A Computational Method for Tracking the Hygroscopic Motion of Wood to develop Adaptive Architectural Skins

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Low-cost programmable materials such as wood have been utilized to replace mechanical actuators of adaptive architectural skins. Although research investigated ways to understand the hygroscopic response of wood to variations in humidity levels, there are still no clear methods developed to track and analyze such response. This paper introduces a computational method to analyze, track and store the hygroscopic response of wood through image analysis and continuous tracking of angular measurements in relation to time. This is done through a computational closed loop that links the smart material interface (SMI) representing hygroscopic response with a digital and tangible interface comprising a Flex sensor, Arduino kit, and FireFly plugin. Results show no significant difference between the proposed sensing mechanism and conventional image analysis tracking systems. Using the described method, acquiring real-time data can be utilized to develop learning mechanisms and predict the controlled motion of programmable material for adaptive architectural skins.

Keywords: *Hygroscopic properties of wood, Adaptive architecture, Programmable materials, Real-time tracking*

INTRODUCTION

The development of adaptive and kinetic systems in building facades has typically relied on rigid and complex mechanical systems (Fox, 2016). Current research efforts are in support of alternative passive solutions that substitute mechanical actuators and rigid systems, calling for a paradigm shift in the development of adaptive architectural skins and kinetic structures. As described by Fox, the "End of Mechanisms" paradigm advocates for the use of solutions including smart materials which were introduced due to their ability to passively mimic natural systems. A significant challenge however in working with passive solutions, natural actuators, and smart or programmable materials is achieving a high degree of precision and control over the behavior of those materials to obtain a desired type and magnitude of motion, especially when the required objective involves regulating building façades that respond to specific and quantifiable factors related to daylighting, shading, solar exposure, ventilation, or the like.

Several research efforts have been done to define and analyze the behavior of smart or programmable materials, and their utilization in developing adaptive architectural skins. Programmable materials are generally known by their embedded system properties, through their ability to sense, compute and actuate with a continuous and reversible motion (Knaian, 2008). As stated by Kretzer (2017), evaluating the response of smart materials relies on studying the relation between the value of transformation and the duration needed to complete a full cycle of transformation. According to Lefebvre et al. (2015), materials that have the ability to change their properties as a response to external stimuli are known as stimuli-responsive materials (SRMs), while those materials that respond for a limited number of cycles are known as functional or semi materials. Addington & Schodek (2005) used five main characteristics to differentiate between smart and traditional materials, including transition, selectivity, immediacy, self-actuation and directness. In addition to their unique ability to change in proportion and size, response to external stimuli with reversible, continuous and bi-directional response and change has been demonstrated as a significant feature (Ritter, 2007).

Iyer & Haddad (1994) analyze the behavior of smart materials as a dynamic system that encompasses sensors to sense external stimuli, a communication network, or memory function, that is responsible for connecting signals from sensors to a processor, which resembles decision making devices, and finally the actuator function which is represented as a transformational output that is inherent in the material itself. Smart materials have been shown to function in architectural building envelopes through their sensing and actuation properties, for example using shape memory alloys or electro-restrictive materials to regulate solar exposure or radiation (Addington & Schodek, 2005). These features related to memory and the formal capture of the material have been demonstrated mostly in alloys and similar materials that exhibit a certain response to electricity, heat or other factors.

With a natural material such as wood however, and particularly with respect to the hygroscopic response of wood to different variations in humidity levels, this has not been sufficiently exploited. It is the aim of this paper to develop a method to track and analyze such response in real time, with the future objective of utilizing such data to develop learning mechanisms and prediction models pertaining to the controlled and regulated motion of programmable materials for adaptive architectural skins.

RELEVANT WORK

Recent research efforts related to the programming of hygroscopic properties of wood encompasses three aspects: (1) controlling and programming the hygroscopic behavior of wood, (2) architectural applications of the hygroscopic behavior of wood, and (3) methods used to track, analyze and evaluate the motion of the material.

Controlling and Programming the Hygroscopic Behavior of Wood

Wood has been studied as a programmable material due to its hygroscopic properties; that is, it has the capacity to change in size in response to changes in moisture content (Correa et al., 2015). Several studies have been conducted regarding the hygroscopic behavior of wood and the hygromorphing properties that allow for developing kinetic and adaptive structures, especially efforts done at the Institute for Computational Design (ICD) at the University of Stuttgart, and the Self-Assembly Lab (SAL) at MIT. Other efforts used synthetic composites inspired by the hygroscopic behavior of wood to self-shape into programmed configurations based on external stimuli (Erb et al., 2013).

