4D printing of wooden actuators: encoding FDM wooden filaments for architectural responsive skins

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Abstract

Purpose – Conventional motion mechanisms in adaptive skins require rigid kinematic mechanical systems that require sensors and actuation devices, hence impeding the adoption of zero-energy buildings. This paper aims to exploit wooden responsive actuators as a passive approach for adaptive facades with dynamic shading configurations. Wooden passive actuators are introduced as a passive responsive mechanism with zero-energy consumption.

Design/methodology/approach – The study encodes the embedded hygroscopic parameters of wood through 4D printing of wooden composites as a responsive wooden actuator. Several physical experiments focus on controlling the printed hygroscopic parameters based on the effect of 3D printing grain patterns and infill height on the wooden angle of curvature when exposed to variation in humidity. The printed hygroscopic parameters are applied on two types of wooden actuators with difference in the saturation percentage of wood in the wooden filaments specifically 20% and 40% for more control on the angle of curvature and response behavior.

Findings – The study presents the ability to print wooden grain patterns that result in single and double curved surfaces. Also, printing actuators with variation in infill height control each part of wooden actuator to response separately in a controlled passive behavior. The results show a passive programmed self-actuated mechanism that can enhance responsive façade design with zero-energy consumption through utilizing both material science and additive manufacturing mechanisms.

Originality/value – The study presents a set of controlled printed hygroscopic parameters that stretch the limits in controlling the response of printed wood to humidity instead of the typical natural properties of wood.

Keywords Hygroscopic properties of wood, Passive actuation, Adaptive facades, Programmable materials, 4D wood printing, Fused deposition modeling (FDM)

Paper type Research paper

1. Introduction: wood as a programmable material

Programmable materials are specifically fabricated materials that respond to external stimuli. Hygroscopic properties of wood have been studied as a programmable material that responds passively to changes in humidity levels to encompass complex programmed motion responses according to its embedded and controlled parameters (Reichert et al., 2015a; Rüggeberg and Burgert, 2015; El-Dabaa et al., 2020a; El-Dabaa and Abdelmohsen, 2020). Numerous studies

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tested the ability of wood to be encoded as a passive programmed material that responds to humidity levels (Abdelmohsen et al., 2019a, b; Vazquez et al., 2019; Reichert et al., 2015a).

Several studies have explored the effect of hygroscopic parameters of wood on its motion response and the ability to encode wood motion response in the form of single or double curved surfaces according to hygroscopic parameters (Abdelmohsen et al., 2019a; Holstov et al., 2015, 2017). Hygroscopic parameters have been divided into two types: embedded and controlled design parameters (El-Dabaa et al., 2020a). Embedded parameters are mainly parameters related to the inherent material properties such as the type of wood, grain orientation, thickness and dimensional ratio of a given sample, while controlled parameters are related to human interference on those embedded parameters such as the fixation position of a sample or isolating specific segments of the sample (El-Dabaa et al., 2020b).

Researchers revealed that several aspects increase the angle of deflection and speed as a tangential cut of wood with grain orientation parallel to the short side of the sample, dimensional ratio of the samples (Abdelmohsen et al., 2019b) and type of wood as hardwood has faster response and more deflection value than softwood (Abdelmohsen et al., 2019c). In addition, results show that the thicker the wood is, the least deflection value and speed response it achieved (El-Dabaa et al., 2020b). However, merging several hygroscopic parameters of wood allows for controlling the wood morphology response behavior (Abdelmohsen et al., 2019c).

It was shown that one of the most effective parameters in designing for changes in wood morphology is grain orientation, which is the direction of wood fibers along the long axis. The ability of wood to absorb and retain moisture content is mostly related to grain orientation (Abdelmohsen et al., 2019a). Plate 1 shows the difference in response behavior of wood in relation to grain orientation.

Two main approaches were used when utilizing hygroscopic parameters in architectural design: adaptive pavilions or façade design with the ability to program various motion response morphologies. The application of hygroscopic properties of wood on a large architectural scale was enabled due to the integration of material testing and simulation into the design process. Series of experiments were done to fabricate the hygromorphic skin and to adjust the speed response and the aperture opening percentage in relation to the change in humidity levels (Menges and Reichert, 2012). Two full-scale architectural prototypes were developed by a team at the Institute for Computational Design at the University of Stuttgart: HygroSkin and HygroScope. Both were done after years of research in the programmable materials and the ability to control wood response through controlling its anisotropic and hygroscopic properties of wood. The pavilions fabrication stages depend on the material embedded response, together with computational design and robotic assembly. They are programmed in an opposite behavior to their response to humidity change. The HygroScope is configured to open when humidity level increases, and the HygroSkin closes at this level of humidity (Reichert et al., 2015b).

