ExCell: High Expansion Ratio Moisture-Responsive Wooden Actuators for DIY Shape-Changing and Deployable Structures

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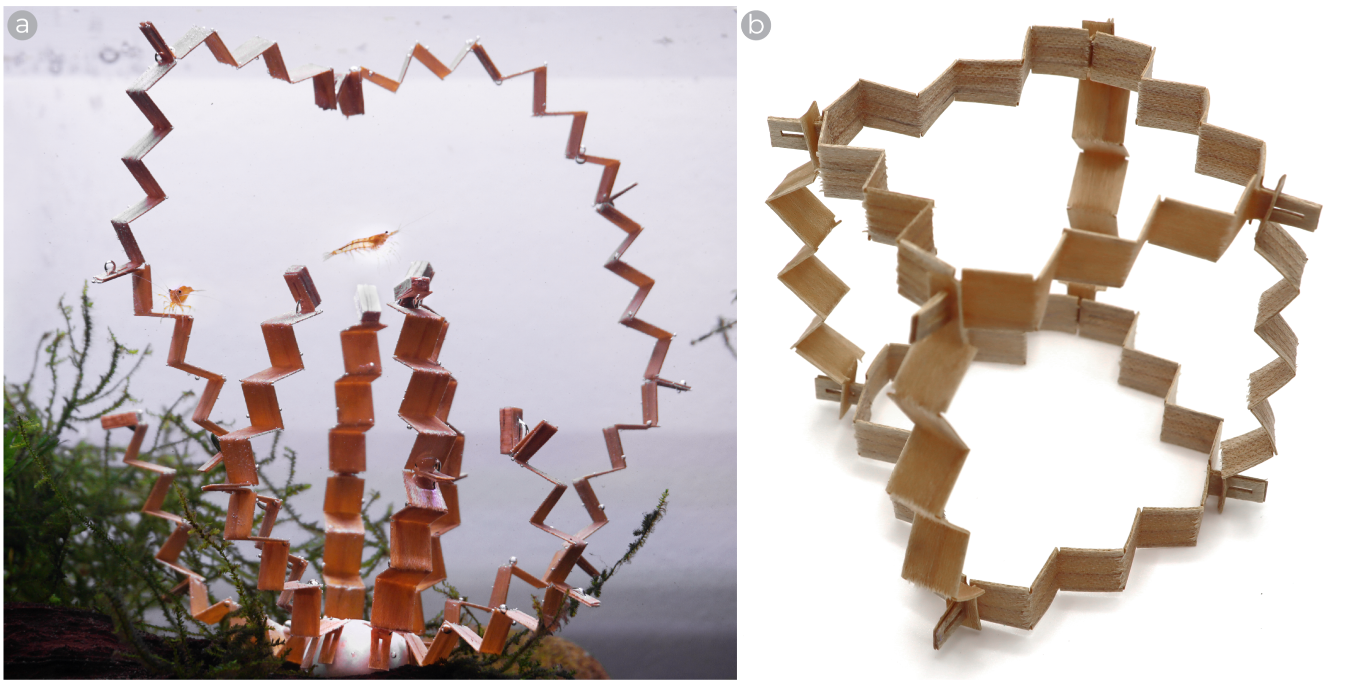

Figure 1: A. An expanding fish shelter deployed in an aquarium; B. An ExCell actuator cube in its expanded state

ABSTRACT

While there has been sustained interest in shape-changing materials and deployable structures, many existing systems require engineering materials, precision fabrication, and computationally modeled kinematics in order to work. Additionally, many rely on external power sources in order to deploy. In light of these factors, we perceive a need for deployable materials that are easy to design, prototype, and deploy, and that can transform themselves in response to environmental stimuli, making them appropriate for ecological applications. In this paper, we present ExCell, a DIY-able system of water-responsive wooden linear actuators for self-actuating deployable structures. We show that ExCell can be used to develop a wide range of geometries, we present a prototyping method that can create accurate models of ExCell structures, and we suggest four possible applications for this system.

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CCS CONCEPTS

• **Human-centered computing** → *Systems and tools for interaction design*; **Human computer interaction (HCI)**.

KEYWORDS

shape-changing interface, deployable structures, sustainable HCI, active materials, morphing materials, human-nature interaction

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1 INTRODUCTION

Ongoing HCI research into shape-changing materials and deployable structures has pointed to a future where objects, surfaces, and structures at every scale of daily life are imbued with the ability to reconfigure their physical form[15][23]. In some cases, this morphing nature allows otherwise unpowered materials to incorporate autonomous functionalities[65]. In other cases, shape change is harnessed to revolutionize the built environment, allowing for previously impossible-to-fabricate forms that are lofted from a flat shape into undulating surfaces with the application of force in strategic places[39]. While both of these research domains remain rich, inspiring territories, the barriers to entry for designing and fabricating shape-changing materials and deployable structures are high for non-experts [16][67]. This stems from the complex coordination of material properties, geometries, and motive forces required in order to effect these novel behaviors. A side effect of this need for the highly predictable characteristics of engineering polymers, metals, and composites [40][58] is that biodegradable, biocompatible examples in these fields are rare.

With all of the possible benefits of materials and structures that can shift between forms depending on their situation or use and autonomously respond to changes in their environment[37], we see a need to create more entry points for designers who are not well-versed in areas such as materials science and graphics research. We propose a line of investigation that complements the mathematically advanced, materially intensive work that has inspired us, building on prior research in smart materials and methods to create a system of self-shaping, biodegradable modules. We present ExCell, short for Expanding Cellulose: a water-activated wooden linear actuator that is simple to produce, to prototype with, and to understand (Figures 2B and 2C). By taking advantage of the method for creating continuous coiling actuators developed by Luo, et al.[27] but chaining individual bending actuators into an accordion-folded series, we have created a material that can expand many times its compressed length. ExCell units can be made in a range of sizes, but our basic unit is roughly 1 cm square and 4 mm thick in its compressed state, making it suitable for small-scale yet complex mechanisms. It incorporates a modular connector, assisting users in composing consistent geometric forms, and it is easily replicated in paper, providing an avenue for recyclable rapid prototyping for initial design and structural exploration.