Several hygroscopic design parameters are responsible for controlling the response of wood to differences in humidity levels such as the type of wood, grain orientation of wood fibers, material thickness, dimensional proportions, and the type and nature of lamination (single, double or multiple cross lamination). Reichert et al. (2015) described the factors affecting the response to wood to humidity to be grain orientation, shape, and dimensional proportions of its samples. Holstov et al. (2016) further investigated and tested four types of wooden composite material fabrication techniques in relation to the speed response of wood and the magnitude of sample deflection. These were gluing, mechanical fixing, spot gluing and direct lamination.

Architectural Applications

The architectural applications of the hygroscopic behavior of wood can be classified into two groups of applications; responsive and kinetic building façade skins, and architectural pavilions that respond to differences in humidity levels. The primary objective in most examples relies on achieving a specific type of passive motion that is triggered by variations in humidity levels. Menges & Reichert (2012) used material behavior testing to fabricate 'Hygromorphic Skin', a large-scale responsive façade. Studies were conducted to control different variations in aperture openings and the response time of wood in relation to variations in humidity.

The Institute for Computational Design (ICD) at the University of Stuttgart studied and documented the behavior of wood in response to humidity and fabricated the 'Hygroskin' and 'HygroScope' large-scale architectural prototypes (Reichert et al., 2015). The two models were programmed in an opposite condition in their response to humidity. 'Hygroskin' is a pavilion that opens upon increase in levels of humidity, while 'Hygroscope' closes upon increase in levels of humidity. The 'Hygroscope - Meteorosensitive Morphology' pavilion exhibited in the Centre Pompidou utilized the dimensional variations of wood to construct a climate responsive architectural morphology, where the pavilion opens and closes in response to climatic changes while being suspended in a humidity controlled glass case.

Methods used to Track and Evaluate Material Motion

Tracking the hygroscopic motion in materials such as wood has been studied widely. Bridgens et al. (2017) proposed a monitoring and tracking method for laminated wood samples in an outdoor condition through a one-year experiment, using a weather sealed GoPro camera, weather station and transparent curvature charts. The parameters under study were material degradation, mechanical decomposition and color change, conducted in weekly and monthly assessments. Holstov et al. (2017) used a one-year duration experiment to measure the response speed and curvature of wooden laminated samples, using a DSLR camera and transparent reference charts for the sample curvature analysis. The achieved degree of precision in these experiments would typically work well under normal circumstances. However, for wood veneer samples with a multitude of parameters, including type of wood, grain orientation, material thickness, and single or double lamination, and response parameters such as changes in sample length, height, deflection value, and radius of curvature through time, a more robust method for capturing and tracking response and motion is required for an accurate representation that can be translated to a 3D modeling tool.

Several input devices have been generally used to sense and manipulate the deformation and curvature of surfaces. Older versions include the Shape Tape, which is a rubber tape that could sense adequate deformation through fiber optic sensors. The shape tape was linked with the Maya 3D modeling and animation software, and was set to control NURBS curves in Maya (Balakrishnan et al., 1999). More recent devices include the use of Flex sensors in conjunction with microcontrollers as a low cost and safe method to track angular measurements. For example, Beyaz (2017) studied the posture movements of human arms and legs using flex sensors as input devices with Arduino Uno as a processing unit and image analysis software for angular measurement. A capacitive flex sensor consists of dielectric material that separates two metal conductive layers. Its working mechanism depends on the dielectric material that reduces the resistance between the two layers involved in the deflection process (Sreejan & Narayan, 2017); an important feature when it comes to measure linear, angular and deflection values for both single layer and multi-layer wood veneer samples.

Tracking the motion of materials has been conducted by image analysis methods and software. Previous research investigated the behavior of shape changing material, and in particular tracking the response of wood to the difference in humidity levels through image analysis techniques. Using these techniques, the response of wood to humidity is tracked by means of assigning color codes on the four edges of the wood sample to facilitate image recognition of the response motion. This method studies motion through the relation between response time and deflection value of the wooden sample under different humidity level conditions (Baseta, 2015).

