Robot Assisted Carpentry for Mass Customization

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Abstract— **Despite the ubiquity of carpentered items, the customization of carpentered items remains labor intensive. The generation of laymen editable templates for carpentry is difficult. Current design tools rely heavily on CNC fabrication, limiting applicability. We develop a template based system for carpentry and a robotic fabrication system using mobile robots and standard carpentry tools. Our end-to-end design and fabrication tool democratizes design and fabrication of carpentered items. Our method combines expert knowledge for template design, allows laymen users to customize and verify specific designs, and uses robotics system to fabricate parts. We validate our system using multiple designs to make customizable, verifiable templates and fabrication plans and show an end-to-end example that was designed, manufactured, and assembled using our tools.**

I. INTRODUCTION

Mass customization is the current frontier of innovation in manufacturing. While advances in additive manufacturing, industrial robotics, and software design tools are enabling laymen to design and create custom items, carpentered items have not yet benefited from these advances. There are few digital design tools for carpentry that include fabrication. Therefore, customization of carpentered items requires expert knowledge for both design and fabrication. This restricts customization of carpentered items to professional and hobbyist carpenters and those who can afford their labor. Carpentered items make up the structures we live in and the furniture around us. Buildings and decks must be adjusted to the terrain they are embedded in, and furniture should adapt to fit spaces and functions. We aim to democratize carpentry by enabling co-design through integration of professional CAD systems with user-friendly customization, verification, and robotic fabrication tools.

The challenges in personalization of carpentered items are twofold. First, designs must ensure proper functionality and performance (structural stability, durability, etc.) while being feasible to manufacture and assemble. Second, fabrication of a design requires skilled tool use and dexterous assembly. We address these challenges by an end-to-end system that handles all the stages from conceptual design, through verification, to fabrication. We leverage expert knowledge for design, robots for fabrication, and code to tie it all together.

In our system, experts define templates that have fabrication guarantees. End users can customize these templates in an interactive interface, with performance feedback from physics simulation. Teams of robots are assigned parts to manufacture from the templates based on fabrication requirements. Assembly plans are generated from expertly crafted composition rules, and are executed by the layman end user.

We accomplish this by leveraging existing CAD for parametric design, and existing finite element method (FEM) systems for verification. Our user interface automatically translates parametric designs into editable models for the layman user and simulates the user specified designs. We developed algorithms for automatically assigning parts to stock materials and fabrication processes. To enable fabrication, we employed two robotic systems: a novel fabrication method in which robots team to use a chop saw, and a mobile robotic jigsaw [1]. We developed a system for automatically generating assembly instructions from inferred hierarchical structures embedded n expertly tagged information in the design.

In this paper we contribute:

- A framework for expert design, layman customization and robot fabrication
- Fabrication methods using mobile robots and standard power tools
- Experimental and simulation verification of design through fabrication of custom carpentry structures

II. RELATED WORK

Design for manufacturability is an important problem in engineering design [2], [3], [4], [5], [6]. More recently, advances in manufacturing have garnered a lot of interest in fabrication-oriented design systems that bring down the design barrier for casual users. A wide range of domain specific design tools have been proposed in previous work, including systems for push toys [7], clothes [8], linkage-based characters [9], model airplanes [10], and robots [11], [12].

Previous carpentry specific design systems focus on either furniture or architectural structures. Furniture design tools generate parts automatically but rely on the shape of the parts to implicitly describe the fabrication process, typically relying on CNC fabrication [13], [14], [15], [16], [17], [18]. Architectural design systems such as the Monta Rosa Hut and Instant house focused on using CNC machines to cut complex interlocks in timber or plywood [19], [20]. While CNC machines allow for complex parts, they limit the scale of parts since parts fabricated using CNC processes must fit inside of a CNC tool. For Instant House, this required decomposing the structures into many sections that can fit into the CNC machine [21].

The cost of CNC machines, the difficulty in transporting them to a job site and the scale limitations on parts means

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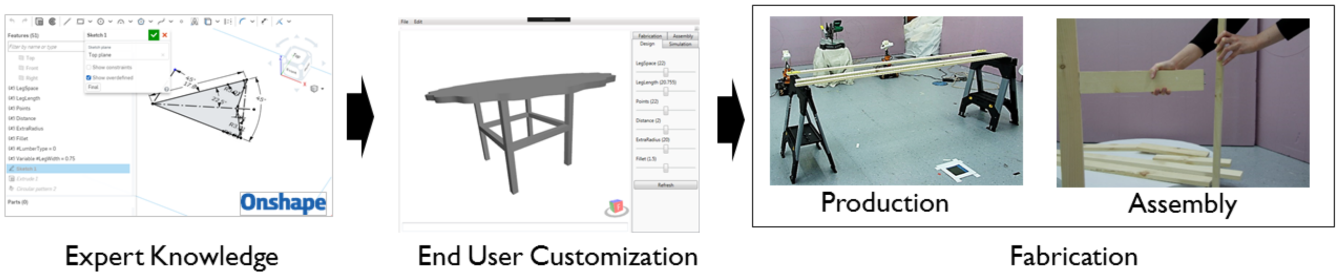


