CircWood: Laser Printed Circuit Boards and Sensors for Affordable DIY Woodworking

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ABSTRACT

Due to its natural warmth, wood is frequently used to produce touchable objects such as furniture and signboards. Laser cutting machines are becoming common in personal wood processing to cut and engrave wood. In this paper, we propose a method and workflow for producing various sensors and electrical circuits for interactive devices by partially carbonizing the wood surface with a laser cutting machine. Similar to wiring on a conventional printed circuit board (PCB), the carbonized part functions as a conductive electrical path. A method for creating electronic circuits and sensors made of carbon graphene on botanical materials has been proposed. This technique makes use of a raster-scanning femtosecond (fs) laser, which is less common for personal fabrication than a constant-wave (CW) laser. Moreover, raster-scanning requires a substantial amount of time to create a circuit that is mainly made of conductive lines. This paper extends the method with a defocused vector-scanning CW laser beam and reduces the time and cost required for fabrication. The proposed method uses an affordable CW laser cutter to fabricate an electrical circuit, including touch sensors, damage sensors, and load sensors on wood boards. The circuit can be easily connected to traditional PCBs and electric parts such as one-board microcomputers using metal screws and nails typically used in DIY woodworking. We develop ease of use software design tool that supports the creation and fabrication of carbon paths. In addition, we report on a series of investigations, including optimizing wood materials and laser parameters to establish design guidelines.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *User interface toolkits.*

KEYWORDS

Laser Beam Machining; Digital Fabrication.

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1 INTRODUCTION

Due to its organic structure, wood has low thermal conductivity and is warm to the touch. Wood has been used to produce various everyday touchable objects, such as furniture and signboards. To create such objects, people have long used manual tools such as saws to cut wood; however, recently, the use of laser cutters has become popular among professionals and DIY enthusiasts. A laser cutter uses a laser beam to process wood, but no other processing methods except cutting and engraving have been widely explored. We propose CircWood, a method and workflow for creating various sensors and electrical circuits directly on wood surfaces by partially carbonizing the wood with a CW laser cutting machine. Similar to a conventional printed circuit board (PCB), the carbonized part functions as a conductive electrical path.

A method for creating electronic circuits and sensors made of graphene using a raster-scanning femtsecond (fs) laser beam has been proposed [14]. In personal fabrication, an fs laser is less affordable than a constant-wave (CW) laser, and raster-scanning requires a substantial amount of time to create an electric circuit pattern that is mainly made of conductive lines. In this paper, we extend this method with a vector-scanning CW laser beam. Our method applies a defocused CW laser beam repeatedly (8 to 15 times) to create conductive electrical paths and reduces the fabrication time by one in six hundred. Besides electronic circuits, we implemented various sensors, including touch sensors, damage sensors, and load sensors. These sensor circuits can be easily connected to traditional PCBs and electric parts such as one-board microcomputers using metal screws and nails commonly used in DIY woodworking. To aid in the design of CircWood, we present a software design tool that supports the creation and fabrication of carbon paths. In addition, we report on various investigations, such as optimizing wood materials and laser parameters to establish design guidelines. Using the

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CircWood technique, we can integrate sensors and wiring patterns, which are essential for the construction of interactive devices, into wooden objects naturally while preserving the warmth of wood. The main contributions of this paper are as follows:

(1) We extend the carbon creation methods with vector-scanning CW laser instead of raster-scanning laser to reduce the fabrication time.
(2) We present a fabrication method for the circuits and sensors with carbon, including a software design tool that supports the creation of carbon paths.
(3) We derive the design guidelines of CircWood by identifying the optimal conditions for preparing a circuit using carbon.
(4) We demonstrate the application of our method to the wood surfaces in our daily lives.

Table 1. Comparison of wooden PCB fabrication methods. A check mark indicates "yes," and a hyphen indicates "no."

Fabrication Method	Max circuit length [cm]	No human intervention	DIY-friendly	Eco-friendly	Resistance [Ω/sq]
Printing & water transfer [7]	42 (A3)	-	✅	-	0.3
Hand drawing [24]	10	-	✅	✅	0.2
Attaching metal tape/foil [1,26,29,38]	15	-	✅	-	0.03-0.2*
Spray [33,36]	240	-	✅	-	0.1
Auto-drawing by robot [3]	200	✅	✅	✅	2.5
Laser-induced graphene [14]	2	✅	-	✅	10
CircWood	70	✅	✅	✅	25

*It depends on the material (copper foil, gold foil, etc.)

2 RELATED WORK

This paper is situated in the areas of (1) fabrication of customized electronic circuits and (2) fabrication using a laser cutter.

2.1 Fabrication of Customized Electronics

Researchers have explored various methods for personal fabricating circuits and sensors. Initially, the methods of creating paper-based handwritten electronics was proposed using conductive ink [23, 24]. Then Inkjet-printed electronics, which uses an inkjet printer to transfer conductive ink onto paper instead of handwriting, became a popular technique in the field of HCI. Kawahara et al. proposed a rapid prototyping technique for printing an electronic circuit on a paper substrate with a commercial inkjet printer using silver nanoparticle ink [11]. The printed pattern is flexible, and conductivity can be established almost immediately after printing. Since it also has the advantage of low-cost prototyping, many studies have used this technique to fabricate sensors [4, 6, 9, 16, 20, 33], NFC antennas [22], multilayered circuits [31], and displays [21]. Although Kawahara et al.'s method enables users to create a circuit without any post-processing steps such as sintering, the printed circuits are of low durability [20]. Soft Inkjet Circuits is a technique for fabricating custom flexible circuits [12]. This technique uses different inks than Kawahara et al.'s method [11], and robust circuits are created on stretchable materials by curing the printed surface at high temperatures.