In this short paper, we contribute:

(1) ExCell, a novel biodegradable modular actuator
(2) Empirical lessons about designing shape-changing materials with wood
(3) A concept for a rapid physical prototyping method
(4) Four demo applications highlighting some of the possible uses for our system

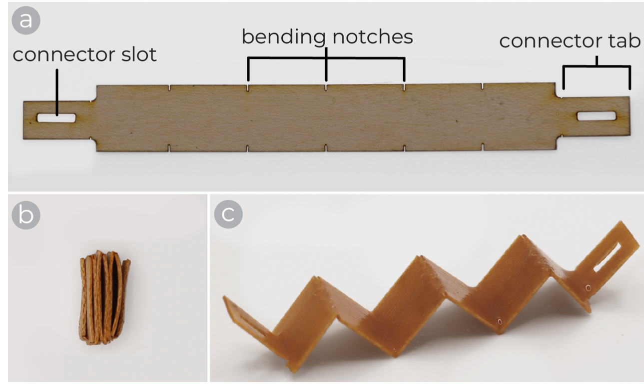

Figure 2: A. The design features of the laser-cut blanks include notches to assist with manual forming and a slot-and-tab connector system; B. Side view of an ExCell actuator in its compressed state. C. Side view of an actuator in its expanded state.

2 RELATED WORKS

2.1 Deployable Structures

While the history of human structures that can be rapidly converted from a compact state into a large volume state dates back thousands of years[50], in HCI and engineering fields, the term "deployable structures" usually implies an integrated mechanism designed to effect a dramatic shape change driven by relatively few power inputs. Because the motion of these mechanisms often involves the coordination of highly interdependent struts or surfaces, they are designed with computational methods, typically by experts. The now classic Hoberman sphere, a simple Platonic solid, merited a patent when it was designed [13]. While representative work in this area includes research on novel geometries that afford transition from flat states to compound curvature states[26] and techniques for expanding the possible geometry space of linkages by incorporating flexible struts [39], some researchers have developed tools to allow non-experts to design linkage-based deployables without needing to get involved in complex calculations for collision avoidance[67], and others have created libraries of modular shapes with practical applications while also exploring the deep geometry of their designs [32]. Diverging from these works, ExCell has a relatively simple geometry and is therefore tolerant of low-precision fabrication and assembly methods. Unlike the building blocks in linkage-based deployable designs, each ExCell unit independently self-morphs: if one element is blocking the expansion of another, it does not cause the entire mechanism to lock up. Together, these aspects make ExCell suitable for hands-on experimentation by non-experts.

2.2 Shape-Changing Materials

The interdisciplinary field of shape-changing materials has many parallels to deployable structures, both in terms of the insights that mathematical analysis can contribute to understanding how materials transition between shapes[47] and also occasionally in terms of the mechanisms employed[63]. Researchers have demonstrated shape-changing behaviors in various materials which can

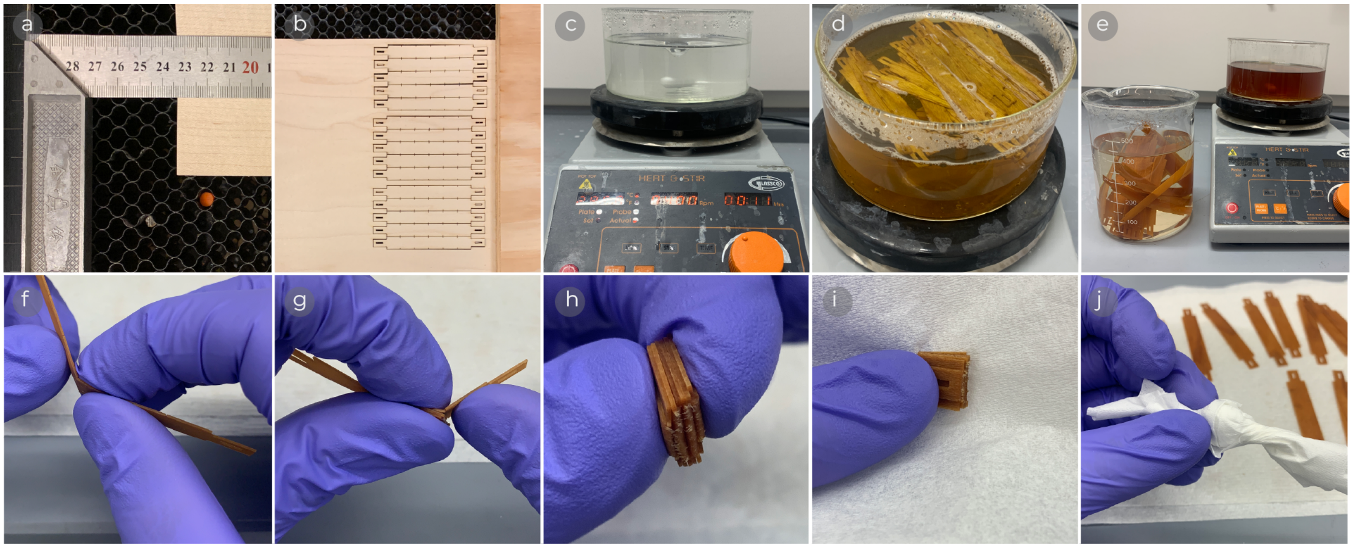

Figure 3: A. Aligning the wood grain with the X-axis of the laser; B. Laser cutting actuator blanks; C. Dissolving the reagents in water; D. Boiling the blanks in solution; E. Rinsing excess reagents from the blanks; F.- H. Bending the blanks along the notches to form the actuator; I.-J. Wrapping the actuator in tissue for drying.

morph in response to external stimuli, including magnetic printed material[21] and food[59]. Shape-changing materials have been used in soft robotics[55] to create artificial muscles, environmental sensors, and biomedical devices. Of particular relevance to this paper are materials that are triggered by the absorption or evaporation of water[17, 22]. Often taking advantage of the bending behaviors of differential bilayers[41], hygromorphic shape-change has been demonstrated in hydrogels[18, 42, 60], pollen paper [66], and wood[4, 6, 33, 51, 61] among other materials. Since water is widely available, hygromorphic materials and mechanisms are being explored for moisture capture, energy harvesting, and actuation[4, 25].