Fig. 1. System workflow. Experts design *templates* in a commercial CAD system. End users customize and verify the designs using our interactive interface. Once the users is satisfied with the model, the system outputs a complete fabrication plan which includes instructions for robot assisted cutting processes and rules for user assembly.

most carpentered items are not made using CNC tools. There have been several attempts to decouple the size of the fabricated parts from CNC machines by making mobile robotic systems. Handheld CNCs such as Shaper Tools and Handibot allow a human user to move a small CNC system over a surface and have it cut features [22]. Autonomous mobile robots such as Goliath CNC have further decreased the skill level needed to cut complex features into large scale wood objects [23]. Despite these advances, most carpentered items use chop saws, jigsaws, and other hand tools because of their low cost, ease of transport, and simple interfaces. For robotic assisted fabrication to be adopted it must be easily deployable and interface with these common tools.

III. WORKFLOW

Our workflow allows collaborations between expert designers and layman users. The experts are responsible for creating designs with a set of exposed parameters which define different possible configurations for the models. We call these designs *templates*. The end users can vary these parameters to customize the templates to meet desired specifications and then fabricate the results assisted by a team of robots (see Figure 1).

When engineers design they should consider the available fabrication processes. In our system, experts are instructed to design templates based on a pre-specified set of carpentry tools. We choose to use a standard CAD software for modeling so engineers do not have to learn new tools to use our system. CAD systems are parametric from construction, allowing the engineer to expose a set of parameters with ranges to define a feasible design space for the layman user [24]. The engineer then annotates the connections between parts with priority tags. Our algorithm uses these tags to automatically compute assembly instructions.

We expose a simple interface for the end users where the designs can be customized by varying the parameters using sliders (see Figure 1). In addition to exploring the parameter space, our interface allows the user to visualize the stress distribution and deformation under certain loading conditions. This enables verification of designs before fabrication.

Once the users are satisfied with a design configuration, the system outputs a complete fabrication plan. The fabrication plan includes cut patterns and assembly instructions. We use two robot assisted cutting processes: a robotic team using chop saws, and mobile robotic jigsaws. After the robots finish cutting all the parts, the users assemble them guided by an interactive interface with assembly instructions.

IV. DESIGN

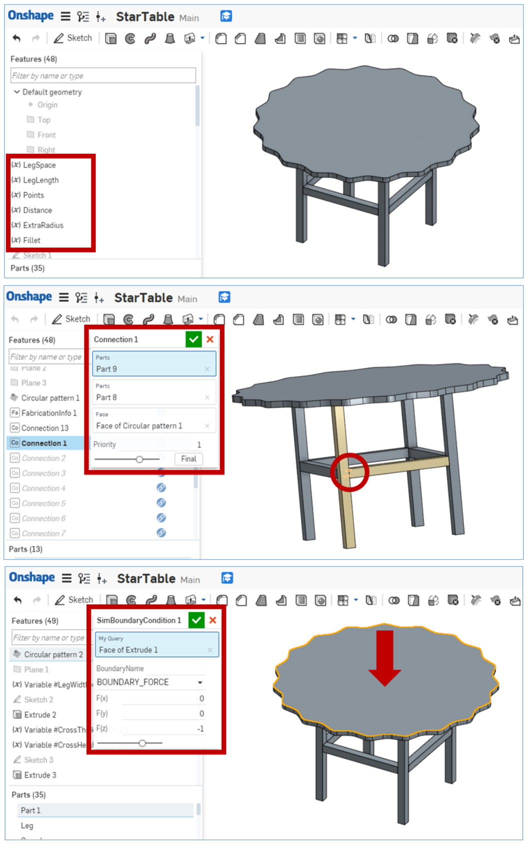
A. Template Design

Templates have been used in many previous works for customization [25]. Abstractly, a template is defined by a feasible set $\mathcal{A} \in \mathbf{R}^n$ that defines the valid regions of the parameter space (where n is the number of parameters), and a mapping function F that maps each point in $\mathcal{A}$ to a design instance. In our work, the design instance must be a model that can be verified with simulation and manufactured as a set of parts that can be cut with the set of predefined processes and then assembled. Therefore, we define templates that have three mapping functions: F_g maps each point in $\mathcal{A}$ to geometry that is composed of a set of 3D parts and their relative positions, F_c returns a set of connectors with tags on assembly priorities, and F_s returns a list of boundary conditions for simulation. In our system, the functions F_g, F_c, and F_s are defined in the CAD system and evaluated using the CAD system's API.

