Chitosan Biofilm Actuators

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Chitosan Biofilm Actuators - Humidity Responsive Materials for Sustainable Interaction Design

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ABSTRACT

Shape-changing interfaces have been critiqued for not being sustainable despite their promising opportunities for tangible interaction. Incorporating nature inspired passive actuation mechanisms with embedded responsiveness can offer benefits for shape-changing interfaces. We introduce chitosan, a widely available biodegradable and humidity-responsive actuator that absorbs moisture from air and undergoes shape changes in response to fluctuations in humidity. Through explorative yet systematic material driven research through design, we uncover the utility and accessibility of chitosan as a reversible actuator to enable interactivity. We present the characterization of a variety of responsive structures made from chitosan films, combined with a variety of substrates. Outcomes from a generative session with designers/engineers from diverse backgrounds, provided insights into experiential properties and possible applications. We conclude with early prototypes that hold potential for wearables, haptics, self-assembly, and data-physicalization.

CCS CONCEPTS

• **Human-centered computing**; • **Human computer interaction (HCI)**; • **Interaction devices**;

KEYWORDS

Sustainable Actuators, Chitosan, Material-driven Design, Sustainable Interaction Design

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1 INTRODUCTION

Despite the growing interest in actuation beyond screens, tangible interfaces have also been critiqued for not being sustainable [2]. Shape-changing and haptic interfaces e.g. make frequent use of mechanical actuators consuming extensive amounts of energy. Unfortunately, existing sustainability frameworks and concepts for interaction design do not apply to materials with transformative properties, focusing more on disposal, re-use, and heirloom [5]. However, there is a growing interest in Bio-HCI, which uses living and non-living organisms as sustainable design materials [18] but projects have concentrated on fabrication rather than interactivity [4, 12], or visual aesthetics [9], while sustainable approaches are also needed for novel materials, fabrication techniques, and design methods for sensing and physical actuation in materials, e.g., soft robotics [11, 24]. It has been demonstrated that living and bio-degradable materials, such as bacteria [27] and hydrogels [11, 21], can also be used as soft actuators. Thus, scientists from different fields have been inspired by the complexity found in nature, leading to the creation of soft and lightweight robots that aim to replicate or mimic the fluent motion and efficient energy management [11, 16]. Nature provides a range of examples where shape change is achieved through passive actuation mechanisms, without the reliance on external sources of energy. One such example is the intrinsic response of hygroscopic materials, which undergo shape changes in response to fluctuations in humidity.

We introduce chitosan, derived from the second most abundant biomaterial on earth [1], as a biodegradable and humidity-responsive actuator, inspired by its hydromorphic transformation, while focusing on exploring its utilization to support more sustainable approaches to haptic and shape-changing interaction. The research-through-design process started by exploring the fabrication process of creating chitosan films. Subsequently, an exploratory approach was adopted to ascertain how chitosan could be programmed to exhibit reversibility, allowing it to return to its original state after being exposed to a certain relative humidity. The material was characterized, in terms of response time and bending curve, in response to changes in relative humidity. A generative session with experts from different fields resulted in design directions. We contribute chitosan films as reversable humidity responsive actuators

Figure 1: Chitosan film reacting to relative humidity changes.

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in the context of HCI; a variety of possible shape transformations which allow for geometric and organic movement; and four possible applications.

1.1 Related Work

Chitosan is a natural biopolymer derived from chitin, a substance found in exoskeletons of crustaceans such as shrimp, crabs, and lobsters, as well as the cell walls of certain fungi. Chitosan is the second-most abundant biopolymer and has nontoxic, antimicrobial, biocompatible and biodegradable properties. One of the unique characteristics of chitosan is its ability to change shape when humidity levels change, which makes it useful in various scientific fields. In biomedical engineering, chitosan is used to create hydrogels responsive to changes in pH, temperature, and other environmental factors, making it suitable for drug delivery, wound healing, and tissue engineering [23]. In food science chitosan is used as a preservative, edible films and coatings can extend the shelf life of food products [3, 24]. Furthermore, chitosan is used to create fabrics that are wrinkle-resistant, moisture-wicking, and antimicrobial. Its shape-changing properties also help to improve the texture and feel of textiles [29].