Another experiment was conducted by Bridgens et al. (2017) for a one-year duration to test the long-term efficiency of wood motion through its hygroscopic properties. Different levels of material analysis were performed such as the range of motion of the wood samples, fatigue value, and material deterioration. The motion of the material was captured through a weather sealed GoPro camera and analyzed through weekly and monthly check points. The tested parameters were curvature, erosion, color change, delamination, waviness and curvature uniformity. Image analysis was also used to test the strength of Carbon Fiber Reinforced Polymer (CFRP), also an anisotropic and brittle material, by means of fracture and strain distributions (Yokoyama & Matsumoto, 2017).

METHODOLOGY AND PROCEDURES

The work in this paper is part of an ongoing research project that aims to utilize the hygroscopic properties of wood in designing adaptive facades, as illustrated in figure 1. Several physical experiments were conducted to understand the parameters of hygroscopic design that can be programmed to predict and control the response behavior of wood to the variation in humidity levels. Different prototypes of adaptive wooden façades were fabricated to control the type of motion needed and tested under different humidity levels to predict their passive motion response. The focus of this paper is to develop a computational closed loop that allows for real-time tracking, analyzing and recording of the response of wood to humidity levels.

Tracking and analyzing the motion of wood in this paper is divided into two parts; the computational proposed tool and image analysis tool, as illustrated in figure 2. The main challenge in studying the behavior of wood as a programmable material due to its hygroscopic properties is the procedures of real time physical experiments. Hygroscopic motion parameters such as response time and deflection angles are measured by the proposed computational method then compared to the image analysis software "Kinovea" to identify any percentage of error between the two tracking methods.

The image analysis software "Kinovea" has been widely used to track different kinds of motion. Kinovea has been identified as a valid and reliable tracking software for human motion analysis for sports and scientific purposes. It has also been validated in measuring and tracking time-related variables through using reference points. It has also been explored in measuring and tracking angular and displacement variables in athletic and clinical studies (Puig-Diví et al., 2017). This paper uses the capabilities of Kinovea to measure motion parameters such as angles and distances in the required analysis in relation to the motion response of wood under different humidity level conditions.

Image Analysis Method

Tracking and analyzing motion is typically found in different disciplines such as material sciences, medical studies, engineering and physical studies. The use of the image analysis method to analyze kinematics is known as a low-cost analysis technique. Analyz-

Figure 1
Framework of research

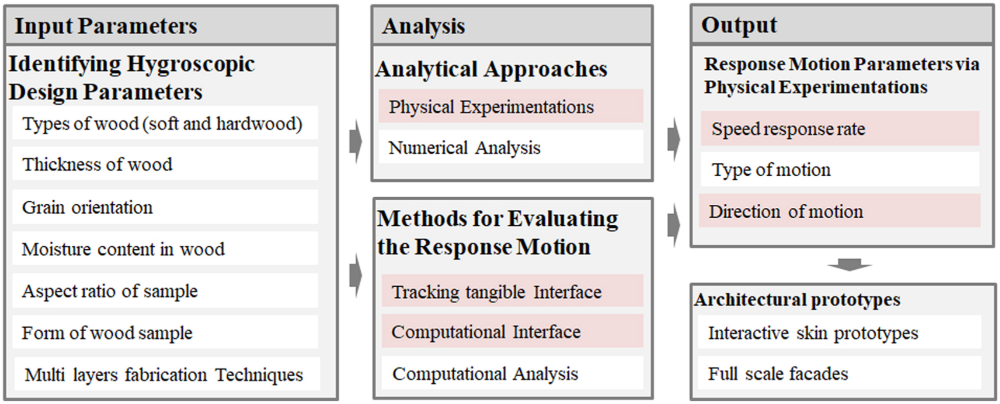
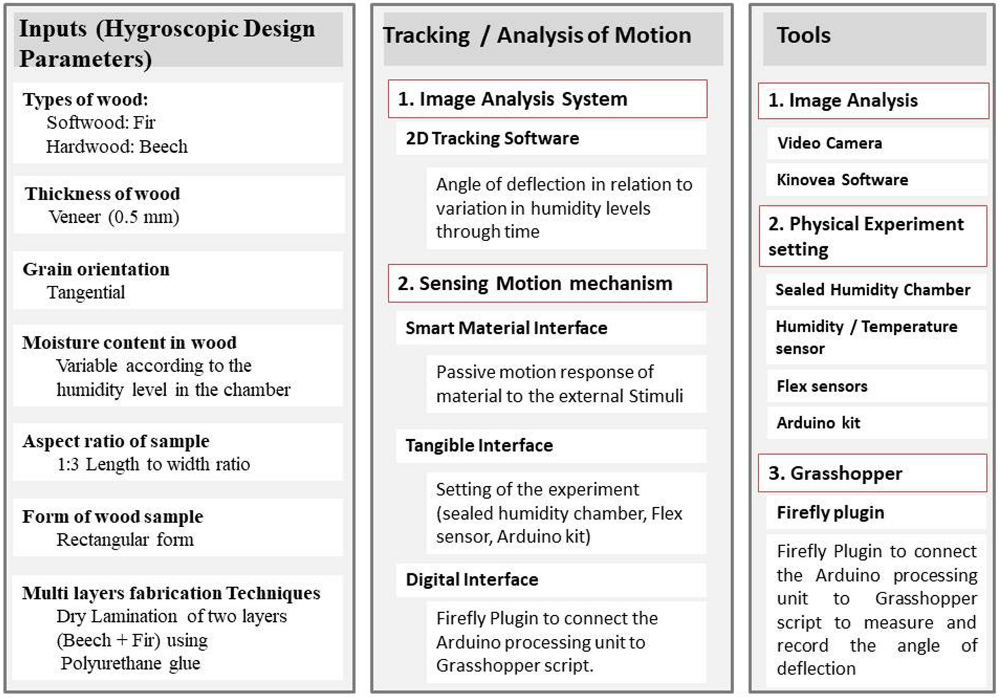