By exposing a set of parameters and selecting valid ranges, expert users specify variations to part shape that preserve structural integrity and manufacturability (see top row of Figure 2). This defines the feasible set $\mathcal{A}$. The manufacturability constraints limit the expert user to a parametric model composed of parts that are either sizes of standard lumber or 2D shapes cut from stock plywood. The mapping function F_g is defined by the list of CAD features that reconstruct the model geometry for a given parameter variation.

In addition to the set of parts, the expert users also need to specify the connectors in order define F_c. Adding connectors is an integral part of carpentry design that typically takes many hours using commercial CAD software [16]. To speed up this process, we used dowel peg connectors. Dowel peg connectors are commonly used in mass produced furniture because of their low cost and simplicity. We defined a custom CAD feature that takes in two parts and a connecting face and automatically outputs a set of pegs. The custom feature also takes in priority tags. By adding these features to the design for all connections (see Figure 2(bottom)) the expert automatically defines F_c.

Finally, the expert defines the boundary conditions for the simulation using a custom feature we designed. The feature takes in a face and the type of boundary condition: fixed boundary, or a boundary with an incident force to a given direction. (see Figure 2(middle)). These tags define F_s.



Connection 1
Parts: Part 9
Parts: Part 8
Face: Face of Circular pattern 1
Priority: 1
Final

SimBoundaryCondition 1
My Query: Face of Extrude 1
BoundaryName: BOUNDARY_FORCE
F(x): 0
F(y): 0
F(z): -1

Fig. 2. Expert input using CAD software. Experts create a model in a standard CAD system which is parametric from construction and exposes the parameters for user customization using the system's variables (top). For defining the assembly, experts use a custom *connection* feature which takes in two parts, a face for connection and the priority of the connection for assembly (bottom). The experts use this feature to define all of the connections on the model and those are used by our algorithm to automatically generate assembly instructions.

B. *User Customization*

Users can customize the templates by exploring the parameter space $\mathcal{A}$. The ranges of the n exposed parameters define $\mathcal{A}$ as a hypercube in $\mathbf{R}^n$. Therefore, we can use a simple interface with sliders, as shown in Figure 3, to display $\mathcal{A}$. In the *design tab* of our interface users can set different parameter configurations for each model. We use the CAD system's API to evaluate F_g and display the model.

When users find a configuration of interest, they select the *simulation tab*. Our system will then make another call to the CAD API to extract F_s and use this to run FEM analysis on the model under the specified boundary condition and display to the user the stress distribution and elastic deformation. Because the templates allow a wide range of variations, the model regions that will be the most impacted by the input forces can vary significantly (see Figure 3). Therefore, the users can switch back and forth between the design and simulation tabs until they are satisfied with a given design.

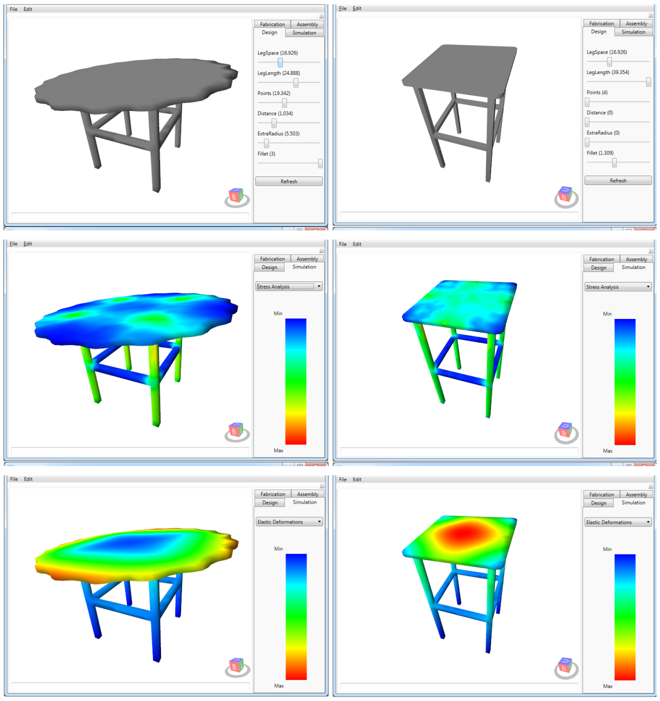


Fig. 3. User customization: the design tab (top) and the stimulation tab that display the stress distribution (middle) and elastic deformations (bottom).