Several techniques in which conductive paints and sprays are utilized have been proposed to implement interactive elements on large surfaces beyond the printable scale. Wall++ [41], FlexTouch [36], Electrick [40], and Sprayable user interfaces [37] demonstrate how conductive painting materials can be painted or sprayed onto walls or furniture to enable touch input by capacitive sensing. The previous systems for fabricating large-scale circuits need human efforts, making it laborious and extremely difficult. To address this challenge, an autonomous circuit drawing system on large-scale vertical surfaces using a robot has been proposed [3].

An alternative approach is to use copper tape or foil, which has the benefits of low resistance, easy cutting and folding, and low cost. Midas is a support tool for fabricating sensor pads and routed connections for capacitive touch interactions [26]. The tool automatically generates a conductive pattern for the fabrication of touch sensors with a cutting machine. Perumal et al. proposed a fabrication technique of PCBs with copper tape and a standard office printer [1]. By utilizing a UV-reactive adhesive and selective adhesion, this technique can produce custom-designed conductive patterns by printing with a standard laser or inkjet printer. FoldTronics proposed a technique for producing 3D objects with integrated electronics using copper tape and laser-cut plastic sheets [38]. However, this process has several disadvantages: removing unnecessary material after cutting is cumbersome and time-consuming, and thin traces can be damaged when removing the surrounding material [26]. In addition to the above, gold foil [25, 29], a water-transferring technique [7], 3D printing of conductive filaments [10, 28, 30, 35], conductive material plated nylon fabric [13], carbon-coated paper [42], and liquid metal [32] have been used for circuit fabrication.

In summary, several techniques have been proposed that provide researchers with quick, simple, and low-cost methods for customizing circuits in the laboratory environment. CircWood, on the other hand, uses laser machining to create a carbonized path on the wood surface. This establishes electrical conductivity and can be used to create personalized circuits. Table 1 shows a comparison of the circuit fabrication techniques described above that can be applied to wood with various metrics. These metrics are the maximum length of the circuit reported, degree of manual labor, availability of the proposed method as a DIY tool, environmental cost of material wastage, and resistance of the circuit wiring. Although the resistance value of a circuit produced by CircWood is higher than those of previous studies, it can fabricate the circuits while negating manual labor. CircWood does not produce waste of conductive material, which typically occurs in methods using screen printing and spray (waste of ink) and foil application (waste of foil). The automatic circuit drawing method [3] requires manual preparation by users (20–30 minutes) to mount the robot on the drawing canvas. Compared to previous methods of printing or painting conductive materials on the surface of everyday objects, CircWood could be more easily combined with DIY woodwork projects where CW laser cutting machines are becoming common. Moreover, CircWood turns wood itself into a conductive material without adding artificial materials, which less affects wood's characteristics and texture.

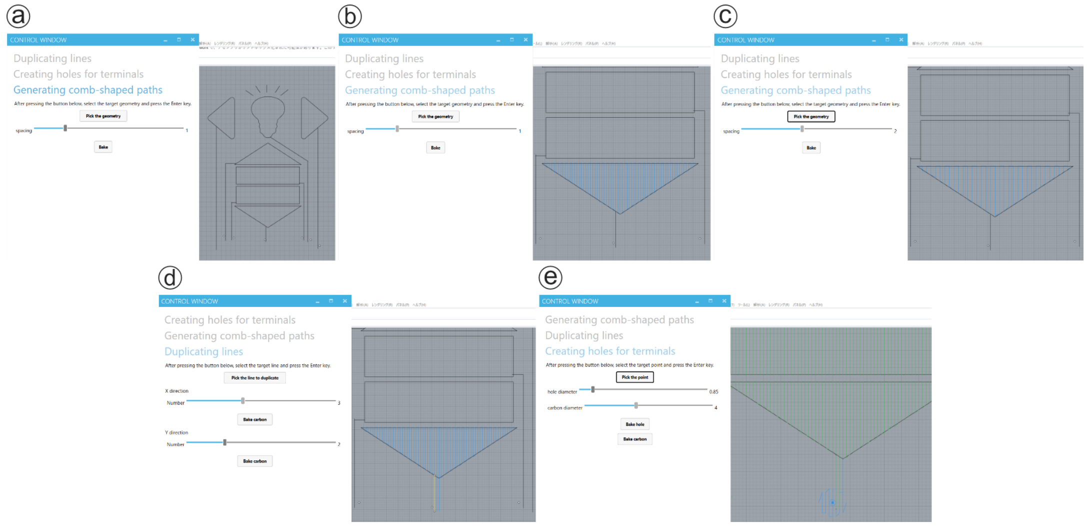

Figure 1: Software design tool for the creation of carbon paths. (a) A user draws a circuit pattern. (b) The tool automatically generates a comb pattern for vector-scanning to fill an electrode outline. (c) A user can adjust the spacing of the comb pattern using a GUI slider. (d) The tool automatically duplicates a connecting line side-by-side to make it thicker. (e) When the user specifies a terminal part, a circular pattern for laser cutting and a comb pattern for carbonized areas around it are automatically generated.

