Upcycling Tree Branches as Architectural Elements through Collaborative Design and Fabrication

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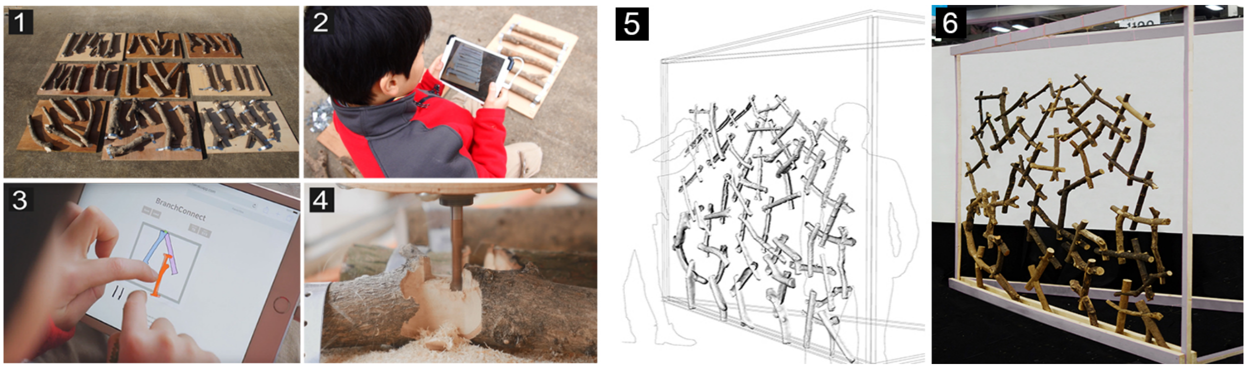

Figure 1: Workflow overview: 1.fix branches on plates 2.scan the plates and upload the model 3. play the game with scanned branches 4.fabricate joineries by a CNC router 5. The layout of a screen wall designed for South by South West (SXSW). 6. An assembled screen wall.

ABSTRACT

While tree trunks are standardized as lumber, branches are typically chipped or burned. This paper proposes a workflow to upcycle such mundane and diverse natural material to architectural elements. Introducing an online design interface, we let users participate in the design and fabrication workflow from collecting branches to CNC milling. The branches are first scanned, and then key geometrical features are extracted and uploaded to the online game "BranchConnect". This application lets multiple non-expert users create 2D-layouts. At the point of intersection between two branches, the geometry of a lap joint and its cutting path are calculated on-the-fly. A CNC router mills out the joints accordingly, and the branches are assembled manually. Through this workflow, users go back-and-forth between physical and digital representations of tree branches. The process was validated with two case studies.

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CCS CONCEPTS

• **Applied computing** → **Computer-aided design**; • **Human-centered computing** → *Participatory design*;

KEYWORDS

Design and Fabrication, Crowdsourcing, Upcycling

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1 INTRODUCTION

Effective use of natural resources is becoming an important theme in architectural design. Although wood has been used for building throughout history, it is nowadays particularly promoted as a sustainable construction material [16]. While tree trunks are processed and standardized into lumber, the rest of the tree, mostly branches and bark, are typically chipped or burned as fuel. In the DIY community we can observe some activity making objects out of naturally shaped branches, but these are often limited to handmade decorations. Since tree branches account for 25 % of a whole tree, there is a large potential contribution to the effective use of natural resources if we can use branches for building. [1].

More than being resourceful, the use of tree branches can provide a desired character for architectural design. Active use of local materials is a recognized design approach, called vernacular architecture [12]. Weston claims that a building made out of local materials represents the local community, which helps to foster a sense of belonging [15]. We put emphasis on this hub aspect of local materials. We take fabrication as an opportunity for non-experts to foster their knowledge, skills, and even the sense-of-belonging [5]. In terms of educating or supporting non-experts, various tools have been developed to assist non-experts to complete and realize their designs [6]. We also developed the design game which assists users to complete their designs, however, our motivation is to provide opportunities to connect others. In this sense, tree branches perform as tangible medium to participate in a community [4, 10].

