bioLogic: Natto Cells as Nanoactuators for Shape Changing Interfaces

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Figure 1: Example applications. (a) Living teabags; (b) "Second Skin" as responsive clothing; (c) Animated origami toys; (d) Artificial plants that change both form and color; (e) Transformable lampshade.

ABSTRACT

Nature has engineered its own actuators, as well as the efficient material composition, geometry and structure to utilize its actuators and achieve functional transformation. Based on the natural phenomenon of cells' hygromorphic transformation, we introduce the living *Bacillus Subtilis* natto cell as a humidity sensitive nanoactuator. In this paper, we unfold the process of exploring and comparing cell types that are proper for HCI use, the development of the composite biofilm, the development of the responsive structures, the control setup for actuating biofilms, and a simulation and fabrication platform. Finally, we provide a variety of application designs, with and without computer control to demonstrate the potential of our bio actuators. Through this paper, we intend to enable the use of natto cells and our platform technologies for HCI researchers, designers and bio-hackers. More generally, we try to encourage the research and use of biological responsive materials and interdisciplinary research in HCI.

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Author Keywords

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ACM Classification Keywords

H.5.2. User Interfaces: Haptic I/O; Prototype

INTRODUCTION

Looking into nature, from the wilting of flowers to the opening of fallen pinecones, biological sensors as well as actuators are omnipresent. Utilizing such mechanisms from nature through the integration of living organisms into design and engineering has gained increasing interest amongst scientists and engineers [3][16]. On the other hand, in the field of Human-Computer Interaction (HCI), material-based interface design and shape-change interfaces are emerging topics[24]. Ishii describes "Radical Atom" and suggests the dynamic manifestation of digital information in the physical world [9]. To add one more type of smart material for such research, we introduce a biological cell actuator, *Bacilus Subtilis* natto that responds to moisture changes to design interactive objects.

Using living cells as an actuator has several distinctive advantages: electronic free, safe and edible, the lack of wires or tubes, quiet transformation, potential biological synthesis, self-reproduction and flexibility of deposition as a liquid form. However, there are still challenges when we seek to use living cell actuators in the HCI context. For example: how to gain access and use the material in a common prototyping environment while reducing biosafety level concerns? How to synthesize material on a macro scale with nano scale actuators? How to integrate digital fabrication for more precise manufacturing in order to embed a certain level of programmability to achieve desired transformation? How to integrate the human factor and digital controllability into a hydromorphic actuator that responds to the change of relative humidity? Through this work, we hope to address those challenges.

In this paper, our main contribution, particularly compared with the closely related technique - *Bacillus Subtilis* endospore [1] based bio actuator, includes:

- Introducing natto cells as nanoactuators for designing transformable thin sheet materials that respond to humidity change. Based on our test, the natto cell has stronger force and faster response time compared with *Bacillus Subtilis* endospore [1].
- Integrating the nanoactuator with a digitally controllable humidity changing system, as well as sensing composite to build up the interaction loop.
- Developing the experiment setup to characterize performance of the nanoactuator.
- Implementing application prototypes that either use biofilm as a self-contained sensing and actuation mechanism, or use biofilm within a computer modulated interaction loop to demonstrate the wide design space with the cell actuator.
- Developing digital simulation and fabrication tools to facilitate HCI design study.
- Providing transformation structure examples that cell actuators can achieve.

INTRODUCING NATTO CELLS AS ACTUATORS

Cells' hygromorphic phenomenon has been well studied, especially in some plants such as pinecones and wheat awns[1]. In collaboration with biologists, we observed a similar hygromorphic behavior from the *Bacillus Subtilis* natto cell. By varying the relative humidity (RH) around the cells, the size of the cells can change by 50%. With the natto cell, we introduce the idea of developing cell-hybrid biofilms that can transform with the change in relative humidity.

Originally, we began our exploration with the *Bacillus Subtilis* endospore, which was reported as one option for biological actuators [3]. Through the process, we fortuitously found that the vegetative natto cells perform even better (Figure 2d). Our comparison test shows that the cell-hybrid film has an average bending curvature that is 5 times greater than that of the spore-hybrid films, with a 2.5 times more rapid response. For example, under the condition of 40% relative humidity and 3.6 μm cell thickness, the natto cell based film can reach an average bending curvature of 470 degrees (Table 2), while the endospore based film can reach an average of 80 degrees.

While the endospore solution requires mixing with Polylisine in order to be attached to latex surfaces, the hygromorphic bonds between natto cells and latex substrate behave as natural glue that can resist up to a 2 minute flush of water**.** Culturing cells also takes a much shorter time and poses fewer technical requirements than culturing spores. Since natto cells have been used to ferment food in Japan since 1906 [25], they are safe for use and do not require a lab environment with specified biosafety levels.