Within HCI, various actuators have been introduced, which make use of embedded responsiveness of the material. Shape Memory Alloys e.g., are metals that change shape when heated or cooled. They have been used in shape-changing interfaces because they can be programmed to actuate quickly. E.g., they can animate paper and allow for actuation of clothes [17, 20]. Another type of materials that change shape when heated or cooled are Shape Memory Polymers (SMPs). SMPs are often 3D-printed, or screen printed onto a substrate surface [24, 26]. Furthermore, Electroactive Polymers (EAPs) change shape when an electric field is applied [8, 28]. Unfortunately, these actuators are made from non-sustainable materials and use external energy sources to enable actuation.

To support more sustainable practices in HCI research addressed the use of biological responsive materials. Yao et al. e.g., describe a novel approach to designing interfaces that change shape using living biological natto cells as actuators with Biologic [27]. When exposed to changes in humidity, natto cells contract or expand, allowing for shape change. These promising explorations into biodegradable materials in HCI, unfortunately still rely on non-regenerative materials like Polyethylene terephthalate (PET) and Kapton for actuation. Furthermore, natto cells are not an abundantly available material. Wang et al. [23] introduced the concept of transformative appetite, involving the use of edible films made from commonly available food materials such as protein, cellulose, or starch. These films undergo transformations into 3D food structures when exposed to boiling water. The process is initiated by water adsorption and creates food that has both expressive and sustainable qualities. Also, in the context of cooking, Van Doleweerd et al. [6] explored the potential of shape-changing food materials to enhance culinary experiences. They introduced an edible version of chitosan film to create shape-changing and visually engaging dishes that transform under changes in pH. Both Wang et al. [25] and Van Doleweerd et al. [6] do not elaborate on the reversibility of their transformations and only explain one-way actuation. Finally, Kan et al., introduce Organic Primitives [13], a toolbox to enhance the range of input-output devices in HCI enabling the design of interactions with organic, fluid-based systems. They characterized chitosan as a pH-responsive actuator, which limits the application possibilities to changes in pH. We consequently aim to investigate whether responsiveness to changes in humidity can also be reversible, thereby increasing the application possibilities of chitosan as a bio-based actuator.

2 APPROACH

Our approach draws from both material-driven design (MDD) [14], as well as from material engineering approaches in HCI [e.g. 27]. We first introduce the production of the chitosan biofilm, following the methodology outlined by Kan et al. [13]. Secondly, we describe a hands-on process of exploring suitable substrates, essential for creating a bilayer effect and thus programmability of the material following MDD. Thirdly, we evaluate how relative humidity and time affect the bending curvature of chitosan films to understand the material's performance impact on different applications. We conclude with a focus group involving both industrial/interaction designers and engineers from diverse backgrounds to explore possible applications or functional goals, as well as experiential qualities of humidity responsive chitosan biofilm actuators. Our iterative approach combining creative and engineering foci can be considered as research-through-design [15, 30].

3 FABRICATION PROCESS

3.1 Actuation Principle

Chitosan is a biopolymer (hydrophilic polysaccharide) which has a high affinity for water and can absorb water molecules from its surrounding environment. When a chitosan film is exposed to a humid environment, water molecules can diffuse into the film through the amorphous regions and hydrogen bonds in the polymer matrix, a network of connected polymer molecules in the material structure. This uptake of water causes the chitosan film to swell, leading to an increase in its free volume, which is the space between its polymer chains. This expansion of the material results in greater flexibility.