V. FABRICATION

A. *Fabrication Plan*

Once the users are satisfied with a given configuration, the system will guide the users though fabricating the resulting model. The geometry mapping F_g for a given parameter setting returns a set of body parts p_i which are represented in the CAD system using the internal Boundary Representation (BREps) [26]. To process the design for fabrication, our algorithm takes each part p_i and assigns it to both material stock and a fabrication process, and it defines the information needed to complete the fabrication process.

We use two fabrication processes: chop saw and jigsaw. The chop saw process requires a part to be assigned to a dimensional lumber standard [27] and a length specified for cutting. The lumber is placed on the chop saw at the specified distance from the end, and cut using a single pass of the chop saw. This generates the desired part as well as a scrap part from the input lumber.

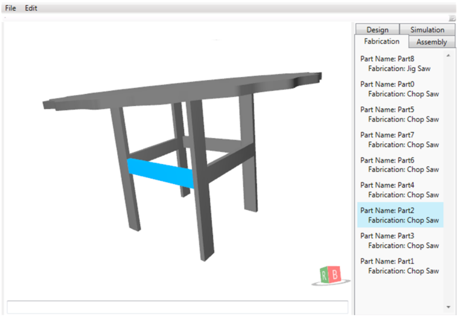
The jigsaw algorithm requires a DXF defining the boundary of the final part, and a specification of the thickness of the material to be used [1]. The DXF is parsed into a movement trajectory for the jigsaw. The jigsaw is placed on a piece of stock of the specified thickness, follows the trajectory, and cuts out the part.

Our part processing algorithm was written in the domain specific language of the CAD software we used (Onshape's

Algorithm 1: ProcessPart(p_i)

```
OBB ← getOBB($p_i$);
foreach lumberType do
    if compare (OBB, lumberType, tolerance) then
        length ← getLength(OBB, lumberType) ;
        return ChopSawProcess(lumberType, length) ;
end
face ← getLargestFace($p_i$) ;
thickness ← getThickness(OBB, face) ;
return JigSawProcess(thickness,getDXF(face)) ;
```

FeatureScript) to leverage internal referencing and geometry processing functions. For each input part, we first find the oriented bounding box (OBB) that optimally encompasses the shape. We use the part's OBB to compare it with the list of lumber standards. If a match is found, the algorithm assigns a chop saw process to the part with the given lumber type and length computed from the OBB. If a match is not found, the algorithm finds the largest face and assigns a jigsaw process using the DXF of that face and thickness computed from the OBB (see Algorithm 1).



Part Name: Part8
Fabrication: Jig Saw

Part Name: Part0
Fabrication: Chop Saw

Part Name: Part5
Fabrication: Chop Saw

Part Name: Part7
Fabrication: Chop Saw

Part Name: Part6
Fabrication: Chop Saw

Part Name: Part4
Fabrication: Chop Saw

Part Name: Part2
Fabrication: Chop Saw

Part Name: Part3
Fabrication: Chop Saw

Part Name: Part1
Fabrication: Chop Saw

Fig. 4. The list of parts and processes shown to the user in the customization interface. The users can see the full list and click on a specific part to see its fabrication process information.

In Figure 4, we see how the information is displayed to the layman user in the customization interface. When the user clicks on the *fabrication tab*, the parts are assigned to the processes using Algorithm 1. The users can inspect the fabrication plan for errors, or transfer the plan to the automated fabrication processes.

B. Fabrication with Robots

We used two robotic systems to automate the chop saw and jigsaw processes. The jigsaw process was automated using a previously developed robotic jigsaw. This jigsaw robot is a modified Roomba Create with a jigsaw installed in the center. It uses a Vicon positioning system for state estimation and a previously developed MPC and planning algorithm to perform the cuts [1].

The chop saw process requires multiple robots to automate. To use a chop saw, lumber must be placed aligned to the two reference planes on a chop saw. One plane defines the back of the lumber, and the other defines the bottom. Lumber can then be located along its major axis for cutting (see Figure 5A). Often humans require specialized stands or multiple people to use a chop saw for large lumber. The torque required to control large lumber necessitates a team lift. Specialized stands allow the lumber to rest along the reference planes of the chop saw and be slid into position for cutting.

We used multiple mobile robots to replicate the utility of both the specialized stand, and a human worker. Two Kuka Youbots lift lumber and place it on the chop saw (Figure 5B). Each Youbot was outfitted with special complaint grippers (Figure 5C). The grippers allow the robots to clamp onto material, to drive the material along a direction, and are complaint perpendicular to the major axis of the lumber. When lumber is placed in the gripper, a force perpendicular to the lumber and parallel to the gripper can cause the gripper to shift its grip. The chop saw is automated by attaching a relay to the 120V line and a linear actuator is attached to the saw. Both are connected to a ROS node via a microcontroller.