Beyond natto cells, we have also tested a variety of other cells, e.g., E. coli and yeasts. Natto cells were eventually chosen based on a few criteria: biosafety level, expertise level to handle, synthesis complexity and actuator performance. For example, E.coli has a higher requirement on its bio-safety level; and, although yeast is safe to use, the actuating performance is inadequate compared to the natto cell.

Our hypothesis on the natto cells' working principle at the molecular level is as follows: it was found that the functional layer of the endospore system is the "cortex" composed of peptidoglycan (protein and sugar) [3]. In our living cell system, there is no cortex but proteins. We hypothesized that cell expansion behavior is due to water absorption by intracellular proteins. We further strengthened our hypothesis by testing out that pure proteins have hygromorphic behaviors as well, but with a much longer response time, possibly due to the lack of cellular scaffolds. In the future, more scientific study will be conducted to establish the underlying mechanisms.

DEVELOPMENT OF BIOFILMS

A *composite biofilm* contains two layers: the cell layer and the substrate layer. The biofilm can vary the bending curvature triggered by the RH change (Figure 2b,c). We obtain the composite biofilm by applying cell-water solution onto the substrate layer and vaporizing the water content (Figure 2a). The ideal substrate material includes 0.2mm thick latex, 0.3mil Kapton and 0.3mil PET.

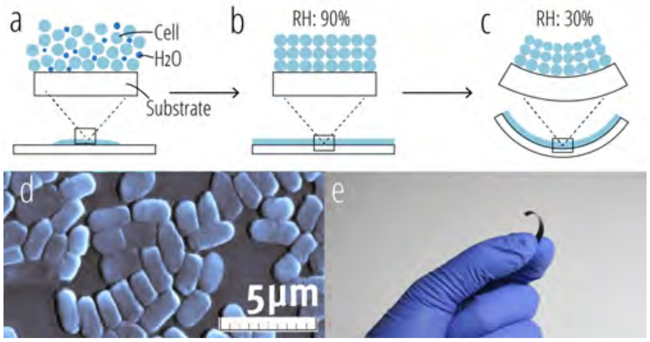

Figure 2: (a) Liquid cell solution deposition; (b, c) Composite biofilm bends when relative humidity (RH) changes. (d) SEM image of the nanoactuators, natto cells; (e) Composite biofilm.