2.2 Fabrication using Laser Beam Machining

Fabrication methods that involve laser beam machining are widely used for the rapid prototyping of 3D objects by folding [18], stacking [34], soldering [19], and assembling 2D pieces [15, 17], as well as flexible or stretchable objects using ablation and parametric cut patterns [2, 8]. A vector-scanning beam is typically focused on the material being cut or engraved. Another method involves using a deliberately defocused vector-scanning beam to heat a specific region without damaging the material's surface [18, 19, 34]. CircWood also uses this approach to provide a moderate temperature laser beam and generates a carbon path on the surface of the wood substrate.

Electronic circuit fabrication techniques that utilize a laser cutter have been proposed. In LASEC [8], a stretchable functional device is fabricated by cutting and ablating a transparent conductive sheet using a typical laser machining technique. In contrast, the CircWood generates a carbonized path on the wood surface without applying additional conductive material.

Several methods have been proposed to create small-scale graphene patterns by carbonizing the surface of materials using a laser beam [5, 14, 39]. In the earliest work [39], an inert atmosphere chamber has been used to create graphene without burning. In the latter work, graphene is created without an inert gas chamber by using multiple defocused scans of a CW laser beam [5] or a single scan of an fs laser beam [14]. In CircWood, we focus on creating electrical circuits and sensors on a wood surface so that the method can be applied to personal fabrication projects. All previous work [5, 14, 39] uses a raster-scanning laser beam, while CircWood uses a vector-scanning laser beam. In fabricating an electrical circuit pattern mainly made of conductive lines, the required time for fabrication tends to be shorter by using a vector-scanning beam along the lines than by using a raster-scanning beam in all areas of the circuit pattern. The detailed comparison is shown in Section 7.1. The shorter running time of the laser cutter can also reduce power consumption and cost[1]. Although the research using fs lasers [14] has led to creating small-sized circuits and temperature sensors[2], an fs laser is not affordable in personal fabrication. Also, its enormous fabrication time makes it difficult to fabricate large circuits. CircWood uses more common CW lasers and allows the creation of larger-sized circuits for DIY projects (the detailed scalability is discussed in Section 7.2).

3 DESIGN AND FABRICATION PROCESS

In this section, we explain the workflow of the design and fabrication of CircWood. The workflow starts from the design of the carbon paths, followed by a fabrication process based on laser carbonization and connecting to external conductive parts, including conventional PCBs.

3.1 Software Design Tool

Similar to conventional PCB patterns, a CircWood circuit pattern can be described by closed outlines that enclose electrodes for external parts or touch sensors, and lines that connect the electrodes. Some of the electrodes may enclose holes for screws used for fixing and connecting external electric wires or conventional PCBs. We implemented a specialized design tool that supports the creation of the CircWood circuit pattern using Rhinoceros and Grasshopper platforms (Figure 1).

A user starts the design by drawing outlines of the electrode pattern and lines connecting them. Because the CircWood method

[1]CircWood consumes around 300 Wh to process A4 size board.
[2]The maximum size of the created circuit is reported to be about 2×2 cm^2.

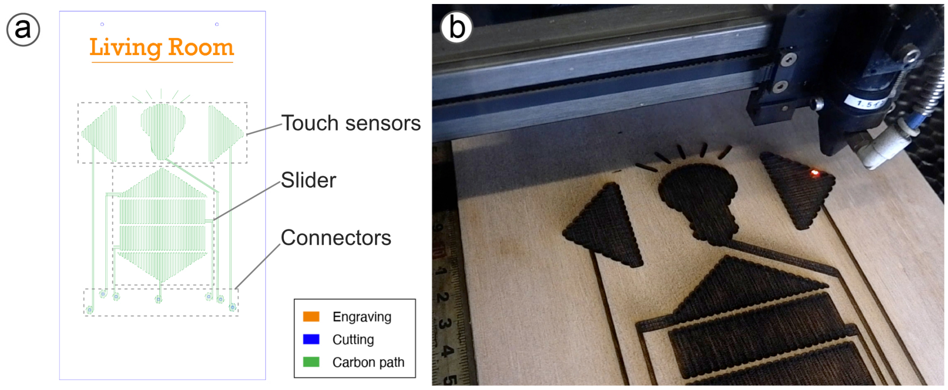

Figure 2: (a) A design example of touch switches and a slider on a wall board. (b) A laser beam generates the carbon paths to create the circuit. The laser is defocused to provide a moderate temperature to the wood.

employs a vector-scanning laser beam, each electrode part should be converted to a laser scan line that encompasses the entire area of the part. A comb-shaped laser scan line is automatically generated to fill the given outline by activating our add-on function. The user can adjust the spacing of the comb-shaped path using a GUI slider. The optimal spacing of the comb-shaped carbon path depends on the distance at which the cutting table is lowered for defocusing, which is 1 mm when the distance is 5 mm below the focal point and 1.25 mm when it is 6 mm below. The user can also adjust the angle of the comb-shaped path.

Although a single connecting line is enough to create a conductive line in CircWood, it is preferable to thicken the line to improve the electrical characteristic if spare space permits. The second function of the tool is to thicken a connecting line. When a user selects the target path and invokes the function, the tool automatically duplicates it side-by-side at equal intervals. The spacing and the number of duplicates can be adjusted with the GUI slider.