To cut lumber, the robots are assigned a length l and a spec for the dimensioned lumber. the process is seen in Figure 6. The robots identify the lumber using Vicon markers and position themselves $\frac{1}{4}$ of the way in from each side. They lift their grippers in place, grab the lumber and then lift further to separate the lumber from its stand. The robots then form a fleet, and move towards the saw in a synchronized and coordinated fashion. Once near the saw, they move down towards the height of the chop saw's base plane. They proceed to move slightly past the back plane of the chop saw and lower the lumber down. Because the grippers have compliance, the lumber aligns to the chop saw. The realignment occurs as long as the position of the grippers can be within a tolerance window.

Once the lumber is placed on the chop saw, the Youbots re-grasp the wood. They position themselves at the expected center of mass location for the two pieces of post-cut lumber. One robot then releases its grip and acts as a support while the other robot uses its gripper to adjust the position of the wood so the desired length of lumber is left on one side of the blade. The support robot re-grasps and the chop saw is activated. Once the part is cut, the desired length of lumber is transported to the user, and the other is returned to the stock.

C. Assembly

In order to guide the layman user through the process of assembly, we automatically generate a visual guide based on the evaluated F_g and F_c which returns the parts and the set of connections for a give model instance. Each connection references the connected part pair, the list of physical connectors and a priority tag. In Algorithm 2, we use this input to generate a list of assembly steps from a composition hierarchy.

To define the composition hierarchy, a series of nodes are created. We first assign each part to a leaf node. Then, for each (sorted) unique tag, we generate a parent node that

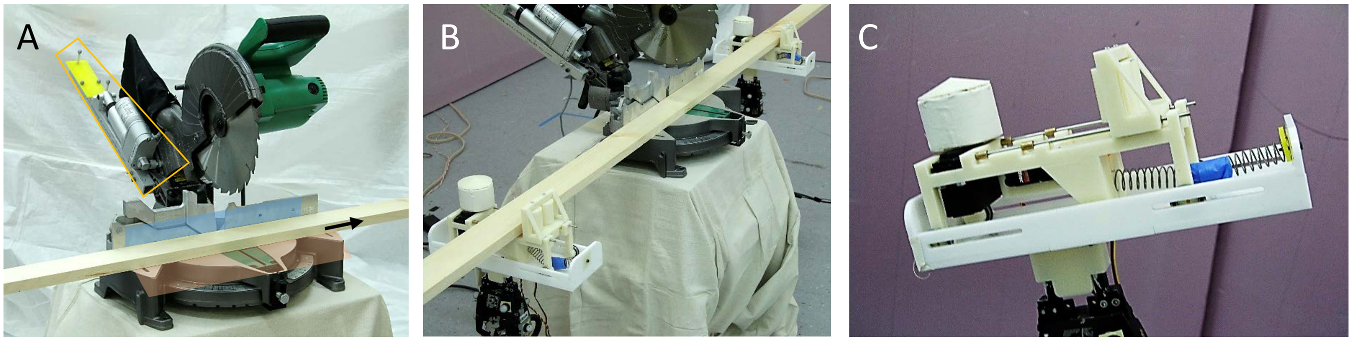


Fig. 5. A) Orientation of the lumber: the lumber must be aligned to the chop saw with the back (blue) and bottom (orange) planes. The desired length of lumber defines the distance along the major axis (black line) between the blade and the end of the lumber. The chop saw is automated with the highlighted linear actuator. B) Compliance in the grippers allows the lumber to align with the back plane of the chop saw as long as the grippers are withing a tolerance window. C) The robot gripper has directional compliance from a track and spring system, can accommodate wood between 2 and 4 inches across. It has a multi rotation servo for sliding the grasped lumber.

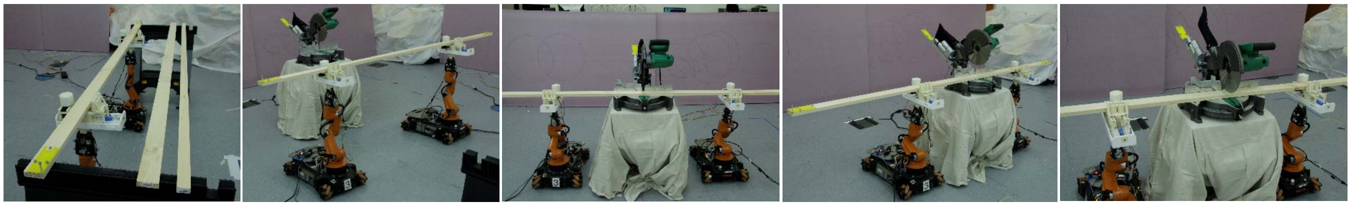


Fig. 6. Chop saw process from left to right: Robots team lift the lumber, transport it, place it on the chop saw to re-grasp, slide the lumber to the proper length, and the chop saw cuts the lumber