In the field of HCI, smart materials have garnered growing interest due to their capacity to empower designers in crafting interfaces capable of altering material characteristics and to provide novel dynamic affordances, such as fluid fibers which can exhibit strong forces[20], electroactive polymers[12], venous materials[35], and soft composite materials[38, 64]. Shape-changing materials are also used in personal fabrication[36, 52, 57] and crafts, such as 4D printing artifacts using thermoplastic[2, 7, 53, 56]. ExCell focuses on utilizing wood, which is sustainable and biodegradable, to extend practices in materiality in HCI. With ExCell, users can create their own shape-changing interfaces, robotic mechanisms which can react to the natural environment, and sustainable crafts.

2.3 Wood as a smart material

Despite the fact that wood was one of the first materials intentionally modified by humans[14], research into applications for wood-derived materials has expanded into radically new directions in recent years. Much of the interest in wood as a smart material stems from the combination of its potential as a sustainable material and its unique cellular structure. That structure gives it *hygromorphic* behaviors: in response to changes in moisture, wood undergoes anisotropic expansion and contraction. While this is a property that has historically been designed around, [8], researchers have made novel use of it by developing wooden bilayer actuators [43] and moisture-activated building skins[34]. Going beyond wood's natural material properties, researchers have developed ways of increasing its strength [49] and of compositing wood waste into structurally sound material[10]. Conversely, researchers have also inverted the familiar properties of wood, making it flexible enough to be tied in knots without permanent deformation [48], and making it spongy and absorbent [5]. Taking advantage of its microstructure to push wood into new application areas, others have developed wood-based transistors [54], optically transparent wood [68], and constituents for energy storage devices [46].

Tying these seemingly disparate projects together is the fact that they all start with the selective removal of lignin from wood[24]. Lignin is one of the three main components of wood along with cellulose and hemicellulose. Two of its functions are to bind together cellulose fibers, much like a fiber-reinforced polymer, and to protect more hydrophilic cells [9]. Among other things, delignification increases the moldability of wood, an effect that HCI researchers have applied to the E-Seed project, which develops shape-changing interfaces that drill themselves into soil [27][28]. Notably, the molding process of E-Seeds imparts their predictable coiling behavior. We build upon the work of E-Seed by integrating elements of their fabrication method, with which they target specific environmental applications, to create a general purpose linear actuator.

3 PROCESS

In this section, we detail the fabrication process of the actuators, the design parameters that affect their performance, and the geometric combinations afforded by their design.

3.1 Actuator fabrication

The fabrication process comprises four parts: laser cutting blanks from wood veneer, chemically processing the blanks to make them moldable, folding the processed blanks into accordion shapes, and drying them while constraining them to a compressed form.

We cut our actuators from 0.5 mm thick sheets of sugar maple veneer [3] using a CO2 laser (Universal Laser Systems ULS 4.75) (Figures 3A and 3B). To ensure that the longitudinal grain of the wood is parallel to the long side of the actuator, we align the grain with the X-axis of the laser cutter (Figure 3A). As the pieces have a tendency to curl upward once released from the sheet, we order the features so that the outer contours are cut last.

Following the method of Luo, et al. [28], we boil the wood blanks in a solution of sodium hydroxide (NaOH) and sodium sulfite ($NaSO_3$), both of which were sourced from Amazon.com (Figures 3C and 3D). We replicate their ratios of 100 mL water to 10 g NaOH to 5 g $NaSO_3$, but we differ in the length of time that we boil the wood. While we are using the same thickness of wood, we have changed the radius of curvature of the bends and their angle relative to the wood grain. Whereas samples in [28] is molded around a 0.4 mm radius mandrel at a slight angle to form a spiral, ExCell is sharply creased perpendicular to the longitudinal axis of the wood. In practice, this meant that blanks that were boiled for 10 minutes frequently splintered along the fold. We experimented with different processing times and found that it took 20 minutes, rather than 10, to render the wood sufficiently moldable to form sharp creases with minimal splintering while still maintaining structural integrity. Additional boiling time further improved moldability, but also resulted in decreasing stiffness and ultimately undesirable deformation of the blanks after 50 minutes. After delignification, we remove the blanks to another container and rinse them in clean boiling water four times, until the solution remains relatively clear (Figure 3E). Given the natural variation of wood, some samples (approximately 5%) are noticeably warped after boiling and are consequently removed.

The ExCell actuators begin as flat 87.8 mm x 10 mm x 0.5 mm laser-cut wooden blanks and end up as folded 11.2 mm x 8.5 mm x 4.2 mm units. As we will discuss in further detail below, we fold them manually using laser-cut notches as guides. Starting in the middle of the blank and working outward, we make alternating valley and mountain folds until the connector sections are folded over (Figures 3F - 3H). At this point, an additional 10% of samples commonly incur more-than-superficial splintering along the crease and are discarded (Figure 7B).

We allow the actuators to dry overnight at standard room temperature (~20°C) and humidity (~45% relative humidity). We individually wrap each molded unit in moisture-wicking tissue (Kimberly-Clark KimWipes), twisting the outer ends of the tissue (Figures 3I and 3J). These wipes serve a dual purpose. They allow us to apply light pressure to the actuators to keep them compressed without densifying any areas— while Song, et al. dried delignified wood under high pressure to increase its strength[49], we did not want to introduce additional variation to individual actuators. These tissues also to allow the wood to reach an equilibrium with the ambient moisture of the room, whereas other clamping method that we tried prevented water from evaporating. Once dried, the tissue can be flattened and reused multiple times.

3.2 Parameter Optimization

We experimented with a number of geometric, material, and process parameters and found the most salient to include the radius of the folds in the actuators ("molding radius"), the length of the arms connecting the folds, the wood species, and the growth ring orientation of the veneer sheets. In this section, we discuss the influence of these variables and how we determined their importance.

3.3 Geometric Parameters

In simple geometric terms, the difference in length between the compressed state of ExCell actuators and their actuated length is determined by the number of bends in each unit, the length of the sections between bends, the radius of each bend, and the angle that each bend actuates to, with the first three variables being design parameters and the final variable being dependent (See Figure 4A). We found each of these design parameters to involve significant trade-offs, so simply maximizing them was not a practical option. In the section below, we discuss how we arrived at the final design.