This paper proposes a method to upcycle organically shaped materials to fabricate architectural elements leveraging computational fabrication techniques. For collecting and designing, we developed an online interface where users can freely post branches they have found. Further, users can create and post layout designs of branches through the online game BranchConnect. The submitted layout designs are directly translated to custom lap joints. As lap joints work as rigid joints and do not require additional systems such as screws, the assembly process of is simple and user-friendly (Figure 1.4). In this paper, we share the technical details of our workflow, and report from two case studies where we let non-expert users design and build a 2D screen wall. In summary, our contributions are

- A workflow enabling to use diverse and natural material as design components.
- An online game-based approach to collaborative architectural design.
- A method to design and fabricate customized non-orthogonal lap joints using high-resolution contours.

2 RELATED WORK

Several design and fabrication projects focused on organic shape of trees. Monier and colleagues virtually explored architectural design with branch-like components, and Wood Barn project realized a structure from forked tree trunks built with custom joineries milled by a robot arm [9, 11]. While they used large tree trunks, our work uses tree branches, which are more obtainable and reasonable size for crowdsourcing without requiring special equipment. The challenge is the size and fragility of branches, thus it is more difficult to process. Schindler and colleagues used digitally scanned tree branches for furniture and interior design elements [13]. While they demonstrated the capability of digital fabrication processes to handle irregularly shaped branches, the design process was dependent on experts. Our work scaled their approach by gamified collaborative design interface and fabrication workflow for non-experts. Architectural design is inherently collaborative among users and architects. Computer mediated participatory design in architecture was further explored by Cimerman [2]. Talton and colleagues developed a collaborative design tool for users to design trees and plants [14]. FoldIt crowdsourced protein structure prediction to game players [3]. DrawAFriend is an app to collect stroke data for auto-stroke assistance [8]. Human-in-the-loop construction methods were proposed in architecture-scale [7, 17]. While these works take users either on design or fabrication, our work let users participate in the whole processes not only for problem solving but also for providing experience.

3 WORKFLOW

The workflow is summarized as follows (also see the left of Figure 1). Branches are first collected and attached to plywood plates. Then they are scanned, processed and uploaded to the online game BranchConnect. Players create their layout design by moving branches around in the game. Once a design is finished, it is exported to another application that calculates the unique milling paths of each pair of joints. The CNC router mills out the joints accordingly, and users assemble the branches by hand.

Collecting and Scanning Branches

The first step is to collect branches. Then they need to be trimmed down below a fixed length, determined by the reachable area of the CNC router used for fabricating. In our setup, the maximum length is about 50 *cm*. Branches are manually cut using a saw. Then they are attached to plywood plates, with about 5-8 branches per plate. They need to be firmly fixed to stay in place during the milling process. We use metal fixtures and screws to attach them.

To be able to import the collected branches to the game, their shapes are captured by digital 3D-scanning. After a textured mesh model is acquired, we extract skeleton, contour, and radius as a simplified representation of the branch. First the branches are segmented from the background by simply applying a height threshold. The top view 2D contours of each branch are obtained by contour detection. The skeleton is detected by applying Delaunay Triangulation to the contours and extracting the middle points from the triangles. After extracting the skeleton points, their order is analyzed, and a curve is drawn to connect them. In this process we need to consider the case of a grafting branch (Y-shaped) consisting of multiple segments. To avoid cutting metal fixtures during milling, their locations are identified by mouse-clicks and marked with a red dot. After all required data is extracted, it is uploaded to a cloud database, and the game is ready to run. The left of Figure 2 shows a textured mesh model on the left, and corresponding contours and skeletons on the right.

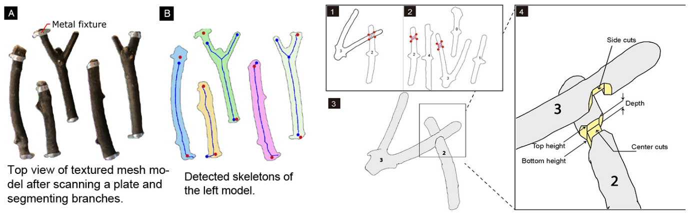

Figure 2: Left: A and B show an interface of branch importer. Right: diagram of our joints. 1. A layout design 2. Branches on a plate with milling paths in red 3.An assembled pair of branches 4. A close-up joint geometry.