Figure 2
Research methodology



ing motion using image analysis relies on different techniques such as the evaluation of center of mass displacement or body motion, such as in Ubersense, Nintendo MarkWiiR remote and Microsoft Kinect. Kinovea software, created in 2009 (Puig-Diví et al., 2017), is a free 2D software that analyses motion by means of evaluating angles and distances in a frame-by-frame fashion. It can also use different perspective angles in the analysis due its capability to calibrate non-perpendicular planes and non-accurately positioned views, and its ability to define fixed marker points and moving markers in any view. Kinovea has been widely used in different types of studies for image analysis and tracking, and is generally characterized by its friendly interface, frame-by-frame recognition, and tracking of the same object under study using different views. The tracking and analysis process typically follows these steps:

1. Adjusting the marker position: The process begins by selecting the best frame to start tracking, then putting "Marker" signs to the selected points that will be either tracked in motion or in static position for measurement extraction. Markers need to be clear and unique for the software to capture them easily and accurately.
2. Taking measurements: In this experiment, measurements are conducted through the "Angle" component. This is done through defining three points. One of them is the center point and the two other points are the points enclosing the measured angle. These points are configured by the "Marker" component.
3. Tracking: The "Start Tracking" component is applied on the markers to initiate tracking and calculations. When playing the video, the angle is tracked in each frame as a movable point, thus resulting in an automatic tracking and measuring of the angle in real-time, as illustrated in figure 3.
4. Recording the output angles: The measured angle is automatically tracked in each frame and the angles are recorded in a Microsoft Excel sheet.

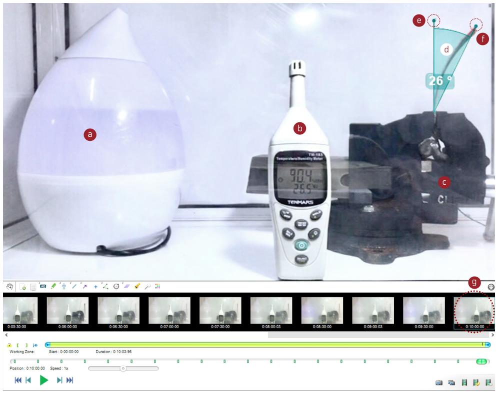


Figure 3
Tracking the motion of wood through image analysis: (a) Humidifier; (b) Temperature and humidity sensor; (c) Metal clamp; (d) Tracked angle; (e) Fixed marker point; (g) Tracked frame

Motion Sensing Method

The proposed computational closed loop links the smart material interface (SMI) with a digital and tangible interface. SMI is represented in the detection, programming and controlling of the response of wood to the difference in humidity levels due to its hygroscopic properties. The tangible interface comprises the physical setting of the experiment, including a humidifier, a controlled humidity chamber, flex sensor, circuits, in addition to an Arduino Uno microcontroller kit. The digital interface consists of the Grasshopper parametric modeling interface and the FireFly plugin, its physical computing interface. The proposed method for tracking and monitoring the response of wood to the change in humidity level is illustrated in figure 4.