By treating each bend as the vertex of a triangle with known adjacent side lengths, we can derive an approximate model for the actuated length of an ExCell actuator (Figure 4C2). While this model ignores some geometrical aspects such as the effect of molding radius (r) on arm length (L_r) and variation between the individual actuation angles (ϑ_i and ϑ_e) of fabricated units, it gives us a strong sense of the relative impact of different parameters. Our model for the length of compressed actuators (Figure 4B2) similarly ignores minor differences in real units. From these models, we can see that for actuators with the same molding radius and number of bends, the largest influence on actuated length is arm length, and we can also see that for actuators with the same number of bends, the greatest influence on molded length is the molding radius. Additionally, it is clear that the actuated angles have a large impact on the extended length, so factors influencing those are of interest.

While they are independent of each other, we found that significantly increasing either the number of bends or the length of the arms resulted in actuators that behaved as soft springs when extended. Even though some of our samples were capable of expanding over 3000%, we felt that the relatively square shape and compact compressed height of our chosen design made it easy to assemble into complex forms and that its expansion of 1500% still afforded an interesting amount of shape change. That said, we plan on characterizing these two variables more rigorously in the future.

Given that the folds made in the wood do most of the work of the actuators, we were interested in trying to understand how their curvature affected performance. To gather data, we molded blanks around 3D-printed forms with increasing radii on one end (note that we refer to a sharp crease in the wood as a 0 mm radius) (Figure 5, bottom), triggered them, and measured their angles. We found a nonlinear effect, with the largest actuation angles coming from samples with a 0.5 mm or 0.25 mm molding radius (Figure 5. While we have not confirmed it empirically, we believe that this range represents a "sweet spot" with a maximum gradient from compression of the interior cells to stretching of the exterior ones,

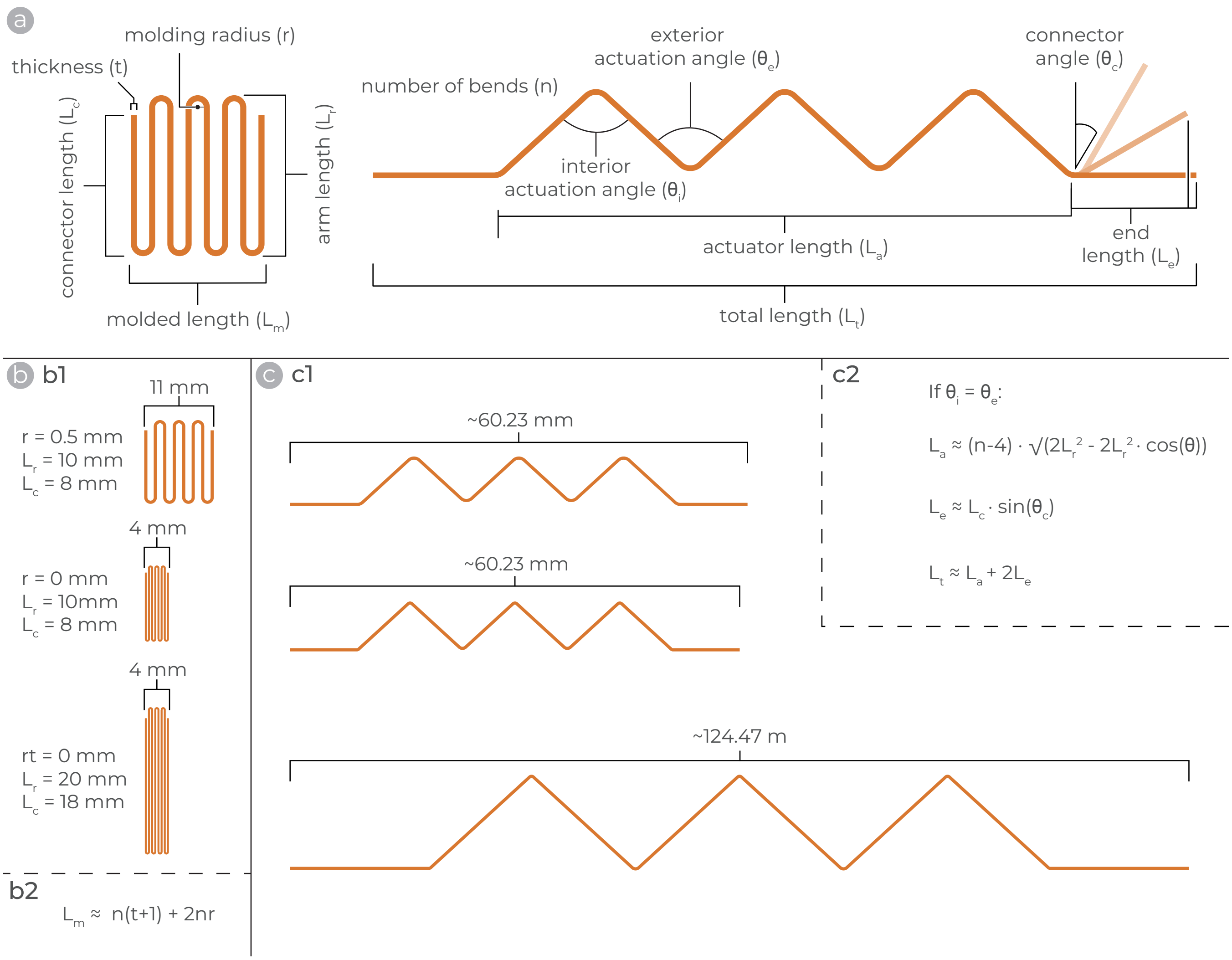

Figure 4: A. Geometric parameters of ExCell actuators; B1. Side diagrams of molded actuators with relevant dimensions; B2. A geometric model for the length of molded actuators; C1. Side diagrams of expanded actuators with dimensions calculated from the parameters given in B2; C2. Geometric models for estimating the actuated length of an ExCell unit.

optimizing the actuation mechanism [28]. Additionally, we found that splintering increased with smaller molding radii, and we suspect that this fracturing along the bend decreases the performance of sharply creased actuators.

From Figure 4B1, we can see that molding radius has the largest cumulative effect on the length of the actuator in its compressed state. Our goal was to achieve large expansion, so we considered whether we should pursue further characterization to determine if the increased actuation angle of these larger radii offset their increased width. In the end, however, we considered that actuators with nonzero radii require molds, introducing significant complexity to the forming process. We attempted three different molding methods: pressing the veneer blanks between shaped plates, rolling the blanks through two meshed gears, and interleaving each fold with a 3D-printed form (Figure 6B). While the final method yielded attractive actuators with no splintering (Figure 6A), the small scale of the mold components (roughly 14 mm x 10 mm x 0.5 mm) made them extremely difficult to handle and align, so we opted to trade greater potential expansion for reduced complexity. Because we were forgoing molds, we incorporated laser-cut notches into the veneer blanks to make the folds more consistent (Figure 2A).