The third function of the tool is to generate a circuit terminal, that is, the cutting pattern for a hole and comb-shaped carbon path around the hole. The hole is used for a screw fixing an external PCB or electric wire, and the carbon path around the hole connects the screw and CircWood circuit electrically. To use the function, a user makes a mark at the location where a screw hole will be drilled. Then, a circular laser cutting pattern is automatically generated around that point. A circular comb-shaped carbon pattern is also generated automatically around the cutting pattern, which will be the area in contact with the screw. The size of these cutting and carbon circular patterns can be adjusted individually by the user using a GUI slider. The finished design file can be saved in any format. We used PDF/SVG files as output.

3.2 Fabrication Process

In the following walkthrough, we describe the fabrication of a wall board (total board size: 255 mm × 155 mm) for controlling a room light. It consists of three touch switches (one for on/off toggle and two for selecting the color) and one slider (controlling the brightness). The actual wall board is shown in Figure 7. We use the VD7050-60W (COMMAX Co., Ltd.) laser cutter and set the power to 30–50 % (=18–30 W) and the speed to 25–30 % (=381–457 mm/s).

3.2.1 Carbonization using a laser. Figure 2 (a) shows a design example of a wall board that contains several touch switches and a slider. Once the user is satisfied with the design, it is exported to a laser cutter. Conventional laser engraving using a focused raster-scanning beam generates gaps between scan lines that impair the conductivity of the carbon. In contrast, using standard laser cutting with a focused vector-scanning beam, the wood is burned and cut entirely and does not generate a sufficient amount of carbon for use as circuit wiring. To produce a sufficient amount of carbon, moderate heat must be applied repeatedly. To provide sufficient heat, we use a defocusing technique that is similar to that used in a previous study [5] , namely, we move the cutting table down from the focal point (see Figure 2 (b)). We identified the most suitable distance as 5–6 mm below the focal point.

We also set the power parameter lower and the speed parameter higher than those that were used for standard cutting, and we repeatedly run the laser back and forth over the region instead. This generates a sufficient amount of carbon with high electric conductivity. In our setting, 8–15 times is suitable for the number of repeated laser runs. The laser parameters are determined based on the results of the technical evaluation that is described in Section 5.1.2.

3.2.2 Connecting the PCB. In the final step, we connect the microcontroller/PCB to the carbon circuit using common screws and nails. Laser drills a hole in the area set as the terminal in the design tool, and screws or nails are inserted into it. To increase the area of connection between the carbon area and the screw, washers and nuts are attached to the screw (see Figure 3). In the current setup, we use mainly M2 screws and nuts, along with washers with a diameter of 6 mm.

4 CIRCWOOD

This section describes several interaction capabilities of CircWood, including the connection to common woodworking components.

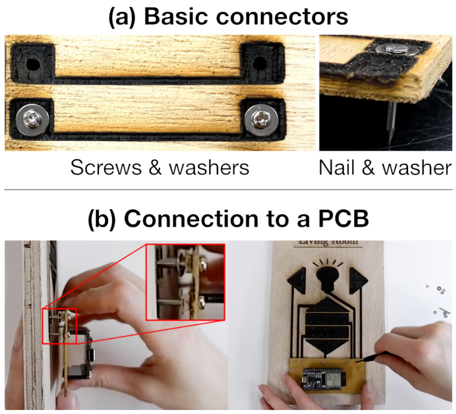

Figure 3: (a) Holes drilled by standard laser cutting and connection using screws and washers. Nails and washers can also be used. (b) The connection of a PCB with a microcontroller to a carbon path.

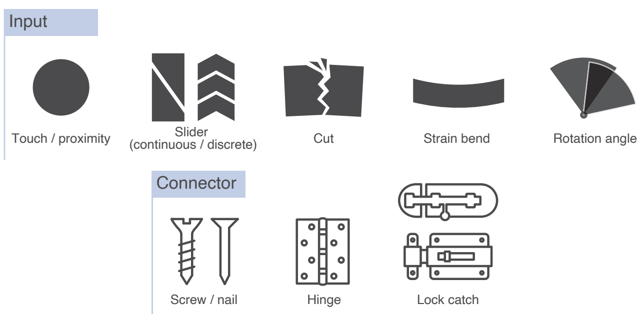

Figure 4: CircWood has various input elements (touch/proximity sensors, sliders, damage sensors, load/bend sensors, and rotation angle sensors) and connector elements (screws/nails, hinges, and lock/catchs).

4.1 Interactive Elements

Figure 4 shows various input and connector elements that are available to CircWood. In this section, we introduce several sensing functions.

4.1.1 Touch/proximity sensing and slider sensing. CircWood can realize touch sensing via the same mechanism as a conventional capacitive touch sensor. When the human body is close to an electrode that consists of carbon paths, the capacitance value changes and touch can be detected based on transient electrical characteristics. We used the Capacitive Sensing Library of Arduino for the prototype implementation.

4.1.2 Damage sensing. When exposed to high-impact forces, wooden boards will crack. This property can be used to detect damages such as breakage. When Vcc is divided by a series of a fixed resistor and a CircWood path and connecting the divided output to an Arduino digital input pin, the input pin will pull up (or down) when the resistance of the CircWood path becomes infinite due to cracks caused by damage. As a result, we can clearly detect the damage caused by breakage.