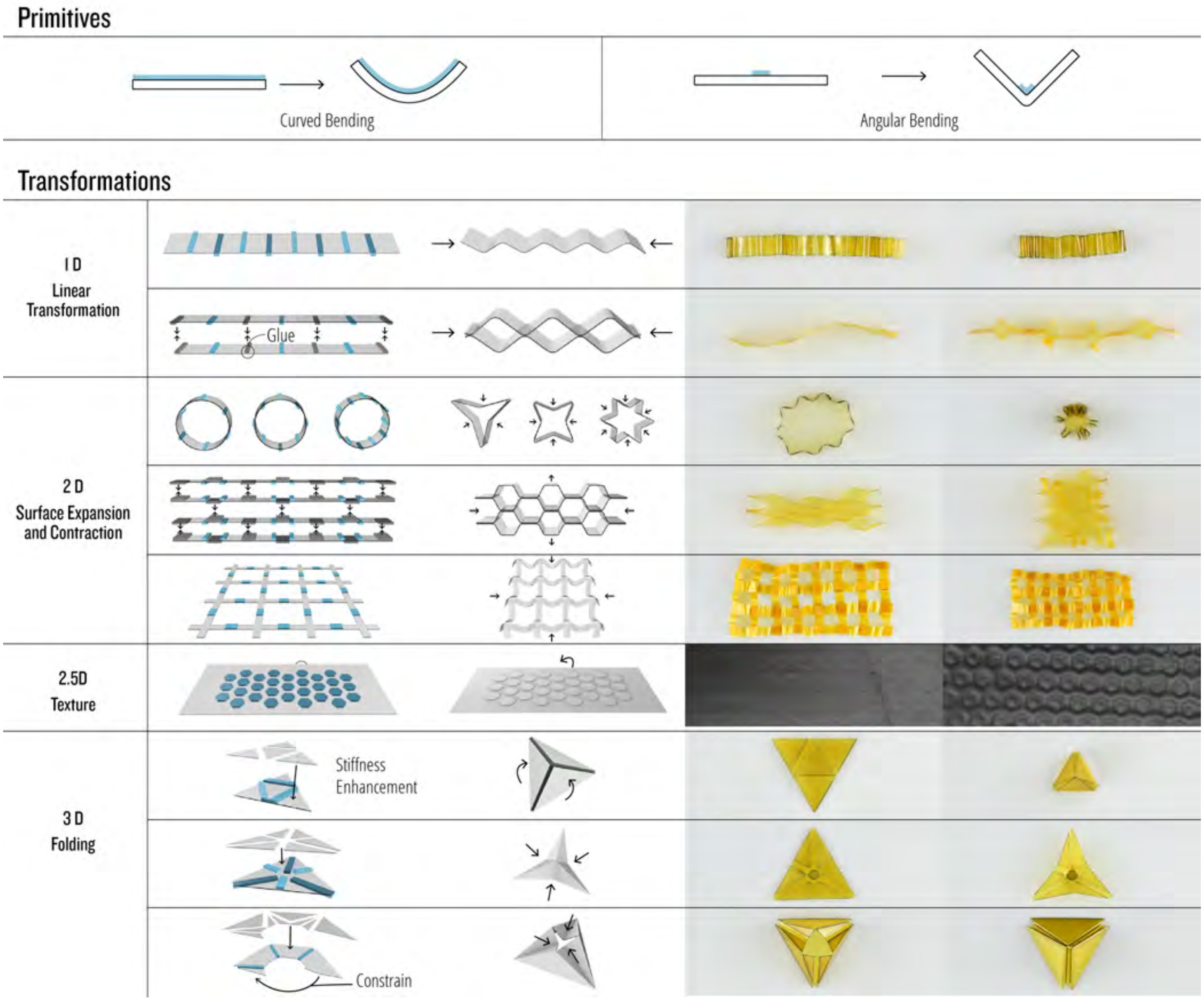

Table 1: Design of Responsive Structures. Two basic bending primitives can be translated into 1D linear transformation, 2D surface expansion and contraction, 2.5D texture change and 3D folding.

DEVELOPMENT OF RESPONSIVE STRUCTURES

With biofilm as the basic building blocks, we design responsive structures and transformations, which can be referenced when we try to achieve a certain shape change in the design of HCI systems. The detailed simulation and fabrication process will be described in the later chapter of the paper.

Transformation design is based on two bending primitives: (Table 1): Curved bending is for more organic transformation; angular bending is for more geometric transformation. To achieve a curving transformation, cells were applied across the entire strip; for an angular transformation, cells were applied in lines. In the latter case, a stiffer material can be attached to substrate regions without cell actuators, to stabilize the structure and enhance the effect of a sharp fold.

Through combining the bending primitives across different dimensions, we can create a variety of responsive transformations including lD linear transformation, 2D surface expansion and contraction, 2.5D texture change and 3D folding (Table 1).

CONTROL OF THE BIOFILMS

To design interactive systems using our biofilm, we seek ways to modulate the regional relative humidity around our biofilm samples in a relatively fast manner.

To quickly raise the relative humidity, we set up a water bubbler that can convert dry, compressed air into wet air that reaches above 90% relative humidity (Figure 3).

To quickly lower the relative humidity, we composite conductive traces on top of the biofilm. When we apply a certain voltage to the conductive traces, the heat generated by the traces will raise up the temperature around the biofilm. This causes the relative humidity to decrease rapidly (Figure 3).

To alternate the high and low relative humidity, we alternatively switch on the wet air from the bubbler and the power which provides a certain voltage to the conductive traces. The alternation is achieved by three relay switches and a microcontroller. Figure 3 shows one circle time for the biofilm sample to bend up and down will take less than one minute.

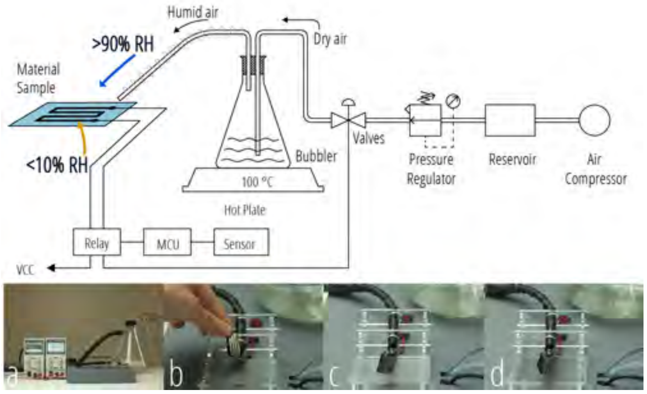

Figure 3: (a) control setup; (b) The sample with heating traces (c) Control button pressured; (d) Control button released;

We develop our own process of compositing conductive traces to the existing biofilm. To maintain the flexibility of the biofilm for transformation purpose, a flexible conductive ink (125-19, Creative Material, Inc.) customized for silicone substrates is applied to the biofilm through a screen printing process. To enable faster iterations of prototyping, rather than customize a photo-emulsion screen, we laser cut double-sided tacky paper to create masks. The mask is then placed on the back of a screen (××8, Blick) (Figure 3a). Squeegees are used to apply the conductive ink to the latex substrate (Figure 4). We have successfully printed conductive traces between 0.35mm and 2mm using this method.