3.4 Material Parameters

Wood is a highly anisotropic material, but many of its properties are generally predictable based on the species and the orientation of the grain. A huge variety of wood veneer is available[3], but as we were designing an actuator that transmits bending force when it absorbs water, we focused on selecting species of wood with high stiffness and relatively high shrinkage ratios, or change in dimension between saturated and fully dried wood[29]. We limited our

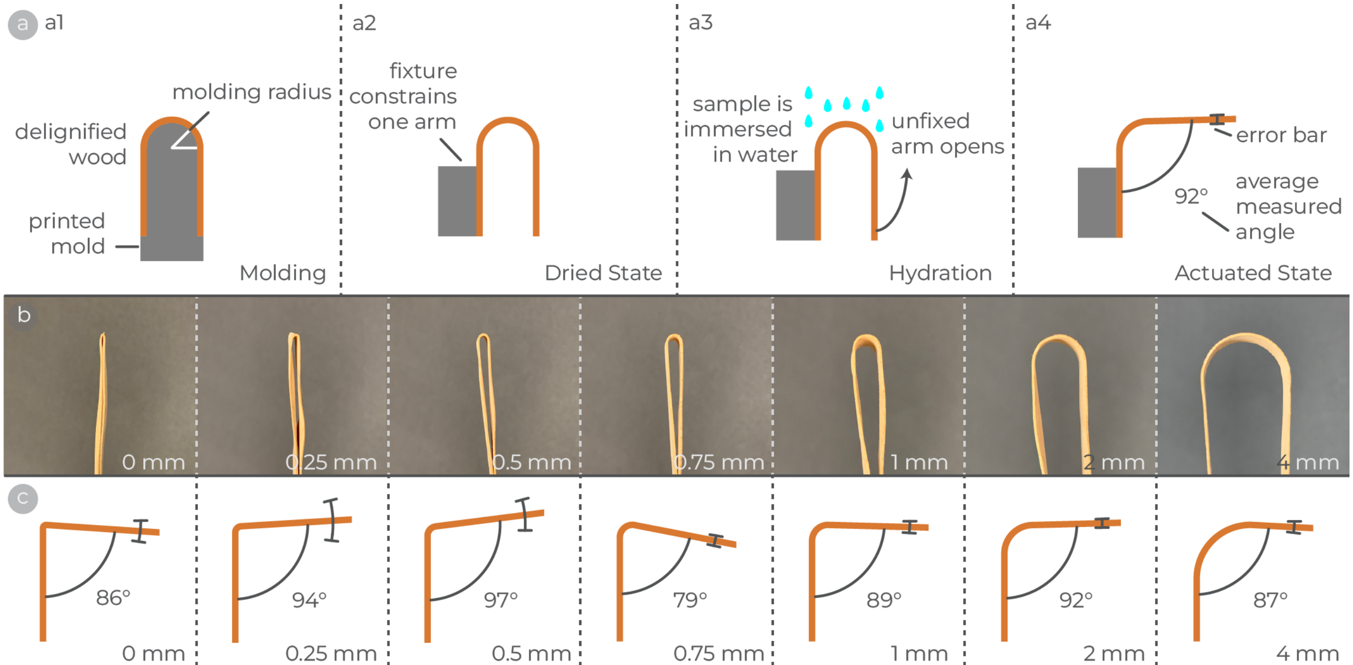

Figure 5: A1. Samples were molded around 3D printed forms with increasing radii; A2. Once dried, one arm of each sample was fixed to a block of aluminum; A3. Each sample was immersed in water for 10 minutes; A4. The actuated angle was measured for 4 samples of each molding radius; B. Photographs showing molded samples; C. Average actuation angles for each molding radius.

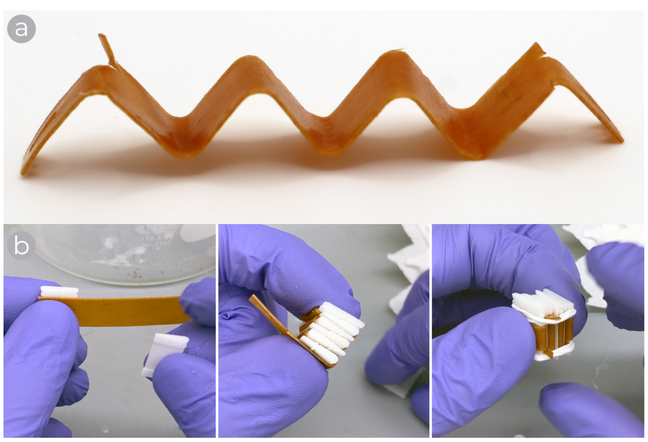

Figure 6: A. An actuator formed using interleaved 3D-printed molds; B. Timelapse stills from the molding process.

wood choices to widely available local species and selected white oak, as was used in E-Seed[28] (flexural modulus: 12.15 GPa, shrinkage ratios: 5.6% radial, 10.5% tangential, 16.3% volumetric[31]), and sugar maple (flexural modulus: 12.62 GPa, shrinkage ratios: 4.8% radial, 9.8% tangential, 14.7% volumetric[30]) for testing. We quickly found that the homogeneous grain of maple was preferable to the alternation between dense and open-grained sections in white oak, which often resulted in fracture during folding or required careful, individual cutting of blanks resulting in lower yield, so we proceeded with investigating different forms of maple.

Wood veneer is commonly produced by either rotating a log against a straight blade to slice off a continuous sheet of material (rotary slicing), or by pushing a flat board past a straight blade in a linear trajectory to pare away individual sheets (plain slicing). We did not find a source for rotary-sliced veneer without a backing material, so we experimented with plain-sliced sugar maple veneer in two different grain orientations: flat-sawn and quarter-sawn. These designations refer to the way that the boards they were sliced from were cut out of a log (Figure 7A). In the case of flat-sawn wood, parallel cuts were made across the log in the longitudinal direction. The growth rings of the tree intersect the face of the board at different angles in different locations. With quarter-sawn wood, the log is first sliced into quarters and then sections of each quarter are cut such that the growth rings intersect the face of the board at approximately 90°. While there is more waste with quarter-sawn wood, it is prized for its visual quality and the predictability of its anisotropic behavior.