3.2 Development of the chitosan film

Our biofilm is based on work by Van Doleweerd et al. [6] and Gupta et al. [10]. While Van Doleweerd et al. [6] created a fully biodegradable film from widely available materials, the biofilms produced by Gupta [10] contained materials that are less accessible and even harmful such as sodium hydroxide. Our biofilm consists of three ingredients: chitosan powder, distilled water, and vinegar. When the ingredients are mixed, they form a solution that can be used to create a chitosan film. First chitosan powder 5%wt is mixed with 50% distilled water and 50% vinegar in a container (5mg chitosan per 10ml of mixture). The mixture is stirred to ensure that the chitosan powder dissolves evenly. The acidic solution serves as a solvent for the chitosan. The mixture is heated to 60°C, to promote dissolution of the chitosan powder and to ensure a homogeneous solution. Once the mixture is prepared, it can be cast onto a flat surface. A custom-made acrylic mold of 80x80x4 mm was used (20 ml chitosan solution). Subsequently, the film is placed into a dehydrator for 6 hours at a temperature of 55°C. After drying and

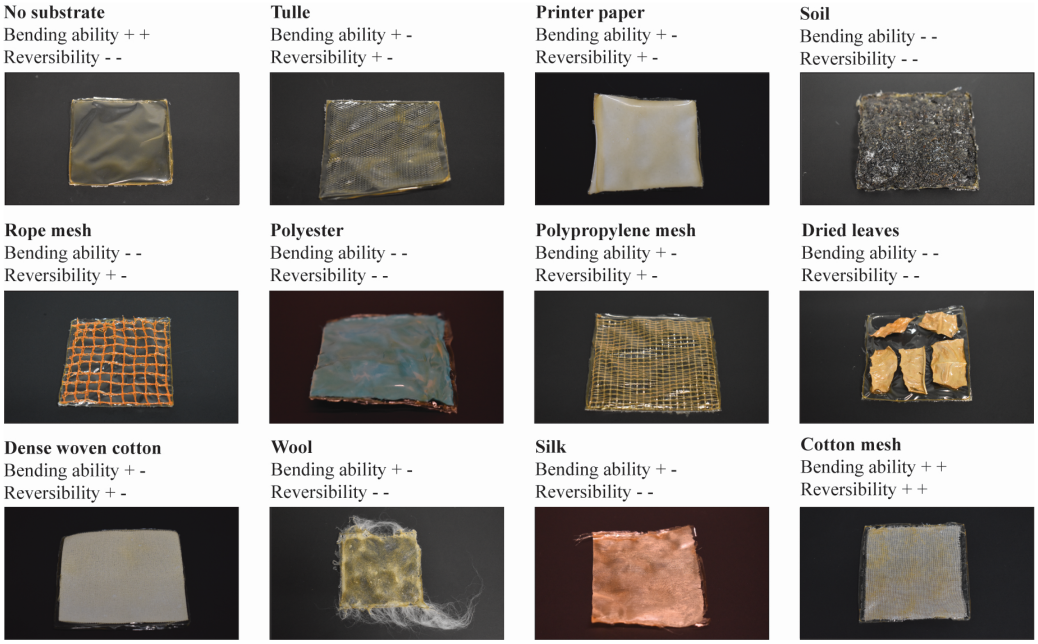

Figure 2: Chitosan film reacting to relative humidity changes.

Figure 3: Chitosan film reacting to relative humidity changes.

reaching its final form, the film is removed from the acrylic mold and collected.

3.3 Development of programmable chitosan film

A biofilm alone lacks the ability to exhibit controlled and programmed movements. To achieve reversible and robust film behavior, a bilayer structure is necessary. We conducted an exploratory process to evaluate various substrates and their impact on actuation capabilities (fig. 2). To create the bilayer film, a thick layer of chitosan solution was poured onto one side of the substrate, while a thin layer was applied to the other side following the steps described in 3.2. This arrangement generated the desired bilayer effect, enabling controlled movements (fig. 3). The bending capabilities and reversibility of the material depends on the substrate’s material properties. Some key properties include stiffness, density, water absorption capacity, attachment to film, stickiness, and firmness. After careful evaluation, we found that woven cotton is the most suitable substrate to achieve our desired outcome. Cotton is stiff when in relatively low humid environment and flexible in relatively high humid environments, resulting in a good bending ability and reversibility.