International workshop between American University in Cairo, Princeton University and University of Rome was held to design responsive architectural facades prototypes using the

Plate 1.
The response of beech veneer samples with different grain orientations to increase in humidity (from left to right: 90° grain orientation, 45° grain orientation and 0° grain orientation)

Source(s): (Abdelmohsen et al., 2019)
hygroscopic properties of natural wood. The prototype designs vary between shading devices and responsive hinges that move lightweight louvers as shown in Plate 2. Several hygroscopic parameters, such as difference in moisture content during the lamination phase of wooden samples, differences in thickness and percentage of laminated area to program the morphology of a precurved façade vertical panels with different angle of curvature to flatten when humidity increases, were studied. The output prototypes illustrated the ability to program specific wooden motion response in response to humidity levels, according to the hygroscopic design parameters in the fabrication phase in the wooden composite fabrication phase. Combining different hygroscopic design parameters was used to encode various types of shape-shifting mechanisms with different types of motion including responsive faces, hinges and louvers (Abdelmohsen et al., 2019a, b).

There still exists a lack of customized geometric configurations and double curved surfaces due to the nature of wood. Typically, 3D printing is used for static fabrication rather than interactive design. Printable fabrication techniques rely on printing several parts that are connected and used as a base for programmable skins (Raviv et al., 2015). Utilizing additive manufacturing in the process of 4D printing hygroscopic programmable materials has been studied as an approach to encode passive motion responses (Tibbits et al., 2014; Wood et al., 2016). Controlling specific parts of wood to actuate can be made by laminating specific parts of the wooden sample. Self-Assembly Lab at MIT dedicated its research on the multimaterial programmability and its reaction when bring submerged under water through accurate control of its geometric transformation. Experiments were done using multimaterial with printed nylon and wood layers together, under water in a submersion state with temperature 70°C. Parameters such as the control of the folding angle and percentage of reversibility were tested (Correa et al., 2015).

This paper introduces a passive programmed self-actuated mechanism that can enhance responsive façade design with zero-energy consumption through utilizing both material...
We explore the ability of 4D printing hygroscopic hinges and joint actuator prototypes as an embedded actuator that responds passively to humidity levels. The study focuses on using wooden filaments (PLA) without being merged with other multimaterial in the printing process as an additive manufacturing mechanism that can be utilized in adaptive facades. The idea of testing small wooden prototypes can be utilized as adaptive hinges that respond to humidity levels. It emphasizes on studying the parameters of printing hygroscopic hinges as part of a programmable façade. Geometric patterns and infill properties are illustrated as additive hygroscopic parameters. The bending motion response is evaluated through measuring the variation of wooden angles of curvature when exposed to the same humidity levels. Average measurements of the angles of curvature are taken using the “Kinovea” image analysis software. These adaptive hinges widen the research to encompass in future results testing effect of lightweight materials on the response of these hinges.

2. Encoding printed wood motion response

2.1 Materials and method

The process of experimenting with 4D printing was divided into three phases as shown in Figure 1.

2.1.1 4D printing parameters. 4D printing is a process where we integrate the use of 3D printing technology to build an object that has the ability to change its shape or properties over time. The reaction can occur due to variation in temperature, humidity or even electric current. The 4D printing phase includes the material-tested parameters and printing setup. Wooden filaments with fused deposition modeling (FDM) were used for the purpose of the conducted experiments, with 80% PLA and 20% bamboo wood powder fill and 60% PLA and 40% bamboo wood powder fill. PLA stands for polylactic acid, and it is a plastic made from natural materials such as corn starch. The programmable wooden actuators were printed using an FDM printer, as shown in Plate 3, and Cura 4.8 software with filament diameter 1.75 mm and nozzle size 0.4 mm.