While there has been recent research into using machine learning to predict the morphing behavior of individual samples of wood based on optical scans of their grain [1], we wanted to establish a simple and easily repeatable fabrication process. We hypothesized that actuators cut from quarter-sawn veneer would outperform flat-sawn ones in terms of consistency and power output for two reasons: first, because there is less variation in the grain orientation,

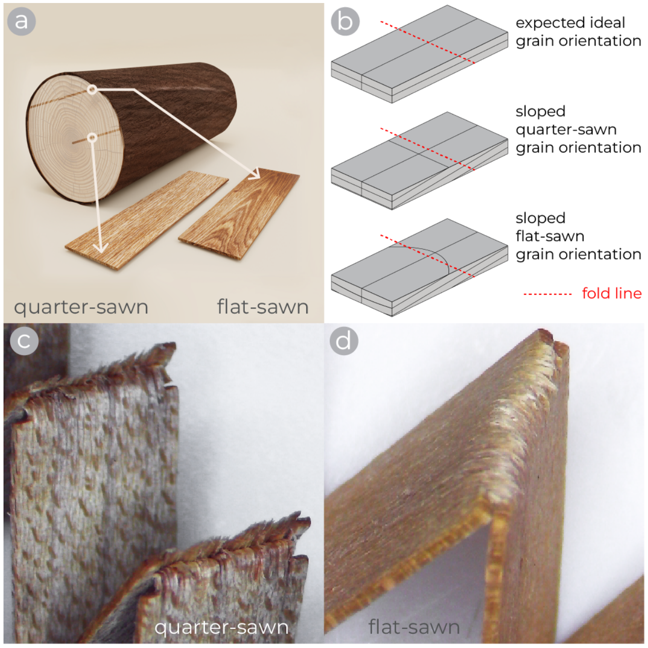

Figure 7: A. Due to the way they are cut from a log, the orientation of the growth rings varies across a flat-sawn board and are more consistent in a quarter-sawn one; B. In contrast to our initial expectations, we suspect that the slope of the grain in real wood coupled with the alignment of the quarter-sawn grain results in a weak spot along the fold; C. Severe splintering of quarter-sawn maple; D. Minor splintering of flat-sawn maple.

and second, because the tangential grain axis, which expands and contracts more than the radial one, is perpendicular to the face of the board, whereas in flat-sawn wood it fluctuates throughout the board. In spite of these facts, we found that quarter-sawn veneer was significantly more prone to fracturing during folding (Figures 7C and 7D), so the yield of acceptable actuators was, ironically, roughly a quarter that of flat-sawn wood. We suspect that this fracturing may in fact be due to the alignment of the grain. In practice, rather than running perfectly parallel to the edges of the wood, the grain axes have a nonzero slope (Figure 7B). In quarter-sawn wood, this could lead to well-aligned weak spots along the fold, whereas in flat-sawn wood, fibers likely intersect with the face in a less regular manner. Regardless, more microscopic morphological analysis is required to better understand this phenomenon.

Another hypothesis we made was that storage method for the veneer, which was shipped rolled up, would create a difference between the inside and the outside of the roll. The process of folding the actuators compresses the cells on the inside of the fold and stretches cells on the outside, and we supposed that the material's storage condition would have pre-programmed it in a similar fashion to some degree. To test this, we marked the inside face of a veneer sheet with graphite and fabricated twelve actuators. After submerging the actuators in a water tank for three hours, we measured the angle of each of the bends, noting whether they were inwards or outwards with regard to the storage roll. With 48 data points for inward bends and 42 outward bends, we found very little difference between the two orientations.

3.5 Actuation

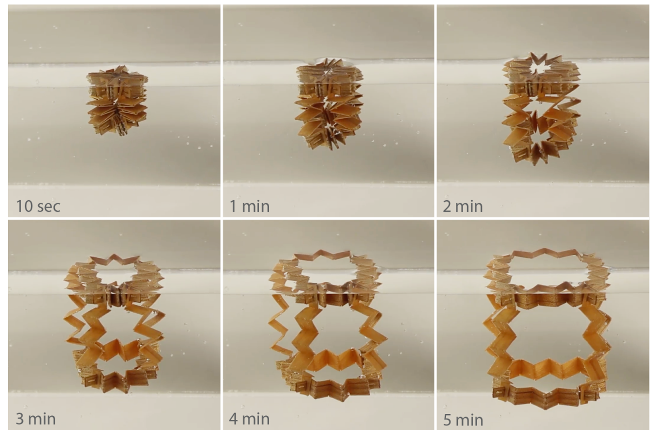

Figure 8: Timelapse stills of a cube construction expanding in water.

When they get wet, ExCell actuators begin changing shape within seconds. Depending on factors such as whether they are fully submerged and whether they encounter external resistance to their actuation, they reach approximately 80% of their maximum extension after 3 minutes, 90% after 6 minutes, and continue to expand for roughly 2 hours, changing negligibly after that (Figure 8). In the future, we would like to get a better understanding of which parameters affect the speed of actuation.

Unlike the bilayer actuators in Rüggeberg and Burgert (2015) that respond dramatically to changes in humidity, ExCell actuators primarily change shape when they are immersed in or otherwise coated in water. While we did observe minor changes in length when molded actuators were placed in a chamber with >90% humidity, these were negligible compared to their expansion when wet. This can be explained by the way that dead wood interacts with moisture: over time, wood absorbs or releases moisture to reach an equilibrium with its environment, and at standard indoor conditions (20°C and 30-50% humidity), the moisture content of wood ranges from 7-10%. At the same temperature and 100% relative humidity, the equilibrium moisture content of wood is 30%. Under normal conditions, this water is bound up in the cell walls of the wood, rather than present in the vessels, or open volumes of the cells [19]. When immersed in water, however, the vessels can fill with water, far surpassing the moisture absorbed from humidity[62].