The same conductive traces can potentially be used as sensing elements as well. For example, the resistance of the conductive traces is changing as the biofilm bends at varying curvatures. With precise calibration, the bending angle can be read directly. A single conductive trace can serve either as a capacitive sensor or heating element through the use of two relay switches. “Responsive Plants” in the application section is an example of this technique (Figure 11).

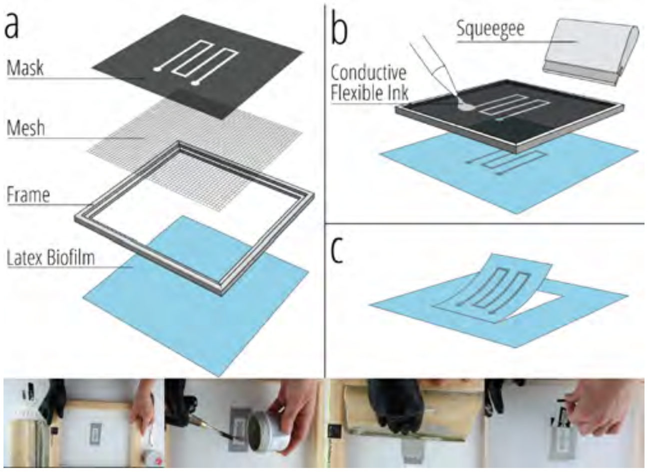

Figure 4: Process of screen printing flexible circuit onto the biofilm

DESIGN PROCESS

Our design process contains three steps: mechanical characterization, simulation, and fabrication.

Mechanical Characterization

We characterize the mechanical performance of the biofilm with the consideration of two factors: bending curvature and response time.

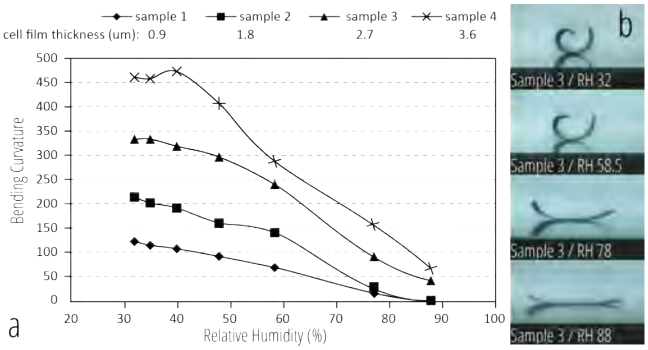

Table 2: (a) Bending curvature versus RH curve; (b) Contrast of bending curvature of Sample 1 at different RH.

Table 2 measures the curvature changes on four biofilm samples, which are prepared on the same 0.2mm latex substrate with varied film thickness of cells. Firstly, the bending curvature becomes smaller as the relative humidity is decreased. Second, under the same relative humidity, the thicker the cell layers are, the bigger the bending curvature is. The sample with the most cell layers has the maximum bending angle at the lowest relative humidity.

Table 3 describes the response time of the biofilm to reach its maximum curvature under two alternated RH conditions. It shows that it takes 9.04s for sample 1 to reach its maximum curvature and it takes longer (14.98s) when layer thickness is increased for sample 2.

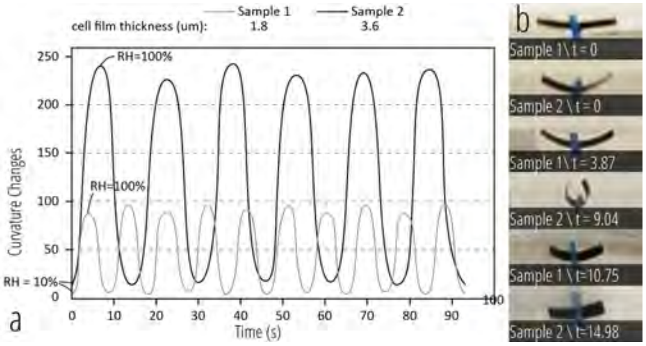

Table 3: RH alternates between 10% and 100%, the curvature changes versus time.