Wood filament is a composite material manufactured from both plastic polymer and wood sawdust; the mixture ratio varies from 80% plastic to 20% wood sawdust or up to 60% plastic to 40% wood sawdust. The plastic polymer is usually PLA plastic, but wood sawdust varies per manufacturer. The printing parameters are shown in Table 1.

2.1.2 Physical experimental setup. Physical experimental phase: The tested samples were fixed vertically with clamps to avoid friction with the surface. Increase in humidity was
applied by means of spraying water on a single side of the printed samples. Digital camera is fixed on a tripod to record the motion response of the printed wooden samples. The relative humidity of the surrounding area ranges between 56 and 59%. Three identical samples are used in each experiment, and the average of reading is taken. Series of experiments were conducted to measure the effect of 3D-printed hygroscopic parameters on the angle of curvature of the wooden-printed actuator.

As a base case, and to establish a reference to the study of 4D printing wood, we conducted a series of experiments on natural wood samples to identify the typical responses for different basic grain orientations. The dimensional ratio of the tested samples was 1:3 (4 × 12 cm.) with a thickness of 0.3 mm. The ratio of width to length of wooden samples is called dimensional ratio. Studies show that dimensional ratio of wooden samples affects the angle of deflection of the samples. Longer samples tend to have higher deflection value and response speed. In this paper, 1:3 dimensional ratio was used as a base for the experiments, as it was demonstrated in earlier studies that it exhibits fairly higher deflection with angle of curvature 36° than ratio 1:2 with 28° and 1:1 sample ratio with 20° (Abdelmohsen et al., 2019b), while samples with more than 1:4 ratio with 0.3 mm are fragile.

2.1.3 Image analysis evaluation. Kinovea, a validated image analysis software, is used to measure the angle of curvature for each 4D-printed wooden sample. Three markers are aligned on the side of the samples to facilitate tracking process. The measured angle of curvature lies between the two endpoints and the midpoint of the sample, as shown in Figure 2. The angle of curvature was measured as the maximum deflection value for each experiment. However, the highest deflection value tends to show lowest angle of curvature.

<table>
<thead>
<tr>
<th>Printing parameters</th>
<th>4D printing of wooden actuators</th>
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<tr>
<td>Printing parameters</td>
<td></td>
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<tr>
<td>Material</td>
<td>Wood PLA</td>
</tr>
<tr>
<td>Filament diameter</td>
<td>1.75 mm</td>
</tr>
<tr>
<td>Slicing software</td>
<td>Cura 4.8</td>
</tr>
<tr>
<td>Extruder temperature (°C)</td>
<td>220 (°C)</td>
</tr>
<tr>
<td>Build plate temperature (°C)</td>
<td>55 (°C)</td>
</tr>
<tr>
<td>Nozzle size</td>
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<tr>
<td>Layer thickness</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Printing speed</td>
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</tr>
<tr>
<td>Printer used</td>
<td>FDM printer</td>
</tr>
<tr>
<td>Extrusion multiplier</td>
<td>100%</td>
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</table>

Table 1. Extrusion and printing parameters

Plate 3. Printing setup and process of the wooden samples
2.2 Natural wood and 4D-printed wood

In terms of single layer thickness, the 0.3 mm thickness was chosen as a threshold for 4D printing, the thinnest possible layer with the highest anticipated deflection. Thicknesses below 0.3 mm were shown to break upon printing. For beech veneer samples with a tangential cut, and upon increase in humidity, the results demonstrated that the highest bending or deflection value and fastest response take place with the 0° grain orientation, with an average angle of curvature of 36° (fibers parallel to the long axis), while the least deflection value with the slowest response takes place with the 90° grain orientation (fibers perpendicular to long axis), as illustrated in Table 2.

We then explored the ability to encode the embedded parameters through the process of 4D printing of wooden responsive actuators. 4D printing is used to encode wood embedded parameters, specifically focusing on wood grain orientation. The printing process controls grain orientation to produce a variety of motion types with single and double curved surfaces when exposed to differences in humidity levels, as shown in Figure 3.

As a pilot study, we compared the deflection of natural wood (beech veneer) to that of a 3D-printed wood sample with the same orientation and dimensional ratio with the different concentration of wood in tested filament. Figure 4 shows a comparison between the angle of curvature achieved from natural beech wood and 3D-printed wood (20% wood filament with 80% plastic filament and 40% wood filament with 60% plastic filament) with 0° grain orientation. The natural wood angle of curvature was shown to be 36° on average, while the angle of curvature of the 3D-printed wood sample with 20% wood shows 167° on average, and the 3D-printed wood sample with the 40% wood shows average of 147°, indicating a higher deflection in natural wood samples followed by the higher percentage of wood in wooden filaments.