BranchConnect: The Game

The goal of the game is to connect predefined target points on a frame with a limited number of branches. Users can pick a branch from the available set displayed on the bottom and create layouts by moving, rotating, and mirroring branches. The user continuously receives visual feedback and a score, guiding the user to a feasible design. The game is completed when all the target points are connected. It is, however, still possible to keep modifying the layout to improve the design and to try to reach a higher score. Joint and group evaluation are the two key functions of the game, and the basis for the scoring system.

Joint Condition Score. A joint is detected when two branch skeletons are intersecting. An important rule of the game is that every other branch needs to be flipped, i.e., mirrored, in order to make a valid joint. This is due to fabrication constraint of the CNC router which can approach a branch only from above. Mirrored branches are indicated by a thicker outline in the game. Figure 3 presents other joint conditions for calculating score.

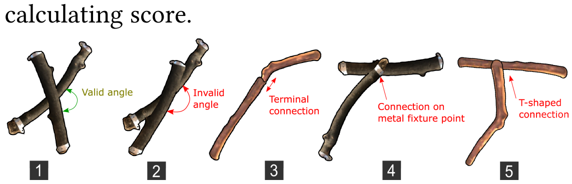

Figure 3: Joint conditions. 1. Valid joint. 2. Invalid - angle out of range. 3. Invalid - terminal connection. 4. Invalid - metal fixture point. 5. Invalid - T-shaped connection.

Iterating all branches in a frame $\mathcal{B}$, we get the number of all valid/invalid joints and connected target points, N_{valid}, $N_{invalid}$, $Ntarget$ respectively. When a branch $b_i \in \mathcal{B}$ is connected to one of target points, the number of the connected target points N_{target} is appended and the branch is trimmed at the target point. We calculate the score of joint conditions $\mathcal{S}_{\text{joint}}$ as follows.

$$\begin{aligned} \mathcal{S}_{\text{joint}} &= w_1 N_{valid} + w_2 N_{invalid} + w_3 N_{target} \\ &\text{s.t. } w_j \in \mathbb{R} \ \wedge \ \forall j \in 1, \dots, 3 \\ &\quad N_{target} \leq T_{all} \in \mathbb{R} \end{aligned} \tag{1}$$

Group Condition Score. Major group conditions are detected as in Figure 4. After updating the group, group condition and the connectivity of target points are evaluated. Denoting a group and a set of groups as g_k and $\mathcal{G}$ respectively, we check each branch $b_i \in g_k \in \mathcal{G}$ whether it has a connection with a target point or not. If it has, the target point is stored in the group g_k. Denoting the number of

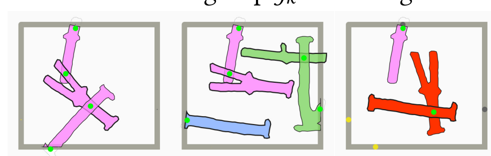

Figure 4: Left: valid group with two target points connected. Middle: valid but non-optimal because there is more than one group. Right: invalid due to *Islanded* situation.

groups as N_{group}, the number of islanded groups as N_{island}, the number of bridged target points as $N_{bridged}$, the sum of distance of bridged target points as $Dist_{bridged}$ the score of group conditions $\mathcal{S}_{group}$ is calculated as

$$\begin{aligned} \mathcal{S}_{\text{group}} &= w_5 N_{island} + w_6 N_{bridged} + w_7 Dist_{bridged} + w_8 N_{cycle} \\ &\text{s.t. } w_j \in \mathbb{R} \ \wedge \ \forall j \in 1, \dots, 4 \\ &\quad N_{bridged} \leq T_{all} \\ &\quad N_{island} \leq Br \end{aligned} \tag{2}$$

The game is completed when N_{group} is one, and all the target points are connected to the group without invalid joints. The state of completion C_{complete} is binary and described as

$$C_{\text{complete}} = \begin{cases} 1, & \text{if } N_{group} = 1 \wedge N_{bridged} = T_{all} \wedge N_{invalid} = 0 \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

We calculate the score S_{all} by adding the results from Eq 1, Eq 2, and Eq 3. Note that the weights $w_1 \dots w_9$ are non-negative weight coefficients pre-adjusted in advance by the authors.

$$S_{\text{all}} = \mathcal{S}_{\text{joint}} + \mathcal{S}_{\text{group}} + w_9 C_{\text{complete}} \quad \text{s.t. } w_9 \in \mathbb{R} \tag{4}$$

Fabrication and Assembly

After a design is selected for fabrication, fabricatability of the design is further analyzed in a high-resolution model. If an invalid joint is detected, the layout can be modified by adjusting the branch positions using the mouse. Users can also control fabrication parameters such as milling bit diameter, joint depth, cutting speed, moving height and so on. After confirming the fabrication settings and joint validity, G-Code is exported to the CNC by one click. The joint is a lap-joint with full side cuts and a half-way-down center cut. The resulting geometry creates rigid joints, adapted to the unique branch shapes and angles of intersection (the right of Figure 2).