Actuators can be reset and dried following the process described above, but their autonomous cyclic behavior is an important consideration for some applications. To assess their repeated expansion and contraction without intervention, we tested three samples for four hydration-dehydration cycles, measuring their overall length after each phase. We found that both the expanded and contracted lengths increased with repeated cycles. While the units shrank to an average of 40% their actuated length after the first drying cycle,

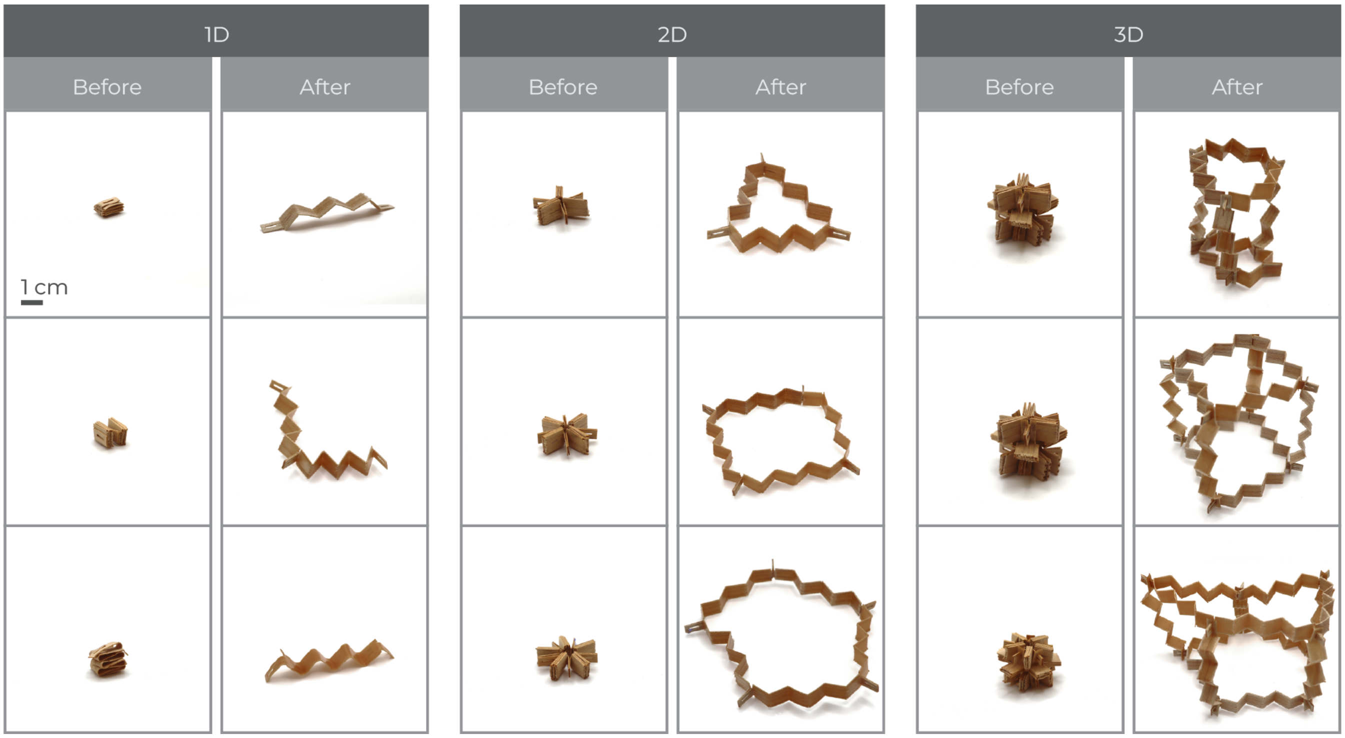

Figure 9: Example linear, flat, and volumetric combination of ExCell units in both compressed and actuated states.

by the fourth cycle they contracted to an average of 56% their actuated length. Additionally, their expanded lengths in the fourth cycle were 7% longer on average than in the first hydration cycle. While the performance of the actuators decreases with repeated, autonomous use, additional characterization is required to understand whether the actuators eventually establish a static state.

3.6 Modular primitives

The tab-and-slot connectors integrated into the ends of the ExCell actuators (Figure 2C) afford a simple means of joining units into regular building blocks at 90° in the X, Y, and Z axes (Figure 9). To form prisms, 2D shapes are assembled by attaching adjacent connectors together in-plane using cyanoacrylate glue (Zap-a-Gap). The doubled connectors are then inserted through the slot in connectors at 90° to the 2D shape, and this can be repeated to form long masts. The connectors also serve as a convenient gluing tab for the attachment of actuators at arbitrary locations and to other materials, as in our animated diorama example (Figure 11).

3.7 Prototyping

ExCell can be used as a standalone system or incorporated with other materials, as we will demonstrate in Section 4. For example, they can be affixed with adhesive, attached with mechanical fasteners, or sewn onto substrates. To aid users in designing ExCell constructions and testing their deployment, we developed a simple paper-prototyping method using the same design file as the wooden blanks (Figure 10A). Laser-cutting and accordion-folding cardstock results in models of the ExCell actuators with similar dimensions and kinematic properties, but without the same moisture-responsive actuation. Users can assemble these paper stand-ins using the same methods as the wooden actuators, and the paper mock-ups can be expanded and compressed manually. In order to model the compact state of their construction, users can compress each accordion section and secure it with a paperclip. With access to a laser cutter, these paper mock-ups are fast to produce and allow for the rapid testing of ideas, and they could be die-cut in bulk in the future. We foresee including these paper actuators in a kit along with morphing wooden ones, adhesives, and tweezers for future participatory design activities.

4 APPLICATIONS

We propose four concepts for applying ExCell: in art, environmental sensing, habitat remediation, and environmental stewardship.

4.1 Animated Diorama

One rich application area for ExCell actuators is for incorporating motion into otherwise static arts and crafts. When combined with water-resistant materials, they can be used to create animated pop-up cards and interactive dioramas (Figure 11). In this example, laser-cut wood mushrooms are semi-concealed between scenographic layers of plywood cut to resemble a forest environment. When a user pours or sprays water into the art piece, the mushrooms spring up, providing a physically animated illustration of the growth cycles of many fungi.

Figure 10: A. The design of ExCell lends itself to paper prototyping. Laser-cut models (a1) are folded (a2) and assembled into larger constructions (a3 and a4). To model the compressed state of ExCell structures, the paper models can be compressed with paperclips; B. The construction process of ExCell structures involves assembling discrete actuators together using glue (b1 - b3). Deployment can be tested in water (b4), and the structure can be re-compressed and dried for later use.