2.3 Controlled printed hygroscopic parameters

The study proposes a 4D-printed hygroscopic joint prototype that is used as a passive actuated skin upon variation in humidity levels. The wooden joints studied in this paper are

<table>
<thead>
<tr>
<th>Grain orientation</th>
<th>90°</th>
<th>45°</th>
<th>0°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection value</td>
<td>Lowest</td>
<td>Medium</td>
<td>Highest</td>
</tr>
<tr>
<td>Response speed</td>
<td>Slowest</td>
<td>Fast</td>
<td>Fast</td>
</tr>
<tr>
<td>Type of motion</td>
<td>Bending along the long axis of sample</td>
<td>Twisting along the diagonal axis of sample</td>
<td>Bending along the short axis of sample</td>
</tr>
</tbody>
</table>

Figure 2. Image analysis measurement method used in the Kinovea image analysis software

Table 2. Grain orientation effect on deflection value, type of motion and response speed in beech veneer samples

Source(s): (El-Dabaa et al., 2020a)
used as a responsive actuation system with hinged motion mechanism that immediately respond to variation in humidity levels and temperature with zero energy consumption. We tested several printed hygroscopic parameters that were seen to manipulate the response behavior of the printed wooden samples in a controlled manner. Three parameters were tested against the wooden angle of curvature: fill saturation percentage of wooden filament, grain orientation and infill printing height.

The samples were marked from the midpoint and endpoint to facilitate tracking of the sample in the “Kinovea” image analysis software, a validated motion-tracking method (Puig-Divi et al., 2017; Abdelmohsen et al., 2018). The results were then exported and analyzed in Microsoft Excel. The average angle of curvature for each grain orientation was recorded. Humidity was applied on a single side of the sample. Lamination was not applied and is out of the scope of this paper. The two sections below describe two newly introduced parameters that were seen to affect the deflection of the 4D-printed samples: (1) grain patterns and (2) infill height.

Figure 3. The effect of printed wood grain on its motion response when exposed to differences in humidity levels

Figure 4. Comparing average angle of curvature between (1) beech natural wood, (2) 3D-printed wood (20% wood and 80% plastic) and (3) 3D-printed wood (40% wood and 60% plastic)
2.3.1 3D-printed grain patterns. In this experiment, the angle of curvature was tested on three wooden samples with different grain orientations when exposed to increase in humidity. The tested grain orientations varied in the patterns of the linear grains as follows: (1) parallel lines with 0° grain orientation, (2) zigzag straight lines and (3) concentric straight lines as shown in Plate 4. These patterns were selected based on several trials with different configurations and with the most significant response within linear printing.

The printed wood results show that wooden filament with 40% wood had larger deflection than the 20% wooden filament as shown in Table 3.

Experiments revealed that the parallel grains with 0° had the highest angle of curvature with angle 141° in 40% wooden filaments and 167° in 20% wooden filaments, followed by the zigzag straight lines with angle 146° in 40% wooden filaments and 171° in 20% wooden filaments, while the concentric straight line pattern had a double curved surface with the least angle of curvature 178° in 40% wooden filaments and 177° in 20% wooden from the long side as shown in Figure 5.

<table>
<thead>
<tr>
<th></th>
<th>0° parallel grains</th>
<th>Zigzagged straight lines</th>
<th>Concentric straight lines</th>
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<tr>
<td>40% wooden filament</td>
<td>141°</td>
<td>146°</td>
<td>178°</td>
</tr>
<tr>
<td>20% wooden filament</td>
<td>167°</td>
<td>171°</td>
<td>177°</td>
</tr>
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Plate 4.
Printed grain orientation close-up: (1) parallel 0°, (2) zigzagged straight lines and (3) concentric straight lines

Table 3.
Effect of printed grain orientations on the angle of curvature on different wooden saturation filaments when exposed to increase in humidity
Figure 5. Effect of printed grain orientations on the angle of curvature on different wooden saturation filaments when exposed to increase in humidity: (1) parallel lines 0°, (2) zigzagged straight lines and (3) concentric straight lines.
Experiments tend to take 6–8 min to reach the highest deflection point, and then it returns back to its flat original state. The results of the first sample (0° grain orientation) were shown to match the behavior of natural wood samples as the highest deflection grain pattern, only with lower deflection value than natural wood. The patterns and configurations in the other tested samples, however, do not exist in natural wood and are not comparable. Hence, the 4D-printed wood was observed to allow for developing new wooden prototypes that achieve novel controllable motion morphologies.