Algorithm 2: MakeAssemblyPlan($Parts, Connections$)

```
Nodes ← $\emptyset$;
foreach Part $p_j$ do
    Nodes ← Node($p_j$);
end
Steps ← SortAndGroup(connections);
foreach Step do
    N0 ← Node(Priority);
    foreach connection do
        N1 ← HighestPriorityNode(connection.part1);
        N2 ← HighestPriorityNode(connection.part2);
        N0.addChildren(N1,N2);
        N0.addConnectors(connection.connectors);
    end
    Nodes.append(N0);
end
return Nodes;
```

defines an assembly step. The parent nodes include a list of connectors that are added and child nodes that reference the parts that are being connected. This allows us to display the sequence of sub-assemblies (parent nodes) that are created at each step in the *assembly tab* of the customization interface. For each step, we display all of the parts that are referenced on a given parent node and highlight the physical connectors that are being added (see Figure 7).

VI. RESULTS AND DISCUSSION

To validate our system we tested each component of the workflow and show an end-to-end example. We ran experiments with four models: a table (Figure 3), a chair (Figure 8), a shed (Figure 8), and a deck (Figure 9). Since furniture and structures are commonly carpentered, these give us a cross section of potential applications.

A. Expert Input

These models were all designed by a mechanical engineer using the OnShape CAD software. Information on the number of design parameters, parts, the design time, and the connection times can be found in Table I. We did not perform connections for the deck model because of the significant number of parts. In addition to the design, our workflow requires that experts input boundary conditions for simulation and priority tags for assembly instructions. The boundary conditions for the tested models can be added in $1-2$ minutes. The priority tags can be added in just a few seconds for every connection feature. However, the number of connection features can be quite large for a complex model. Assuming that connector specification is an integral part of design, the time it takes experts to input the additional annotation necessary for our workflow is negligible compared to the design time.

B. Customized Designs

We show in Figure 8 a wide variety of geometry variation that resulted from customization of single templates. The figure displays the stress distribution for the chair model

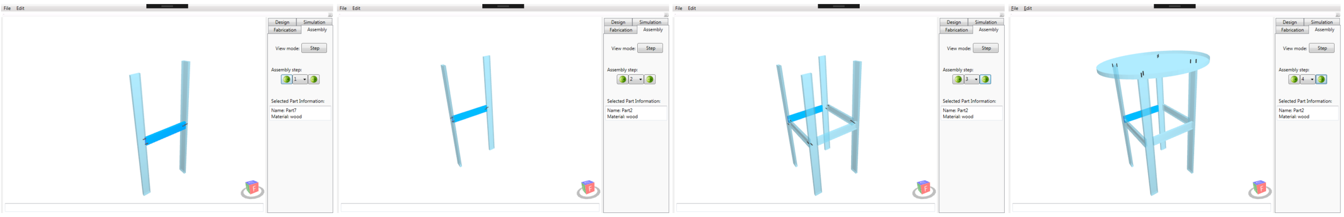


Fig. 7. Sequence of assembly steps shown in the composition interface. The user can traverse the list of steps, select parts to view additional information and use the 3D window to view the connections from different viewpoints.

TABLE I
TEST DESIGNS: NUMBER OF PARAMETERS, AVERAGE NUMBER OF PARTS AND ESTIMATED TIME FOR DESIGN AND FOR ADDING CONNECTIONS.

	Parameters	Parts (Avg.)	Design Time	Connection Time
Table	6	9	4 hrs	10 min
Chair	12	13	6 hrs	30 min
Shed	8	46	8 hrs	3 hrs
Deck	5	1500	16 hrs	-

and elastic deformation for the shed model for different parameter configurations. As shown in this figure, the physical properties of the models vary significantly with geometry changes. Using our tools users can quickly explore this space of variations and verify that the designs meet the necessary physical requirements. While the variations allow for a diversity of models, the ranges imposed by the engineer limit the space so that all variations are structure preserving.

Our method automatically generated a fabrication plan for each of these variations and the results are shown in Table II. The table displays the number of parts that need to be manufactured with each of the cut processes (jigsaw and chop saw), the total number of pegs used, and the number of assembly steps. Our method is robust to discrete variations of the shape. In the chair example, a parameter determines the presence or absence of armrests. When these are absent the assembly requires one less step. In the shed example, we see how variations in size affect the number of pegs and variation in the number of back slabs affects the number of of chop saw parts.