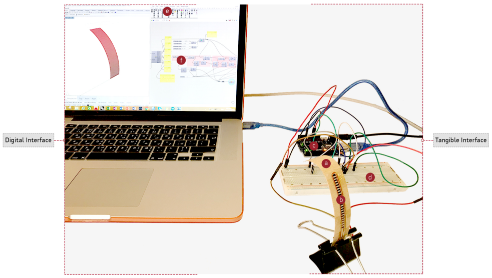


Figure 4
Computational method for tracking wood response: (a) Wood sample; (b) Flex sensor; (c) Arduino Uno; (d) Breadboard; (e) Grasshopper; (f) FireFly definition

The physical experiment utilized a circuit with a flex sensor to sense the curvature of the sample and an Arduino-Uno microcontroller kit as a microprocessor, as illustrated in figure 5. The proposed process for the experiment aimed to measure and capture the response of wood motion in relation to changes in humidity levels. The experiments were conducted in a transparent controlled humidity chamber on a 4*11cm beech veneer wooden sample with a tangential grain orientation. The flex sensor was fixed on the wood veneer sample and connected to the Arduino Uno kit to measure the bending of the wooden sample. The motion response of the wood was captured by the flex sensor, and then processed using the Arduino microcontroller. A humidity sensor was located inside the controlled humidity chamber to demonstrate variations in humidity levels. This experimental phase is divided into four main steps: testing the effect of humidity of the sensor in the chamber, fixing the sensor to the bilayer wood sample, fixing the bilayer wood sample in the controlled humidity chamber, and recording and evaluating the motion of the bilayer wood sample using the digital interface in Grasshopper and FireFly. These steps are described in detail as follows:

1. Testing the effect of humidity of the flex sensor alone in the controlled humidity chamber: It was demonstrated that the flex sensor is not impacted by the difference in humidity levels. It was necessary to isolate this factor from the beginning of the experiment to ensure an accurate representation of the readings of the wood sample without any noise in the measure data from other sources. The water resistance-based glue was also important to use so that it does not impact the integrity of the experiment.

2. Fixing the flex sensor to the tested bilayer wooden sample: A bilayer sample was used in this experiment to simulate the response effect of wood upon variations in humidity levels. Beech (hardwood) veneer acted as the active layer responsible for the motion of the wood sample, while fir (softwood) veneer acted as the passive layer that regulates or resists the motion. The two pieces of wood were glued from their two edges with polyurethane glue (water resistance based glue to avoid any impact of humidity on the sensor and consequently on any measurements or readings of the experiment). The flex sensor was then inserted in between the two samples and connected with the Arduino Uno kit, as illustrated in Figure 5.

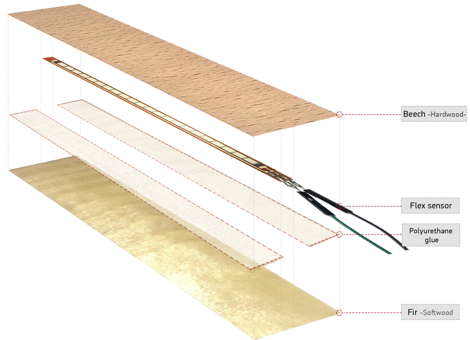


Figure 5
Fixing the motion sensing system in between the bilayer wood sample

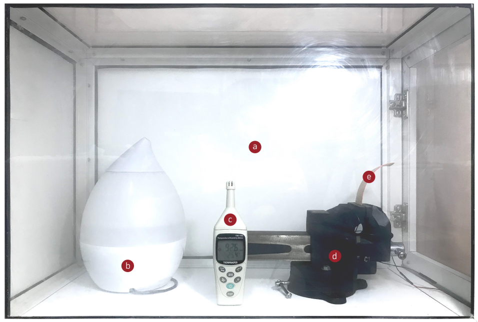


Figure 6
Experiment inside humidity chamber: (a) Chamber; (b) Humidifier; (c) Humidity and temperature sensor; (d) Clamp; (e) Bilayer wood sample

3. Fixing the bilayer wood sample in the controlled humidity chamber: The bilayer wood sample was then fixed using a metal clamp to maintain location and position and located inside the controlled humidity chamber, as illustrated in figure 6. The experiment was run with humidity variations between 65-95%. The flex sensor was connected to the Arduino microcontroller and the Grasshopper interface.