4.1.3 Load and bend sensing. When a wooden board is distorted, the electric resistance of the carbon path on the board increases or decreases. By preparing a voltage divider consisting of a series of a fixed resistor and a CircWood path, and connecting the divided output to an Arduino analog input pin, the distortion applied to the CircWood path can be detected. A carbon path that has been fabricated on a wooden board realizes load sensing without any additional strain gauges. For example, detecting a person who sits on a chair is possible by fabricating a carbon path behind the seating board of the chair. When a carbon path is fabricated behind a living hinge, the extent of the hinge bend can be determined by measuring the change in the electrical resistance.

4.1.4 Rotation and slide sensing. By fabricating carbon electrodes on two separate wooden boards and placing them together, the size of the overlapping area can be determined by measuring the capacitance value between the two electrodes. A rotation angle, for example, can be detected by connecting two wooden boards with a pivot mechanism such as a screw. A metal pivot part can be used to connect the two wooden parts electrically. A rotating dial made of wooden parts can be easily realized by using a laser cutter. The amount of slide is also detectable when carbon electrodes are fabricated on sliding wooden parts. For example, by fabricating carbon electrodes on the edge of a wooden sliding door or a window and its doorsill, a user's action of opening or closing the sliding furnishing can be detected.

4.2 Connectors

A variety of metal woodworking components commonly used in DIY projects, such as those shown in Figure 4, can be used as connectors for CircWood. As described in Section 3.2.2, screws, nails, and screw inserts can be used to connect an ordinary PCB to a carbon path. Two carbon paths on both sides of a CircWood board can be connected with screws and eyelets. Insulating stapler needles can be used as jumpers to get around other carbon paths. Hinges, locks, and catches can also be used to connect carbon paths on the two CircWood boards. Metal rollers on a sliding door and a metal rail on the doorsill can be used to connect CircWood boards on a door and its frame. Doorknobs, handles, and door knockers can be used to detect people who touch them.

5 TECHNICAL EVALUATION

5.1 Optimization for Design guidelines

To identify the optimal conditions for creating a carbon path by using a defocused vector-scanning laser beam, we investigated wood materials and the parameter settings of the laser cutter.

5.1.1 Materials. To identify suitable wood materials on which carbon paths can be created with sufficient low resistance to be used as electrical wiring, we tested various types of wood. We tested several types of lauan plywood and various solid woods (lauan, Japanese cypress, paulownia, Magnolia obovata, Japanese cedar, basswood, beech, oak, and walnut). We also examined the effect of coating the wood surface with a fire retardant that prevents

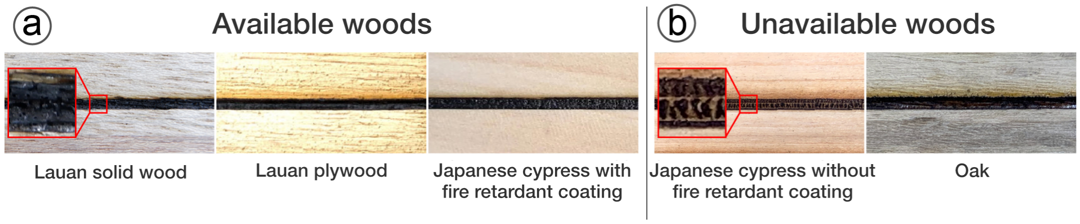

Figure 5: Carbon path examples on various types of wood. (a) Available woods. Lauan wood and Japanese cypress coated with the fire retardant coating could be used to create conductive carbon. (b) Unavailable woods. Since the charcoal grains are far apart and the path is not entirely black, there is no conductivity.

burning and generates carbon. Ingredients of the fire retardant are ammonium polyphosphate and ammonium sulfate. These are food additives and harmless both to the environment and to humans.

Lauan plywoods and solid woods are suitable materials for our method because the carbon paths formed on these materials have a high conductivity. We can create carbon paths with usable conductivity on Japanese cypress solid woods by coating them with a fire retardant. The use of a fire retardant also improves the conductivity of carbon paths on lauan solid wood. The application of a fire retardant to plywood, on the other hand, reduces the conductivity of carbon paths. We assume this is due to a reaction that is caused by the glue between the wood layers. As a result, the optimal materials are lauan solid woods coated by the fire retardant, followed by bare lauan plywoods and fire-retardant coated solid woods of Japanese cypress. Since these materials differ in texture and various other characteristics, we can select suitable materials for the project.

Figure 5 shows some examples of carbon paths that were produced on the tested wood surfaces. The conductive carbon paths are entirely black and filled with charcoal grains, as shown in Figure 5 (a). In contrast, the non-conductive paths are not as black, and there are spaces between the charcoal grains, as shown in Figure 5 (b). These non-conductive paths were either burned at high temperatures or were the result of failure to create carbon at low temperatures, which hindered the production of sufficient conductive carbon. Non-conductive carbon paths tend to be generated from hardwoods, such as beech, oak, and walnut, and very softwoods, such as cedar. In contrast, usable conductive carbon tends to be generated from woods of moderate hardness, such as lauan and Japanese cypress.

5.1.2 Laser parameters. We investigated the laser cutter's setting parameters for efficient carbon production using lauan plywood of 4 mm thickness. The thicknesses of the surface and the second layer of the plywood were approximately 0.5 mm and 3 mm, respectively. The laser-induced carbon was generated mainly on the surface and the second layer. This material generated the highest conductivity carbon among the tested lauan plywoods. No fire retardant was applied in this examination because it would impair the conductivity of the plywood, as discussed in the previous section. We used VD7050-60W (COMMAX Co., Ltd.) laser cutter as described in Section 3.2.