TABLE II
FABRICATION INFORMATION FOR THE MODELS IN FIGURE 8: NUMBER OF PARTS THAT WILL BE PROCESSED WITH THE JIG SAW AND CHOP SAW, TOTAL NUMBER OF USED PEGS, AND NUMBER OF ASSEMBLY STEPS.

	Jigsaw Parts	Chop Saw Parts	Pegs	Assembly Steps
Chair A	4	10	86	5
Chair B	4	8	62	4
Chair C	4	10	66	5
Chair D	4	10	114	5
Shed A	16	37	1050	9
Shed B	16	25	563	9
Shed C	16	25	1333	9
Shed D	16	25	1121	9

One of the main applications for customization is the need to adapt to the surrounding environment. We show how our system can be adapt to terrain using the deck model shown in Figure 9. In this example, the terrain acts as a parameter in the system and the deck template is designed to accommodate the terrain variations. Figure 9 shows the input terrains and how the shape and physical properties of the deck change with the terrain variations.

C. Fabricated Results

In order to evaluate our fabrication system, we first ran the chop saw method to cut ten 1 meter pieces of 1x3 standard lumber. To determine the efficacy of the chop saw system, we used time and accuracy as metrics. Accuracy is measured as the error in the angle of cut, and the error in the length of cut part. As seen in Figure 10, the lumber aligned to the chop saw is more accurate than the gripper. The angular error for the lumber was on average 0.54 degrees with a standard deviation of 0.4 degrees. The grippers had a 0.93 degree error and 0.82 degree standard deviation. The compliance significantly improves the ability of the system to act as an accurate cutting tool. Over the length of the chop saw, the parts were flush or nearly flush with the back plane. We believe that most of the offset in the mean angular error is a result of the warp in the wood, which deflects the Vicon markers on the end of the wood relative to each other. Clearly the system can account for errors in robot positioning, provided the positioning error of the bases is less than the 2 inch travel in the grippers.

For every run except one, the boards were cut with a mean length of 1 meter with a standard deviation of 0.0019 meters, or 74 thousands of an inch. For the run with an error there was a 7 inch positioning error due to an error with the sliding mechanism. When mechanical failures are accounted for, this system is well withing human cutting tolerances.

As a test of the end to end system, an instance of the table design was made. The table design has 8 components that need to be fabricated using the chop saw and 1 using the jigsaw. The fully fabricated parts can be seen in Figure 11. The jigsaw system fabricated the table top with a maximum error of 20 mm. The table and the fabricated parts can be seen in Figure 10. Holes for the pegs were added in a manual step. A human user followed the step-by-step instructions from the user interface to assemble the table. The use of pegs, and tool-less nature of the assembly along with the user instructions provided a simple assembly experience.

VII. LIMITATIONS AND FUTURE WORK

We assumed that all parts being designed can be fabricated either using a chop saw process at a fixed angle using

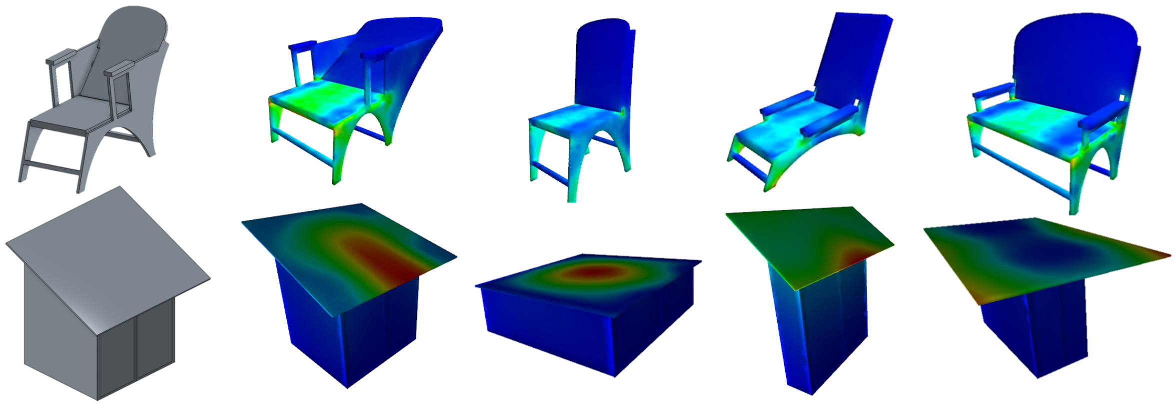


Fig. 8. Stress distribution on different variations of the chair model (top) and elastic deformation on variations on the shed model (bottom).