Simulation

In order to better design and predict the transformation behavior and produce digital files for fabrication (geometry for cell printing and substrate film), we developed a digital material design and simulation platform within Rhinoceros 5 and Grasshopper. It includes two main functions: design and simulation. At the design stage, users can define the geometry of the substrate and regions for actuator application sequentially; and, at the simulation stage, the process of transformation can be animated with the change of RH (Figure 5). Experimental data from Table 2 is integrated into the software for physical simulation. And, as examples of cases used, all of the transformation structures from Table 1 were designed and simulated with this platform.

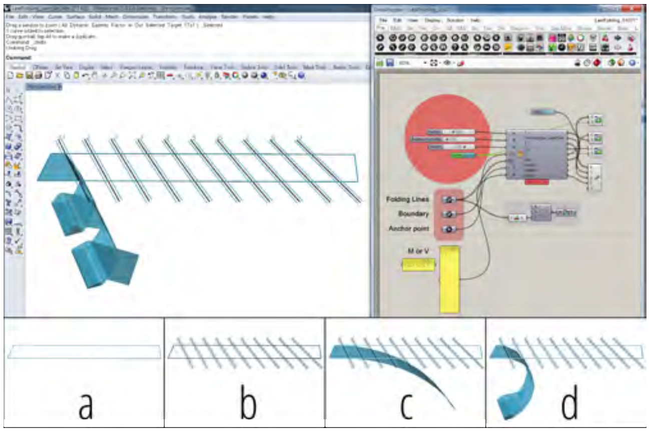

Figure 5: Design and simulation platform. (a) Defining substrate; (b) Defining actuators; (c) Simulating in high RH; (d) Simulating in low RH.

In terms of molding methods at the back end of our software, the central part of our simulation is to simplify the model into curves, divide them into consecutive units, and then calibrate the inner stress and moment equilibriums through evolutionary computing[5] (Figure 6a).

To reduce the calculation time, we create a database that contains a group of pre-calculated curves that are under various boundary conditions (Figure 6b). To simulate a model, we firstly simplify the model into a combination of basic curves, depending on whether they have the cell actuators on top of the substrate material or not. Then, we look into the database and obtain the shape of each basic curve through the interpolation of the existing data. Those curves are then connected to achieve a rough shape of our model. To refine the rough simulation, we apply the same evolutionary computing method to the entire model within a reduced range of possible solutions.

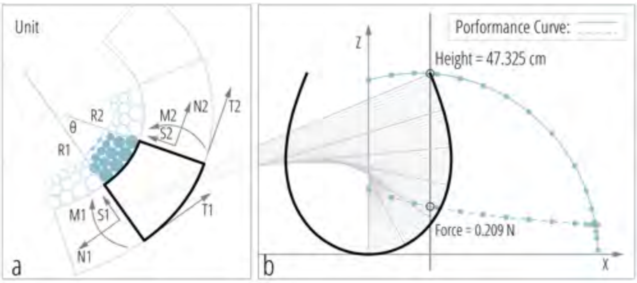

Figure 6: (a) The analysis of force and moment in a single unit with the cell stress and geometric constraint; (b) The shape of basic curve generated by interpolating data from the database.

Fabrication with Bioprinters

Beyond manual pipetting, which is a common liquid application technique in wet labs, we have explored other digital fabrication techniques for more precise deposition of liquid cell solution. Inkjet printing and atomizing are presented as two platforms, one for precise placement of the cell solution for smaller scale and the other for large-scale application (Figure 7).

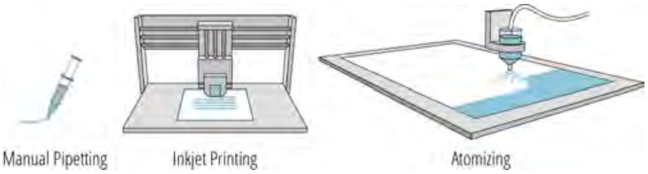

Figure 7: Three fabrication tool options

In both cases, since Table 2 describes that the maximum bending curvature is tightly related to the layer thickness of the cells, we need to control cell layer thickness through a combination of the flow rate and the machine feedrate. To reach a certain curvature under certain RH conditions, we can refer to Table 2 and interpolate a suggested cell layer thickness t. And to reach t, it takes time T:

$$t \times S = v \times T \tag{1}$$

Where S is a certain surface area, v is the machine flowrate.

To allow the deposition to cover the whole surface area S:

$$f \times T \times w = S/z \tag{2}$$

Where f is the machine feedrate, w is the width of the droplet coverage, and z is the stepover of the CNC machine.

Machine feedrate v can be calculated based on (1) and (2):

$$f = v / (t \times z \times w) \tag{3}$$

Inkjet Printer

In order to achieve a higher accuracy of deposition, we assembled an inkjet-based print head (HP C6602A) with a 3-axis computer numeric control system (Zentoolworks). We designed a custom printhead to hold the inkjet cartridge carrier in place, and stabilize two pneumatic tubes to accelerate the drying process of the cell solution by constantly blowing gentle air onto the substrate while printing. Figure 8 shows the printing process. Ultrasonic cleaning is necessary before the filling of empty cartridge.