First, we investigated the optimal wooden board position and found that the resistance of the generated carbon path was lowest at a distance of 5 mm below the focal point. We also found that repeating the laser scan at high speed yielded better results than running the laser once at low speed. When the laser cutter was operated at a low speed, adjusting the laser power became difficult, namely, either higher power would burn the wood, or lower power would not generate any carbon. We confirmed the optimal number of scans by repeating the laser scans consecutively. The resistance continued to decrease until the fifteenth scan, but at the sixteenth scan, the carbon was burned off, and the resistance increased. By fixing the material position and the number of laser scans to the optimal conditions (5 mm below the focus and 15 scans), we investigated the generated carbon resistance by changing the laser power and the scan speed. We made four carbon paths for the same power/speed and measured the resistance of each of them. Table 2 shows the average resistance value for each power/speed setting value. Overall, the resistance was the lowest when the power was 50–70 % and the ratio of power to speed was 2:1. The lowest resistance we measured was 30 Ω/sq, which was realized when the power was 50 % (30 W), and the speed was 25 % (381 mm/s). We identified these setting values as the optimal parameters and used them when implementing the applications.

When the wood type was changed, the parameters also changed slightly. For the thicker lauan plywood with three 1 mm and two 3 mm thick sheets stacked alternately, and for lauan solid wood, the optimal parameters of power and speed were the same, but the optimal focal distance was 6 mm below the focal point. The lowest resistance value of the carbon on this type of lauan plywood panel was 75 Ω/sq. The resistance of the lauan solid wood was further reduced when a fire retardant was applied, with a minimum value of 25 Ω/sq. Japanese cypress coated with the fire retardant burned when the same parameters as for the lauan wood were used; hence, we further investigated the optimal parameters. The results demonstrate that the optimal focal distance was 5 mm below the focal point and that running the laser eight times at 30 % power (18 W) and 30 % speed (457 mm/s) was optimal. The lowest resistance value in this scenario was 76 Ω/sq. Based on the investigation above, Table 3 shows the final recommended settings of our process.

5.2 Effect of the grain direction

The previous experiments were conducted by producing carbon paths along the grain of the wood. In this experiment, we used thicker lauan plywood and fabricated a carbon path orthogonal to

Table 2. Average resistance value [Ω/sq] for each power/speed using lauan plywood with a surface thickness of 0.5 mm and an inner pile thickness of 3 mm. A blank field indicates that the value was over 500 [Ω/sq]. Numbers in parentheses indicate the standard deviation.

Speed (%) \ Power (%)	20	30	40	50	60	70	80
50				174 (47.8)			
45				100.4 (16.5)	123 (25.3)	83.3 (25.8)	272.3 (117.2)
40				**69.3 (11.7)**	94.7 (4.7)	**59 (15)**	149.7 (85.8)
35				**81 (18.7)**	**76.2 (5)**	**54.9 (10.7)**	371 (305)
30				**65.4 (46.3)**	**57.2 (17)**	120.9 (50.6)	
25				**53.4 (18.5)**	**67.4 (63.1)**		
20			129.3 (26.9)				
15			340 (34.1)				
10	265.5 (166.6)	423 (182.4)					

Table 3. The final recommended settings of our method. The resistance value is the lowest value that could be measured.

Type of wood	Fire retardant	Power [W]	Speed [mm/s]	Repeat	Defocus [mm]	Resistance [Ω/sq]
Lauan solid wood	Treated	30	381	15	6	25
Lauan plywoods	Not treated	30	381	15	5–6	30–75
Lauan solid woods	Not treated	30	381	15	6	65
Japanese cypress solid woods	Treated	18	457	8	5	76

the wood grain using the optimal parameters obtained in the previous section. The result showed a significant increase in resistance compared to the carbon made along the grain (27300 Ω/sq). This problem can be solved by arranging the carbon paths side by side to increase the area. We demonstrated that the carbon paths conduct when wide/multiple paths are produced, namely, the conductivity of three side-by-side paths is almost equivalent to the conductivity (105 Ω/sq) under the along-the-grain condition.

5.3 Resistance change over time

We investigated the resistance change of the carbon path that was fabricated using CircWood over time. The resistance change after coating with varnish was also investigated because we assumed that the varnish, which is frequently used to protect surfaces in woodworking DIY, would prevent the resistance of the carbon path from increasing. We used oil-based varnish spray. We created four carbon paths for each of the two conditions, varnished or unvarnished, on lauan plywood with a surface thickness of 0.5 mm and an inner pile thickness of 3 mm. Laser parameters used to create the carbon were optimal values described in Section 5.1.2. We then measured the resistance of each sample over six months.

Figure 6 shows the transition of the average resistance increase rate. After six months, the resistance of the unvarnished samples increased by 1.45 times, while the varnished samples increased by 1.3 times. Judging from the graph, the resistance value seems to be stable around after three months. Although the coating had no significant effect on the resistance value when the carbon paths were first created, the graph shows that varnish coating reduces the increase in resistance in the long term. Moreover, the coating is useful as it increases the physical strength of the circuit and prevents finger contamination by the carbonized touch sensor.

6 APPLICATIONS

We present a range of application examples to demonstrate the capabilities of CircWood. Following applications mainly target common DIY woodwork because we expect that our method will be used in personal fabrication projects.