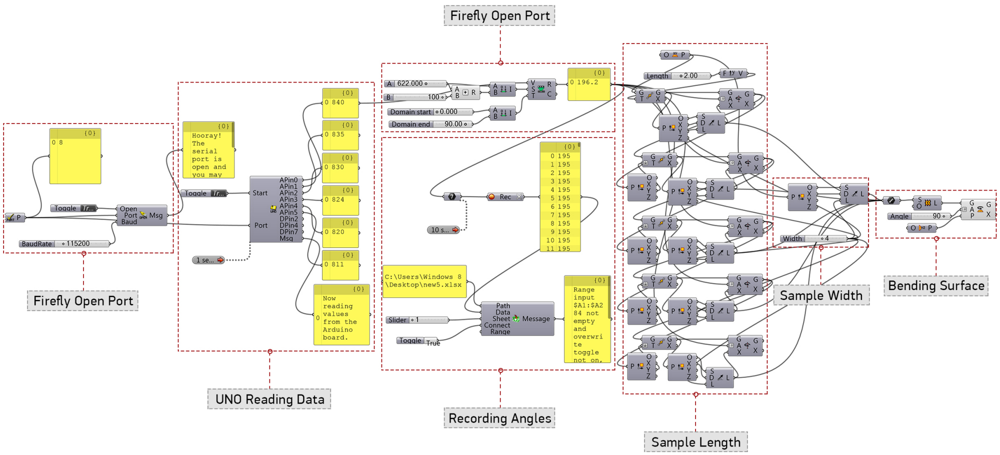


Figure 7
Grasshopper script developed to track the response of wood

The motion of wood was therefore recorded in the digital interface through angle variations. The motion of wood was also recorded using a video camera to validate the motion sensing method.

4. Recording, analyzing and evaluating the motion of bilayer wood sample: The Grasshopper script was responsible for storing the variations of angles and tracking and analyzing the response behavior of wood. The digital interface was used to map, store and evaluate the motion of wood. The tangible interface was read by the Firefly plugin using Grasshopper. Firefly transmits the real-time motion response of wood to Grasshopper. A parametric Grasshopper script was generated to evaluate, analyze and store the motion of the sample, as illustrated in figure 7.

The flex sensor output readings were remapped in Grasshopper to generate the sample bending angle. The resistance value acquired from the sensor was then captured by Firefly, and a parametric model for was generated in Grasshopper according to the remapped angles. The output of Grasshopper introduced both a numerical and graphical record of the wood response motion. The numerical output is the deflection value of wood and the response speed at each humidity level. The graphical output is a 3D animated model for the real-time motion of wood. The process is stored as a digital real-time analyzed video that can easily be integrated in spreadsheets.

RESULTS AND DISCUSSION

Experiments were conducted on two phases; the image analysis phase and the motion sensing mechanism phase using physical experiments. Three experiments were conducted for each phase on the bilayer samples for increased accuracy and calibration and to extract average readings for the angles of motion in wood in response to humidity, as illustrated in table 1. Readings were taken in 1-minute intervals for both phases. For the image analysis phase, the motion range was from 2.3 degrees to 29 degrees for a full duration of 20 minutes. The second phase of the study was conducted in a controlled humidity chamber with a bilayer sample of wood (Beech + Fir veneer). Both samples were of a tangential cut with a sensing input element (flex sensor) in between the bilayer sample. The motion range for this phase was from 0 degrees to 29.2 degrees.

As the image analysis method is typically a well-known method for 2D motion tracking, the image analysis readings were used as a reference for comparison of results of the motion sensing method. By

Table 1
Average readings for deviation angles for bilayer wood samples in relation to the increase in the level of humidity for both the image analysis and motion sensing methods

Time/Min.	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
RH%	68%	72%	78%	89%	91.80%	92.10%	92.30%	92.90%	93.10%	93.30%	93.40%	93.60%	93.90%	94%	94.10%	94.30%	94.50%	94.70%	94.90%	94.90%	95%
Angle- Deg. In Sensing Mechanism	0.0	3.6	5.6	7	8.1	8.9	9.9	11	12.4	13.5	14.6	15.7	17.2	18.6	20.2	21.8	22.2	24	26.8	27.9	29.2
Angle- Deg. in Image analysis	2.3	4	5.3	6.7	8	9.7	10.7	11.3	12.7	14	15.7	16.3	17.7	19	20.7	22	23.3	24.7	26	27.7	29

comparing the readings of the two conducted methods (as illustrated in table 1), it was found that the maximum difference in angle measurement was 2.3 degrees (only at the onset of the experiment, due to calibration logistics, while the maximum difference across the 20-minute duration was only 1.1 degrees), while the minimum difference was 0.1 degrees.