Figure 8: Inkjet printing process on a desktop CNC machine.

On the software side, we customize the G-code generated by standard CNC toolpath software (Makercam in our case), to disable the control of spindle and Z-axis, and add the control of printhead to make sure that the ink spray will be paused when the printhead has to be lifted up and move to a new location.

Atomizer

We modified a medical atomizer (Model 286-RD, DeVilbiss) that can create a fine mist and connect it to a regulated air supply. The device is mounted to a stationary CNC router (PRSalpha, Shopbot), and the production process can be easily translated and used in an industrial context (Figure 9). Atomizing is good for creating homogeneous coating on a large scale, but is less feasible for depositing arbitrary patterns. The way we create patterned deposition is through masking: laser cut mask with photo-mount spray is attached to the substrate surface before the atomizing process.

Figure 9: Masking and Atomizing process on a stationary CNC machine.

APPLICATIONS

We consider two methods for applying the use of our composite biofilms for the design of responsive interfaces: biofilm as self-contained sensing and actuation system (Figure 10a), and biofilm within a computer modulated interaction loop (Figure 10b). In the self-contained biofilm method, human behavior plays a role in causing the change of RH in the biofilm, so it can be utilized as both an organic sensing and actuation mechanism without additional sensors. In the computer modulated biofilm method, human interaction can be sensed by additional sensing mechanisms to control the RH level for actuation.

We provide five example applications, two using self-contained biofilm methods in "Living Teabags" and "Second Skin;" three using computer modulated biofilms in "Artificial Plants," "Responsive Lamp" and "Animated Toys."

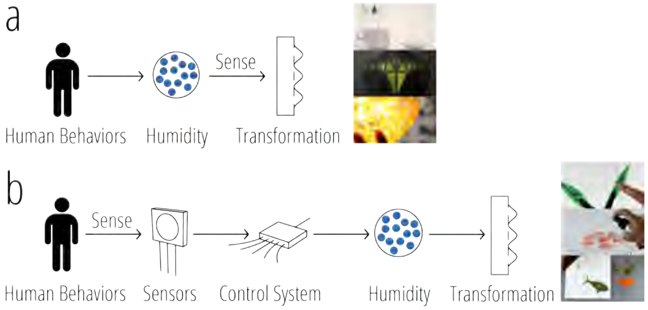

Figure 10: Interaction Loops. (a) Self-contained system with biofilm functions as both sensor and actuator; (b) Computer modulated biofilm incorporates other sensing mechanisms in the interaction loop.

Living Teabag

The leaf on top of the tea bag is curled up in the beginning. After pouring hot water into the teacup, the curled leaf will slowly unwrap to indicate the tea bag is fully soaked in water. Once the tea is ready and the tea bag is pulled out of the cup, the leaf will curl up again to indicate the end of its life (Figure 11). The unwrapping can be triggered by either the steam coming from the hot water, or the capillary force that comes all the way up from the tea bag. Since we can control the length and timing of the capillary movement, the leaf's unwrapping can more precisely indicate the timing of when tea is ready.

Figure 11:Living teabags

Second Skin

If we choose thin Kapton substrate (0.3mil) to synthesize the biofilm, it gets so thin that it reacts to raised human body temperature (Figure 12b,c). We prototype a responsive suit that reacts to the body temperature. It opens up when the skin raises its temperature during running and sweating (Figure12a,d,e). The responsive "Second Skin" creates an ecosystem between the human body and the covering.

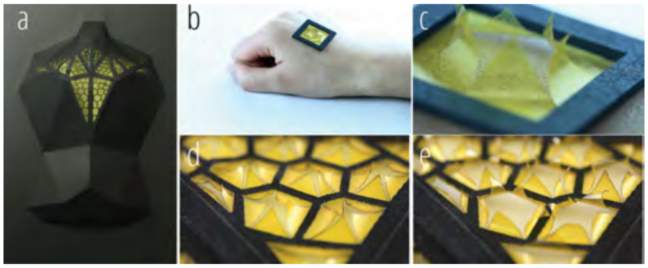

Figure 12: (a, b, c) Biofilm with 0.3mil Kapton substrate reacts to raised skin temperature. (d, e,f) Design of the "Second Skin" as a piece of responsive cloth

Responsive Plants

We print the cell actuators following the vein structure of certain leaves, which creates biomimetic transformation that resembles real, natural organisms (Figure 16). Considering many natural leaves transform due to the gain and loss of water inside the veins, cell actuators swell and shrink to create a similar effect.