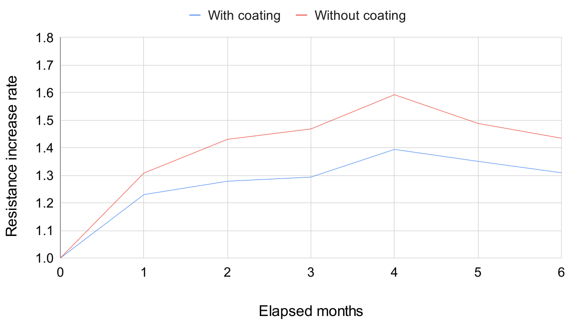

Figure 6: The transition in the average resistance increase rate over six months.

Figure 7: (a) A light control board. A user can control the light's color by touching the arrow-type slider. (b) An air conditioning control board. A user can control the temperature setting by touching the continuous slider.

6.1 Wall boards with touch switches

CircWood uses a vector-scanning laser beam, which is more suitable for creating a large-sized circuit quickly than a raster-scanning laser beam. Thus, it enables novel applications for smart homes, such as home electrical appliance control boards, as described in Section 3. Figure 7 shows two types of wall boards that we have implemented: one for controlling a room light (whole board size: 255 mm × 155 mm) and the other for controlling an air conditioner's temperature (whole board size: 167 mm × 103 mm). For each wall board, an Arduino computer PCB is fixed by screws, and which simultaneously connect the carbon path to the PCB. Using the room light control board, a user can turn an RGB lamp on/off with a bulb-shaped touch switch, change its color with an arrow-shaped touch switch, and control its brightness with an up-and-down slider. The air conditioning control board is equipped with a touch switch for powering on/off and an analog touch-type continuous slider for temperature control. In the future, we plan to apply this method to an entire wooden wall to explore a larger-scale interaction.

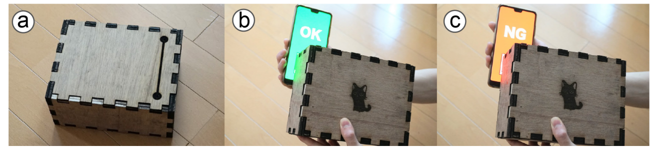

Figure 8: Shock detection box. (a) A CircWood path is installed at the bottom of the box. Carbon path breakage can be easily detected with a smartphone application. (b) Touch input through the carbon path is detected. (c) Since the path is broken, touch input is not detected.

6.2 Shock detection box

For logistics applications, wooden boxes are sometimes used. CircWood can provide a damage sensing function directly on a wooden box's surface to detect if the parcel has been carelessly handled. Figure 8 shows a wooden box with a carbon path on the backside. As in the Off-Line Sensing technique [27], we used the capacitive sensing of a smartphone touchscreen to detect the breakage of the path. When the path is not broken, touching one end of the carbon path with a finger and the other end with the touchscreen will generate a touch input on the touchscreen. This basic function can be applied to the surfaces of building materials and board ladders to detect deterioration by sensing cracks.

6.3 Interactive chair

Wooden chairs are common items in our lives, and some people even make their own using a DIY approach. Our technique enables installing of a load sensor on the seat surface or back of a wooden chair. Figure 9 (a) shows an interactive chair that prevents prolonged and static sitting, which negatively affects health. The chair has a load sensor on the back of the wooden board of the seat. When a user sits on this chair, the seat is distorted, and the resistance of the carbon path increases. By reading the change in resistance value, it is possible to detect whether the user is sitting or not. It promotes posture change (e.g., standing or half-sitting posture) by notifying the user via an application on a laptop PC when it detects prolonged sitting.

6.4 Sound volume controller

We implemented a dial-type controller using a rotation angle sensor that was fabricated using CircWood. Figure 9 (b) shows that two wooden boards with a semi-circular electrode were positioned opposite each other and screwed together to act as a parallel-plate capacitor. When a user rotates the plate, the overlapping area of the two electrodes changes, resulting in a change in capacitance. The volume of a smart speaker can be controlled by reading the continuous change in capacitance caused by the dial's rotation.

6.5 Connection to various woodworking components

As described in Section 4.2, CircWood can use various woodworking components as connectors to carbon paths. We implemented a wooden storage box using a magnetic catch, a hinge, and L-shaped

Figure 9: (a) Interactive chair. A CircWood path is installed on the back of the wooden board of the seat. The chair promotes posture change by notifying the user via an application on a laptop PC when it detects prolonged sitting. (b) Sound volume controller. A user can control the volume of the smart speaker by turning the wooden dial.

metal fittings as connectors (see Figure 10 (a)). These three components are attached to the joints in the box. Carbon paths on different board surfaces can be connected through these components to create a closed circuit. When the user opens this box, the magnetic catches are separated from each other, and they are electrically disconnected. We implemented an application that automatically turns on a LED installed in the box when the door is opened by detecting this electrical disconnection.

It is also possible to detect door opening using touch sensing with a metal doorknob (see Figure 10 (b)). Applying CircWood to a wooden door, it is possible to add a sensing function to the door directly and realize the natural touch interaction through the doorknob.

7 DISCUSSION AND LIMITATION

7.1 Fabrication Speed

Compared with the existing technique of creating graphene using a raster-scanning laser beam [5, 14], our method uses a vector-scanning laser beam, which allows us to create large carbon circuits in a short time. We calculated the time required to create an example circuit pattern of 100 mm square that contains wiring paths of 1,000 mm length in total. According to the process shown in the reports, the total length of raster scan lines of a laser beam to fabricate this circuit is 393,700 mm in [5][3] and 236,200 mm in [14][4].