2.3.2 Infill height. With natural wood, sample thickness is typically shown to affect motion response. Previous studies show that thicker wooden samples demonstrate lower angles of curvature with slow speed rate of response (Abdelmohsen et al., 2019b; El-Dabaa et al., 2020a). Natural wood, however, has a uniform thickness for the whole sample and is not a parameter that can be controlled or regulated. Controlling specific segments in natural wood samples requires isolating specific parts of the sample or laminating different segments with specific percentages (El-Dabaa et al., 2020b).

Another parameter that was deduced upon experimenting with 4D printing was the infill height of the printed material. In 4D printing, it is possible to have different thicknesses within the same sample. This gives the same effect as varying sample’s thickness and the isolation of specific sample segments. 4D printing settings can be controlled to have a gradient or different thickness within the same printed wooden sample. In this experiment, the control of specific parts of the wood was tested through controlling the difference in the thicknesses in one sample.

Encoding different thicknesses in one single wooden sample was applied by controlling the infill height in the 3D printing process. The typical height of the infill used was 0.3 and 0.6 mm. An experiment was set to compare the difference of 40% printed wood response with different infill height of 0.3 and 0.6 mm. The experiment revealed that the 0.3 mm infill height has higher deflection value with angle of curvature 145°, while the 0.6 mm infill height has 168° angle of curvature as shown in Figure 6. This matches the response of natural wood with different thickness; previous experiments show that decreasing the thickness of wood samples increases its deflection value.

Based on the difference in printed wooden behavior due to infill height parameters, three infill configurations were tested to achieve different motion morphologies. The difference in

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**Figure 6.**
Effect of infill height of 4D-printed wood with 40% wooden filament: (1) 0.3 mm and (2) 0.6 mm
the infill height is studied on two wooden filaments with (1) 20% wood and 80% plastic, (2) 40% wood and 60% plastic, as shown in Figure 7. The angle of curvature was evaluated for each infill height configuration.

The first sample (a) was divided into two equal parts with 0.3 and 0.6 mm each. This resulted in a motion of the 0.3 mm segment of the sample as the main hinge in the wooden sample. The second sample (b) was composed of two-thirds 0.3 mm thick at the two ends of the sample with a 0.6 mm third in the middle of the sample. This resulted in a curvature at the two ends only, while the middle segment exhibited a very slight deflection and was almost flat. The third sample (c) had an infill height of 0.3 mm in the middle third and two-thirds of infill height 0.6 mm at the two ends. Higher deflection was observed in the middle segment, while the two ends exhibited slight deflection and almost flat.

These experiments show that the segments of the wooden sample with 0.3 mm infill height exhibited higher deflection values than the 0.6 mm infill height segments. In addition, the angle of curvature is related to the percentage of wood opposed to the PLA in the printing filament. The deflection value increases with less infill height and higher percentage of wood in the wooden filaments. This resembles the thickness of wood in the natural hygroscopic embedded parameters. The value of adding the infill parameters lies in having thickness variation in the same wooden sample.

The results demonstrate an added value to hygroscopic controlled parameters, leading to a wider variety of anticipated motion morphologies and grammars. It also demonstrates the capacity of 4D-printed samples to control motion in specific segments of the printed wooden sample.
sample as a responsive hinge. This opens the door to print several configurations using the infill height, resulting in controlled printed hinge responses.

3. Discussion and conclusion

Architectural adaptive facades typically involve mechanical systems with sensors and actuators of high-energy demand for their operation. Fox and Kemp led the “End of Mechanism” paradigm that replaces the mechanical with passive systems (Fox, 2016). Hingeless adaptive systems have been recently introduced based on biological systems by controlling their passive motion response. Programmable and smart materials have also been developed as passive systems that respond to external stimuli such as temperature or humidity (Kretzer, 2017).

