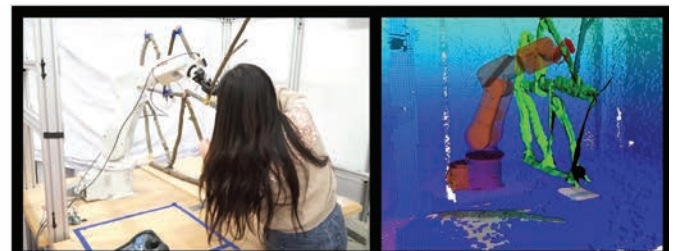
Step 1: Rescan assembly to update structure and the working scene



Step 2: Scan new input and update both assembly and the input from Grasshopper

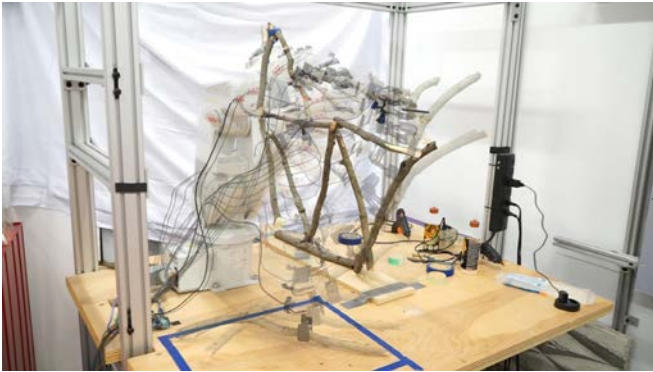


Step 3: Send final pick and place command and attach material to TCP when gripper closes



Step 4: The manipulator stays put while the operator manually enforces the connection and waits for the glue to cure

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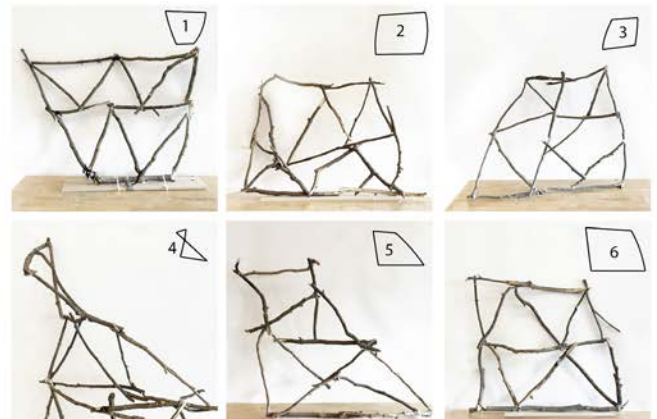
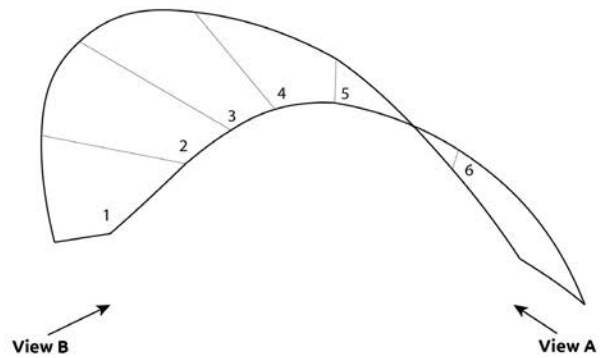
13 A time-lapse photo of module assembly trajectories.

14 Photographs of initial physical prototypes, where each element was placed by the robot and joined with resin glue by a human.

semi-automated customization with non-standardized wood. The resulting structures conformed with the designer's input geometry and flexibility to attempt execution with growing complexity in the working scene (Figure. 13 and 14). With the aggregation of the structure, path planning attempts, additional trials, and longer detours to avoid collision must occur, while negotiating with extreme cases at the maximum reach of the manipulator. For modules where certain locations are impossible to attempt, shifting the structure's orientation and position, with subsequent rescanning and surface fitting in Grasshopper, provides a temporary, but flexible, solution for successful test cases. By dividing a large structure into multiple customized modules, a robot like ABB IRB120, with only 580mm of work range, can construct prototypes that span several meters in both area and height. As shown in Figure 15, this physically constructed installation consists of six divided, modular segments that composite into a twisted arch geometry. The size of each module is limited to 0.3m x 1.3m x 1.1m (height), available for IRB120 to execute individually. Figure 13 shows a single trajectory of constructing module 1, which consisted of 16 branches in total. The assembled arch spans approximately four meters, and each module is connected to each together by manual application of zip-ties. This large prototype demonstrates the scalable versatility of the framework, enabling greater dimension in fabrication with small robots.

CONCLUSION

The framework proposed in this paper bridges environment-sensitive, adaptive planning for robot manipulators and the design process of non-standardized materials. The experiments juxtapose heterogeneity and raw traits of unprocessed wood with a well-resolution localization algorithm to feed design strategy with tactic information. While this framework is tested with the case of unprocessed tree branches, it aims to apply to other varieties of non-standardized materials that are customizable with different design approaches. Iterative experiments are also performed to understand the limitations of physical implementation, and resolve them with specific optimizers. Apart from the UV-guided global surface control, it is open to integrating various fabrication methodologies. By tackling challenges in computing efficiencies and large data input, the system demonstrates adequate performance in extracting core information and analyzing it to perform a design decision. The baseline framework developed in progress presents a case for robotic automated fabrication with an intelligent planning system, and shows the potential for robotic construction with non-standardized material in a transient working environment. Waste creation and management problems have been globally



15 Photographs of a physically assembled installation consisting of six customized modular components, each executed by ABB IRB120 (total dimension: 4m x 1.3m x 1.7m).

recognized as a side effect of standardization, augmented by automated technologies. By advancing methodologies for non-standardized material assembly with real-time sensing and planning algorithms, the framework, instead, presents a potential of material waste minimization with robot autonomy. Unprocessed materials treated with economic, customized logistics, provide opportunities to bypass conventions of capitalization and centralization. In addition, the prototypes constructed based on this framework, with modular segmentation, demonstrate high degrees of flexibility in robotic fabrication at different scales. Future work considers taking in the process of joinery automation, with multi-manipulator planning and structural analysis, as integrative modules to operate at an architectural scale. In addition, framework efficiency and accuracy can be improved by strategies such as multiple sensor fusion, extended kalman filter (EKF) calibrations, and multi-manipulator planning groups to expand and mature the framework.

NOTES

1. All prototypes are completed by ABB IRB120.

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IMAGE CREDITS

All drawings and images by the authors.

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Joshua Bard is Associate Professor in the School of Architecture at Carnegie Mellon University. He was named Associate Head for Design Research at the school in 2021. Joshua is an architectural educator, conducting applied research at the intersection of construction culture and robotic technology. Joshua's teaching and research interrogate traditional binaries in design culture (industry/craft, machine/hand, virtual/physical space, digital/analogue production), discovering new potential for contemporary digital tools in the jettisoned logics of hand and material craft. Joshua creates augmented construction and design systems combining the best of human skill, algorithmic translation, and robotic automation.