4 CASE STUDIES

Workshop

We organized a design and fabrication workshop to examine the feasibility of our system. It was hosted in a public community house close to a forest. The participants were four children (aged 4, 7, 9, and 10) and two parents. We set the goal to create a screen wall (2000 *mm* x 900 *mm*) divided into 8 sub-frames (500 *mm* x 450 *mm*).

Figure 5: An overview of the workshop. 1. The overview of the space. 2. Collect branches. 3. Cut in specified lengths 4. Attach on a plate 5. Scan the plate 6. Play the game 7. CNC milling.

Firstly the participants were asked to collect branches with 2-10 *cm* diameters. The collected branches were cut in appropriate lengths. They could construct two plates by themselves and the rest plates were built by authors. Each plate was scanned using iSence camera running on iPad minis. Figure 6 the left shows the scanned branches on plates. When the plates are scanned, simplified branches were uploaded online. We set 30 minutes for playing the game, including practice to get started. Figure 6 the right shows example layouts in score-descending order. Finally, participants were asked to assemble the branches by hand. The whole workshop took 4.6 hours to complete, including introduction, moving, and breaks.

SXSW Exhibition

What we learned from the workshop is that participants preferred to complete a large wall without subdividing frames. In this case study, a 2D screen wall with a single large frame was designed and built to exhibit at SXSW. The wall size is 2 by 2 *m* and we used 74 branches. Compared to the workshop, we used diverse types of trees and a wider range of shapes. The CNC milling took two weeks in total and the assembly took less than an hour with three people.

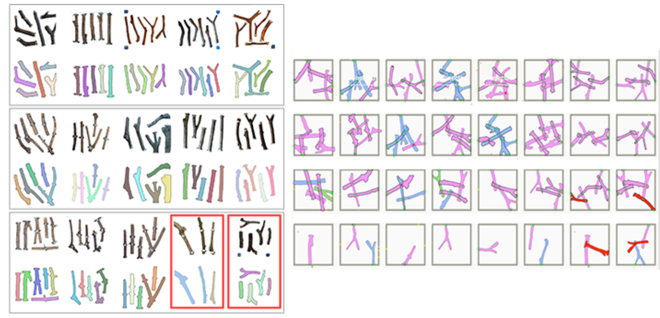

Figure 6: Left: An overview of all the 15 scanned plates. Ortho-top views of scanned mesh models and segmented branches are shown for each raw, top and bottom respectively. The plates with red rectangles are built by participants in the workshop. Right: Example layouts created by the authors in score-descending order. The highest score is top-left and the lowest score is bottom-right.

The main challenge of this study was to decide the best layout of over 70 branches all to be fitted in a frame. At the beginning, a designer focused on the layout task, but we soon realized that it was overwhelming for one person. Eventually we overcame the issue by virtually subdividing the frame into several work areas and restricting the number of branches per area. Each area became a micro-task, thus multiple designers could work collaboratively. For international shipping, branches went through fumigating process to eliminate insects in the branches. The final outcome is shown in Figure 1.6.

5 CONCLUSION AND FUTURE WORK

We have presented a participatory workflow to upcycle tree branches as architectural elements. The participants collect, scan, mill, and assemble branches by themselves, guided by the system. The layout is also designed by the participants in an online game. We run two case studies where the participants successfully constructed wooden screen walls using our workflow. Our study only confirmed the feasibility of our approach. Further investigation is necessary to examine the effectiveness of the collaborative gamification approach in improving the layout quality and in nurturing the sense of belonging. The fabrication process is limited to 2D and inefficient. For future work, it is valuable to work on design and fabrication of 3D structures. The fabrication process has to accommodate higher degree of freedom either by robot arm or other approaches. Structural analysis is lacking in this study and can be integrated in the design process.

6 ACKNOWLEDGEMENTS

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