With a closed control loop, artificial plants that respond to various stimuli are designed as educational toys. In order to mimic the natural flower changing shape and color at the same time, we mix thermochromic paint into liquid latex and produce our own color-changing film substrate. A flower bouquet is designed to transform in both shape and color (Figure 13a,b,c). When we spray water on them, they change from being curled and umber to expanding and red. The control logic is: the heating circuit below the plate is always on until an equipped humidity sensor detects a water spray.

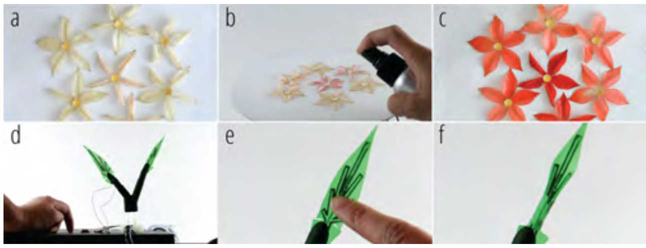

Figure 13: Artificial plants as educational toys. (a,b,c) Flower bouquet that changes both color and form. (d,e,f) Biomimetic leaves that respond to human touch.

Figure 13d,e,f depicts another way to interact with the artificial plants. This leaf mimics the movement of Mimosa, which closes when people touch it. Capacitive sensing uses the same circuitry for heating. Two relay switches control the embedded conductive traces to be connected to either a capacitive sensing board or a direct voltage source for heating.

Animated Toys

Previously, research has used other smart materials to make responsive origami and related objects[13][22][27]. We built a flexible heating board on paper with heating traces made of copper tapes. By folding and unfolding the corner of the card, the heating platform is switched on and off. The paper animals designed with hinges made of biofilm can be animated in real time (Figure 14).

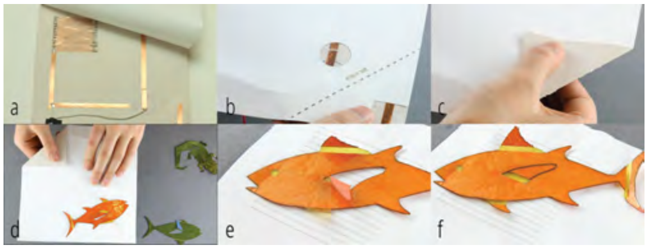

Figure 14: Animated origami toys.

Responsive Lamp

Using one of the 3D folding primitives mentioned earlier, we are able to design a responsive lamp that closes up its lampshade when it is off, and opens up to leak light and create lighting patterns when it is on (Figure 15). Through this example, we intend to demonstrate the fabrication techniques we suggested are easily extendable to more complex systems with more transforming units. All of the actuators on this lamp are fabricated within 12 hours with two experienced fabricators.

Figure 15: Transformable lampshade.

RELATED WORK

Bio-hybrid Cell-based Actuators

As the development of microsystems, such as microrobots, micropumps and micromotors, bio-hybrid cell-based actuators are emerging[2]. Common stimuli types for those actuators include temperature, pH, ionic strength, light and humidity. A tissue engineered robotic jellyfish was created with rat cells [20]. Elastin-like polypeptides (ELPs) are one such class of biopolymers that respond to temperature change [18]. Based on the swelling effect of paper, smart material composited from cellulose has been developed [23].

Based on Carlsen and Sitti's review paper on bio-hybrid cell-based actuators[2], we conclude that so far all the reported systems in this field are submerged in fluid, and none of them utilize relative humidity change as actuation stimuli. In this sense, we introduce a concept to fill in the blank of the non-fluidic humidity responsive cell actuators. The fact that our actuator is simple to fabricate also makes it stand out from other bio-actuators.

Shape Transformation in Soft Material

Kempaiah and Nie have published a review paper summarizing recent progress of shape transformation using soft materials [10]. While mentioned materials in the paper are mainly inorganic or nonliving, we emphasize the natto cell is a living, food-safe organism. The bio-film we produced can be safely integrated into food, wearable and living environments.

For some technical parameters, we compare with other state-of-art soft materials, and conclude the natto cell performance as follows: the required time for synthesizing is moderate, the required expertise level is low, the accessibility for material resources is high, the scalability is high, and the response time is fast. The main limitation of our biofilm is the limited force transferred from cells to substrate, which can be enhanced through introducing covalent binding in the future.