4.2 Clogged gutter indicator

Rain gutters are commonly used on buildings with pitched roofs in order to divert water away from entryways and foundations to prevent flooding and degradation. In tree-filled areas, a common failure mode for gutters is that they become clogged with fallen leaves, allowing water levels to rise and spill over the sides, rather than being channeled to a downspout. When this happens, water can seep into the building, causing cosmetic and structural damage and encouraging mold growth. Existing methods of preventing this include regular cleanings and the installation of guards that prevent the entry of leaves in the first place. While effective, both of these solutions can be expensive, and a basic issue is that because gutters are usually high above the ground, it is difficult to determine whether they are in need of maintenance without climbing up a tall ladder. To address this issue, we have used ExCell actuators to design a simple snap-in environmental sensor. When a clog forms in a gutter and the internal water level rises, the actuators become submerged and expand to push a highly visual indicator over the side of the gutter. This indicator serves a dual purpose as a roof structure, preventing the actuators from being triggered by rain unless the gutter is clogged. The fact that the indicator requires manual intervention to be reset means that it will remain visible until someone accesses the gutter to check for clogs.

4.3 Shelter for fish

Submerged artificial habitats are commonly used for recreational fishing purposes [11] as well as environmental remediation [44]. We designed a deployable, sea grass-like habitat by attaching ExCell actuators to a river stone. Larger, more complicated forms could be developed for use in a larger aquarium or pond. In addition to the possible benefits to wildlife, we propose designing these as an enjoyable activities for aquaculture hobbyists.

4.4 Duckweed clearing booms

Duckweed is a small, floating plant that reproduces rapidly. While it can be a part of healthy pond ecosystems in its native range, it can quickly spread to completely cover ponds that have an overabundance of nutrients due to agricultural run-off [45]. This blocks light from reaching submerged vegetation and also prevents gas exchange between the air and water. We imagine a possible environmental intervention that can be deployed by hand (Figure 14). By adding small buoyant pieces of wood or cork between actuators, 2D forms can act as floating barriers (booms) to sweep plant

Figure 11: An interactive diorama with fungi that seem to grow in response to increased moisture.

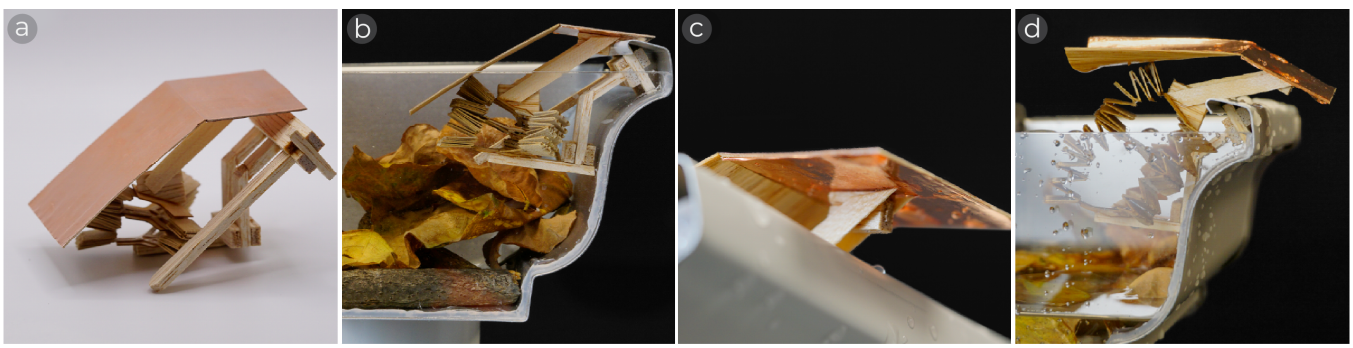

Figure 12: A. A wood and copper foil sensor to indicate that a rain gutter is flooding; B. A sensor snapped into the lip of a clogged gutter before the rain; C. The copper-clad indicator peeking out from the edge of the gutter, visible from below; D. ExCell actuators pushing the copper indicator along rails to extend past the gutter.

matter away from sections of a pond. This can create temporary voids to allow light and gases through the mat of vegetation. As a local intervention, it requires little infrastructure, is unlikely to negatively affect other wildlife, and can foster an ongoing stewardship relationship between people and their environment. These booms can be collected with a pole or even a fishing rod, dried, and reused. In future work, we hope to further investigate the safety and effectiveness of this approach.

5 LIMITATIONS AND FUTURE WORK

Our investigation of ExCell has been a preliminary study with an emphasis on simplicity and user-friendliness. In this paper, we focus on a single kind of actuator that can be assembled into increasingly complex forms. While we do not explore them here, we acknowledge that other types of actuator can be fabricated using the same process. Coiling actuators, such as the one demonstrated in Luo, et al., as well as bending ones, of which the ExCell actuator itself is composed, could further enrich the design space Future work to better quantify performance and material trade-offs could increase our understanding of how ExCell units perform in a wider variety of contexts, such as in varying temperatures or salinities of water. Additionally, working with both novice users and environmental experts could allow us to validate ExCell's utility in both everyday scenarios and our more speculative concepts.

We believe that ExCell's simplicity is one of its strengths and decided that a software design tool would interrupt the immediacy of hands-on prototyping. Moreover, while the action of simple

Figure 13: Timelapse stills of a fish shelter deploying in an aquarium.

Figure 14: A. Three hand-deployable floating booms for creating oxygen and light-permeable voids in overgrown ponds; B. Timelapse stills of ExCell booms pushing duckweed away.

constructions is relatively intuitive, providing an accurate computational model is nontrivial. A simplistic model that does not take collisions, the decreasing Young's modulus as the wood is hydrated, and the triggering orientation into account has limited merit, and the computational costs of analyzing these factors is currently unwarranted. However, if additional developments were made to the ExCell system, for example, if sequential motion were induced in the actuators by selectively coating them with semi-permeable films, a simulation tool would become more relevant.

6 CONCLUSION

In this paper, we presented a new type of hygromorphic shape-changing actuator for the creation of environmentally friendly, small-scale deployable structures. We described the material and geometric parameters governing thin morphing wooden actuators, and we developed a hands-on prototyping method for exploring the design space of this system beyond the concept applications that we propose.

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