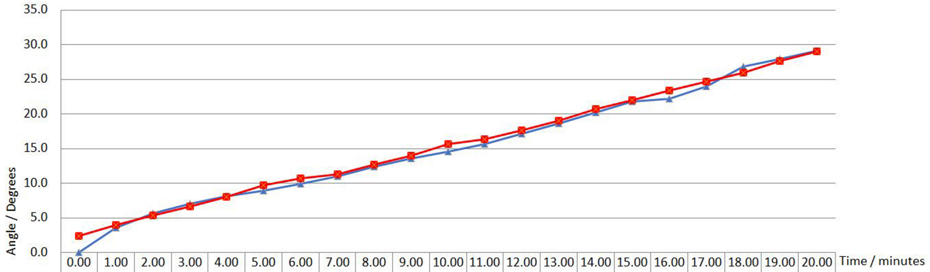
Figure 8 shows the exact angle measurement per minute for the average readings of three experiments for each of the experiment phases. By conducting a T-test with a two-tailed distribution and two-sample unequal variance for the image analysis method and motion sensing method results, a value of $P = 0.87$ was concluded (large p-value >0.05), indicating weak evidence against the null hypothesis of no difference, and therefore indicating no significant difference between both methods. This validates the proposed motion sensing mechanism as a method to measure angle deviations determining the response of wood to difference in humidity levels, as there was no significant difference in relation to the image analysis method.

There were some limitations however in the implemented method in this paper. The Analog to Digital Converter (ADC) on the used Arduino Uno board has a 10-bit resolution. This limits its differentiation to 2ˆ10 (1024) different levels for an analog input. There are some methods however to improve this resolution depending on the required complexity. Most methods will probably get realistically the equivalent of 2-4 additional bits of resolution (12-14 bits total) such as using the Arduino Due or the Arduino Zero. A separate ADC chip however could get an additional 14 bits (24 bits in total). Future research will consider this limitation and use appropriate measures to acquire higher resolution for the implemented tangible interface.

The used sensing system is limited to two-dimensional and unidirectional motion and could not sense three-dimensional motion such as twisting for example when the grain orientation for a wood sample is at 45°. Further research and development in this area will include tracking more sophisticated types of motion for wood that can be acquired through different fabrication techniques of bilayer samples. This requires investigating different hygroscopic design parameters such as grain orientation, material thickness and different types of wood.

CONCLUSIONS

This paper proposed a motion sensing mechanism to capture, analyze and store the real-time motion and response of wood to differences in humidity lev-



	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
Sensing Mechanism	0.0	3.6	5.6	7.0	8.1	8.9	9.9	11.0	12.4	13.5	14.6	15.7	17.2	18.6	20.2	21.8	22.2	24.0	26.8	27.9	29.2
Image analysis	2.3	4.0	5.3	6.7	8.0	9.7	10.7	11.3	12.7	14.0	15.7	16.3	17.7	19.0	20.7	22.0	23.3	24.7	26.0	27.7	29.0

Figure 8
Comparing the angular readings between the image analysis method and motion sensing method

els due to its hygroscopic properties. This mechanism introduces a way to link the tangible interface of the material to a computational interface that records real-time accurate measurements with respect to time and relative humidity. Results of the experiments conducted on bilayer wood samples of beech and fir veneer showed no significant difference between the implemented mechanism and image analysis methods, with the added value of a more grounded precise capturing of actual material motion, accurate digital representation for further operation in 3D modeling, analysis and simulation tools, acquiring numerical data related to wood deflection and response speed at each humidity level, and animated documentation of real-time motion of wood. Further research aims at utilizing the tested motion sensing mechanism to develop learning mechanisms to predict the controlled motion of wood for use in adaptive architectural skins.

ACKNOWLEDGEMENTS

The authors are grateful for the funding provided to the American University in Cairo by the Bartlett's Fund for Science and Engineering Research Collaboration.

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