Unconventional Actuators for Shape Change in HCI

Beyond common electric motors, many more types of actuations have been adapted to design shape changing interfaces: Pneumatic actuation [11][26], shape memory alloy [4][8], piezo actuators [19], jamming material [7][21], ferromagnetic fluids [12], etc. Different techniques have their unique benefits: fast prototyping (electric motors), big force and compliant to malleable surfaces (pneumatic actuators), silent and flexible (shape memory alloy), phase transition (ferromagnetic fluids). In this paper, we try to demonstrate both the advantages and challenges of our bio-actuator for HCI.

Hygromorphic Materials

Many natural and artificial materials respond to humidity change by swelling or shrinking, from the fiber in wood to fallen pine cones. Hygromorphic natural materials have been introduced in both scientific and design fields. Scientists have focused on studying and explaining the mechanism behind the hygromorphism of different organisms [6]. A bio-inspired polymer composite actuator was invented to harvest energy through continuously flipping sides [16]. Additionally humidity-reactive wood has been utilized by designers to build architecture scale, transformable installations [17]. Faz pavilion exemplified that humidity reactive natural wood can achieve simple yet ecologically embedded architecture in reaction to its surrounding environment.

Living Organisms in HCI

Study of utilizing living organisms, especially the field of synthetic biology, has gained increasing attention from HCI and the design community. DIYbio has initiated events and hackerspaces around the topic of synthetic biology and has been inspirational to the interdisciplinary research combining biology with HCI and design [15]. Machines, toolsets and communities have emerged in the field of manipulating DNA and life.

Biological sensors have been explored in interface design as well. The importance of including living organisms such as plants and animals into the current sensing mechanisms was addressed [14].

DISCUSSION AND FUTURE WORK

Collaboration Between HCI and Biology

Materiality/matter based interface design and shape changing interfaces are emerging topics in HCI that are gaining more and more attention. By introducing natto cell-hybrid films, we try to broaden the material library that designers in HCI can use. At the initial stage of exploration, collaborating with experienced biologists was critical. Their intuition and expertise led to the accidental finding and the following quantitative characterization of the natto cell actuator. As the project moved to the step of biofilm development, chemical and mechanical engineering knowledge started to play a more important role. For the structure and application design, HCI researchers with design backgrounds played an essential role.

As the collaboration progressed, HCI designers were empowered with an interesting material that has both unique functions and provocative bio-potentials. On the other hand, our biologist collaborators also commented that this was the first time they perceived and studied cells for their actuation capability, rather than their growth, physiology or DNA synthesis. The scientists mentioned they were surprised to see how designers scale up their research results from glass tubes and pipette tips to objects on the table, ceiling and even human body.

Biological Challenges and Opportunities

The uniqueness of self-evolving, self-duplication and self-assembly of living organism can potentially give rise to critical design concepts. For example, we can design shape-change interfaces that grow. With synthesized life, the "behavior" of the transformation can be evolved as life develops.

Until now, the natto cells that have been used are wild-type bacteria and they have not been engineered. However, synthetic biology, which focuses on engineering of the DNA structure, can bring potentially richer characteristics to the material. For example, it is a mature technique to add genes for bioluminescence into the cells. So, potentially, we could engineer our nanoactuators and make them glow in a dark environment.

Engineering Challenges and Opportunities

It has been proven that the cell has a very high energy density, considering a single layer cell (1μm in thickness) can lift up 0.2mm thick latex film. However, simply adding more cell layers will not help to lift up thicker materials, since each layer of cells needs to tightly connect to each other and to the substrate. Also, adding cell layer thickness will increase the time for humidity diffusion and lower the response time. More multidisciplinary engineering research has to be included in the research on bonding method, material processing, mechanical structure design, and stable control of relative humidity for suitable applications.

Design Challenges and Opportunities

Natural-natural hybrid material is an exciting direction. Combining natural organisms with different characteristics dates back to grafting fruits. As one example, by compositing the spore actuators to natural willow leaves, we could make the leaves transform in a desired way when it is about to rain. Thus, the willow tree becomes a transformable and natural installation and also an environmental sensor.

Since the *Bacillus subtilis* natto is food safe, one potential space is actuated food. Food is inevitable for daily life. Rather than just focusing on the taste and presentation, adding interactivities into the experience of eating can be interesting. For example, shape changing food that indicates when the temperature is right for eating.

CONCLUSION

In this paper we have introduced the development of a new biofilm based on living natto actuators for humidity responsive transformable interfaces. As designing shape-change interfaces draw more and more attention in HCI, materiality becomes one of the important aspects we need to be concerned with in design. Through this research, we hope to look beyond hard and inorganic material and reflect: how can we grow living materials and incorporate them into our man-made interaction systems? How do they enable a bigger design space in the myriad of life - things we eat, drink and wear? We believe the unique properties of the cell actuator - being electronic-free, humidity responsive, safe and edible – can enable the design for improving everyday life.

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