In [5], the laser speed required to make the most conductive path was 150 mm/s, and the scan was repeated three times. Therefore, the time required to make the carbon circuit is 7,874 s $(393,700/150 \times 3)$. In [14], the laser speed required to make the most conductive path was 10 mm/s, and the scan was performed only one time. Therefore, the time required is 23,620 s $(236,200/10)$. In CircWood fabrication, the optimal speed of the vector scan shown in Section 5.1.2 is 381 mm/s, and the scan is repeated 15 times. The time required is 39.4 s $(1000/381 \times 15)$. Therefore, our method is two hundred and six hundred times faster than the raster scan method [5] and [14], respectively.

[3]Raster scan in 1000 DPI for 100 square mm.
[4]Raster scan in more than 600 dpi (reported as linewidth of 40 μm) for 100 square mm.

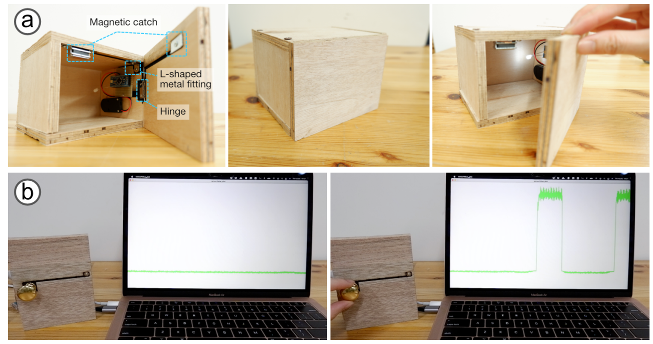

Figure 10: (a) A wooden storage box. We created a closed circuit of a carbon path on the box's inner surface using a magnetic catch, a hinge, and L-shaped metal fittings. The disconnection of the circuit can detect the opening of the door by a user, and the LED inside the box will light up. (b) A touch-sensing doorknob.

7.2 Scalability

The maximum size of the path depends on the processable size of the laser cutter. The laser cutter used in our experiments can process a panel up to 700 mm of aside. We were able to create a path of 700 mm and confirm that the path was indeed conducive. The width of a single carbon path was about 1.2 mm, and the minimum path spacing was about 0.5 mm (about 15 dpi). Therefore, we can create a circuit that exceeds these values, i.e., the smallest circuit size is considered to be about $3 \times 3\text{mm}^2$.

Most of the laser machines on the market are specialized for processing sizes of about one meter at most. However, laser processing itself has no innate size limitations. By using self-propelled portable laser processing machines, which have already been proposed, it may be possible to process large pieces of wood without worrying about the size of the machine. Then, sensors and conductive paths could be formed later on the floors, walls, and wooden houses columns. This could be used to determine the risk of damage to the building from earthquakes and continuous vibration.

When the carbon path was created on lauan wood after 15 laser vector-scanning, the depth of the groove in the path was about 1 mm. Therefore, a minimum thickness of lauan to which CircWood can be applied will be more than 1 mm. As for Japanese cypress solid wood with fire retardant, the carbonized part was not cut. The use of this type of wood will allow CircWood to be applied to thinner wood.

7.3 Conductivity

The resistance of the CircWood path is affected by various conditions of the wood board, such as warpage, cracks, and internal composition. However, we found that fire retardants (except for lauan plywood) and the creation of carbon paths that follow the wood grain effectively improve conductivity and reduce resistance variation. Furthermore, using an assist gas to cut off oxygen during laser processing, it is possible to produce a stable graphene structure with high conductivity [39]. Although it is difficult to implement applications sensitive to power consumption and voltage effects with the CircWood technique, we believe that by decreasing the resistance value, it is possible to realize applications other than touch sensors that require a large current flow.

7.4 Durability

We verified that the touch switch made of CircWood still worked after applying a force of about 0.05 [N] more than 100 times in a row. Furthermore, the load sensor continued to function even after applying a force of approximately 431 [N] more than 100 times in a row. As discussed in Section 5.3, given that resistance varies slightly over time, it is preferable to detect touch or load by properly calibrating the difference in sensing value over a short period. As shown in Figure 6, the increase in resistance seems to hit the ceiling around 1.6 times after four months, and we believe that we can use circuits with tolerance for 50% resistance changes for a year or two. In addition, the figure shows that varnishing reduces the long-term increase in resistance. Therefore, to fabricate wooden circuits for long-term use, it is desirable to make carbon paths with optimal laser parameters and then coat them with varnish. We also confirmed that all the applications except for the shock detection box are still working as they were when created, even after about seven months have passed. Although there was a decrease in conductance in the range described above, no disconnection was observed.

8 CONCLUSION

In this paper, we proposed CircWood, a method for fabricating circuits with carbon on wood surfaces using a defocused vector-scanning CW laser beam, which is applicable to DIY woodwork projects. We presented a software design tool that supports the creation and fabrication of carbon paths. We presented the design guidelines of CircWood by identifying the optimal conditions for preparing a circuit using carbon. Using CircWood technology, we contributed to various applications in which interactive elements were integrated onto various wooden surfaces in living spaces. As future work, we plan to check the reliability of circuits created by CircWood through a daily use setting. We believe CircWood will open up the possibility of natural interaction in scenarios that are more similar to our daily lives because it integrates sensors and wiring patterns into objects while preserving the warmth of wood.

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