This paper utilized the concept of 4D-printed wooden actuators in adaptive facades as passive responsive actuators that respond to variation in humidity levels. Humidity tends to vary from day and night and through seasons, this is utilized as an asset to develop the 4D-printed wooden actuators as zero-energy consumption motion mechanism. The actuators can handle lightweight shading devices. The number of printed wooden actuators on a façade is calculated according to the weight of the shading device.

The contribution of this research lies in introducing additional controlled parameters to the set of conventionally established hygroscopic parameters, resulting in the definition of additional motion response morphologies and grammars. Previously established hygroscopic parameters in natural wood typically involve embedded parameters (such as grain orientation, type of wood, dimensional ratio, thickness and lamination) and controlled parameters (such as fixation type and position, and isolation type and position). The added value of introducing such parameters in the FDM 4D printing process lies in introducing additional controlled parameters that can emulate natural wood response by understanding deflection and motion response speed with a higher level of precision, durability and reversibility, therefore mitigating aspects of fatigue and material deterioration in natural settings and conditions. The advantage of using 4D printing is achieving an accurate programed motion mechanism, as the microstructure of natural wooden samples varies throughout the same sample. This tends to have different variation in the response behavior of the samples.

Accordingly, the printing parameters of wooden samples demonstrate the ability to control their passive motion more than natural wood hygroscopic properties, with a higher capacity to instill specific patterns and configurations that are customized in terms of both thickness and location on the sample.

The focus in this paper mostly involved emulating the thickness and grain orientation embedded parameters and the isolation-controlled parameters, in addition to introducing new hygroscopic printable parameters such as controlled grain pattern with specific thickness, while the percentage of wood in the wooden filament resembles the difference in the types of wood in holding moisture through its pores. Wood response to humidity differs according to its embedded biological and mechanical properties that are related to its type either soft or hardwood. This is manifested in the hygroscopic printed parameters in the percentage of wood in the printing filament. The newly introduced artificial printed hygroscopic parameters include printed grain patterns and infill height, in addition to the percentage of wood in the printing filament opposed to the plastic percentage. Comparing the natural embedded hygroscopic parameters in the previous studies to the results of the 4D-printed parameters in this study, it was shown that hygroscopic parameters of wood are almost the same; for example, infill printing height in 4D-printed wood remaps the thickness parameter in natural wood, and the saturation fill of the wooden filament has the same effect as the variation in natural wooden types.
Merging the percentage of wood in the filament and the infill height in the same sample encodes specific parts of the wooden actuators to move in programmed morphology. This was typically done in natural wood through lamination process and merging several hygroscopic parameters as isolation of specific parts of wood or using different wood thicknesses (El-Dabaa et al., 2020b).

Printing the grain orientations and patterns highlights the ability to control and encode wood motion response morphology. Although the straight $0^\circ$ grain orientation has the highest deflection value as in natural wood, the ability to print the grain pattern and respond to humidity opens the gate to encoding wood motion. Double curved surfaces can be achieved according to the angle of the printed grain orientation. Having different grain orientations in the same wooden sample is not available in natural wood. Several configurations still can be studied according to a computational shape-shifting grammar to encompass the effect of these parameters on the passive response behavior of wooden actuators.

Further investigations require testing with filaments of higher percentage of wood than plastic to simulate the natural wood angle of curvature when exposed to increases in humidity levels. This is expected to affect the significance of the deflection values and perhaps the response speed of the printed sample. Future testing will include an emulation of more controlled and embedded parameters such as dimensional ratio, lamination and fixation. With further testing, future work will implement the deduced 4D printing parameters as responsive hinges in adaptive façades, shading devices and responsive structures.

A clear limitation is the limited deflection value when compared to natural wood angles of curvature and response speed. Limitation lies in the availability of wooden filaments with high percentage of wood in the sample either (20% wood as opposed to 80% plastic) or (40% wood as opposed to 60% plastic). Arriving at thicknesses equivalent to natural wood veneer where higher deflection values are anticipated is currently not possible, where samples with less than 0.3 mm are fragile and are not printed successfully. However, the use of 4D-printed hinges as a passive responsive hinged system can be strategically located in adaptive façade systems that actuate lightweight materials. The programmability of wooden actuators is shown to be encoded during the 4D printing process according to revealed 4D printed hygroscopic parameters.

References


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