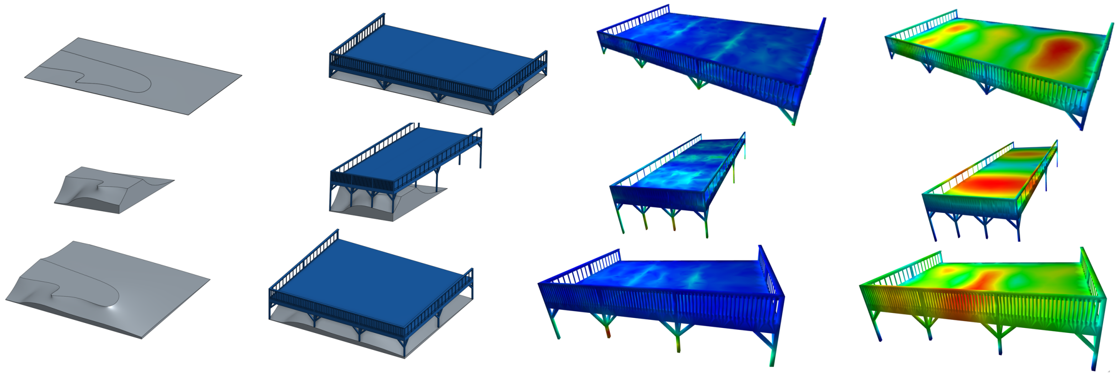


Fig. 9. Variations of the deck model. From left to right: input terrain, deck model instance visualized on the terrain, stress distribution, elastic deformation.

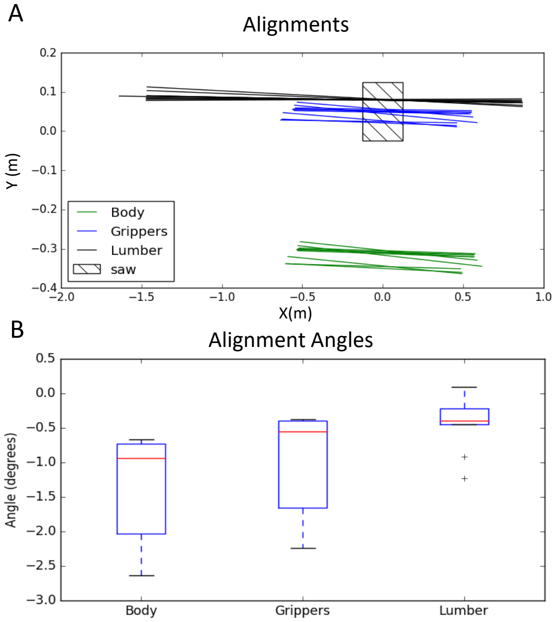


Fig. 10. A) Plot of alignment relative to the back plane of the chop saw for the lumber (black), Youbot gripper (blue), and Youbot body positions (green). B) The angular error in alignment for the lumber, gripper, and Youbot body. The lumber has a more accurate alignment than the grippers or the body because of the gripper compliance.

a single cut or using a jigsaw. In the future the fabrication algorithms can be extended to process multiple cuts on multiple planes using a chop saw. This would require augmenting the chop saw with two additional actuators to control pitch and yaw and a more complex part manipulation and processing algorithm. Additionally the jigsaw process is designed for continuous cuts on the outside of a shape and could be extended to multiple nested cuts. Alternatively, it could be extended for use with band saws and other tools for processing thicker materials. We were limited to the use foam lumber due to the lifting capacity of the Kuka Youbots. Using mobile robots with greater lifting capacity would allow us to use actual lumber.

Our expert design system currently provides no formal verification of the design. The burden of ensuring that the design is manufacturable is left to the expert user. Future methods could include existing verification algorithms [25] to prune the parts of the design space $\mathcal{A}$ that yield infeasible models. Future versions should also extend the connector design and fabrication. It would be interesting to incorporate multiple connector and dynamic joints such as hinges and slides and to include automatic drilling of holes for connectors.

VIII. CONCLUSIONS

In this work we propose and end-to-end design and fabrication system for carpentry items and verify the capabilities

Fig. 11. Fabrication of the table model. From left to right: eight pieces of stock 1x3 lumber, the cutting of the pieces, the final parts, and the assembled table result.

of our techniques with a set of examples. Using templates allowed us to limit the infinite design space of CAD systems into user editable designs, enabling mass customization of structures that can be fabricated on demand and assembled using auto-generated instructions. Our system integrates standard carpentry tools with mobile robots into a new robotic fabrication system. Currently robots only made furniture and building structures at factories, our use of mobile robots allows robots to leave the factory and join us in the workshop or the job site. We expect that integrating mobile robots and design tools will be an integral part of enabling mass customization of carpentered items. We hope that our work will be a significant step in this direction.

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