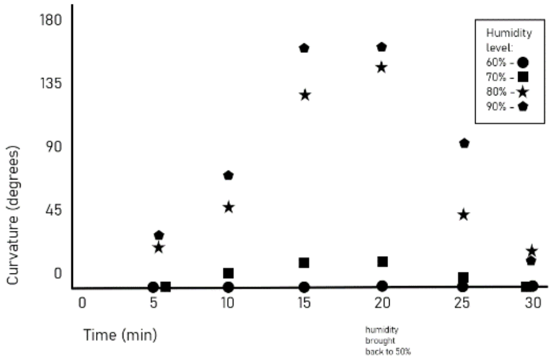

Figure 4: Chitosan film reacting to relative humidity changes. At 20min the maximum curvature was achieved, and humidity level was reduced to room level (50%).

4 MATERIAL CHARACTERIZATION

We evaluated how relative humidity and time affect the bending curvature of chitosan films (fig. 1), which directly impacts the material’s performance in different applications. The films thickness varied between 0.3 and 0.5 mm, inconsistencies resulted from the fact they were handmade. A humidity control chamber including a DHT21 humidity sensor, and a piezoelectric mist maker was developed for our experiments. The movement of four films was recorded by camera at four levels of relative humidity (60%, 70%, 80%, and 90%). To determine the bending curvature, the tip of each film was tracked using JSTrack v1.0, and coordinates were transferred to Excel to calculate corresponding angles (fig. 4).

Figure 5: Interaction with the chitosan films by the participants during the generative session.

5 GENERATIVE SESSION

Towards developing applications for chitosan films, a generative session was organized bringing together individuals from different backgrounds. The workshop was attended voluntarily by students and research employees from various departments of our university, with at least a BSc. Selection of participants was based on their research and project output in domains like wearables, tangible interaction, fluid dynamics, soft robotics, soldering technology, and biomaterials. The workshop consisted of four phases: familiarization, exploration, brainstorming, and a concluding group conversation.

- *Familiarization*, participants got acquainted with the topic and theme of the workshop. They were given an introduction about bio-actuators and chitosan. This background supported them in navigating though the following steps. Subsequently, participants were given a workshop overview and challenge or prompt.
- *Exploration*, participants were given a variety of materials to work with to support the exploration process. Materials included Stanley knives and scissors for cutting the material into desired shapes, skippers, and other clamps for fixing the chitosan films in place, sticky notes, and pens for recording thoughts and to support the thinking and explanation process, as well as paper, wool, acrylic, and glue for assembling the materials. During this phase, participants were encouraged to identify the material qualities and record their thoughts on paper. After the exploration, each participant was asked to share the qualities they had identified with the group. This sharing process helped stimulate participants' creativity and aided the development of concepts for the third phase of the workshop.
- *Brainstorming and idea generation*, participants were asked to make a first prototype/concept using biofilms and support materials (fig. 5). They were requested to write down or draw their ideas.
- *Concluding group conversation*, participants presented their thoughts and ideas in the group. Everyone was encouraged to give feedback on each other's work. The workshop lasted 60 minutes.

5.1 Data collection an analysis

Undisguised observations were made of participants and their interactions, noting any relevant behaviors or actions. Photographs were taken capturing the room as well as any materials and interactions between material and participants during the sessions. Audio recordings made of conversations and discussions were transcribed and salient quotes were marked. Transcriptions were analyzed using open and inductive coding, by assigning codes to quotes based on represented concepts. Following the coding process, quotes were grouped into the three themes described below by thematic analysis.

6 OUTCOMES

6.1 Material Properties

Participants were able to identify and explain different material qualities. Differences were noticeable depending on the scientific background of participants. Participants with an engineering background focused mostly on mechanical properties and participants with a design background focused mainly on experiential and sensorial qualities of the material. Regarding sensorial qualities three participants indicated not liking the material as it was provided to them, because they did not like most of the sensorial qualities. One participant suggested to add food coloring to change the material's color. Three participants started coloring the material. Participants mentioned mechanical characteristics, e.g. that the material allows for making folds and has a certain resistance. They were surprised by its bendability and flexibility.

6.2 Manufacturing Processes

Participants suggested how to manufacture the chitosan films, to make them more suitable for aesthetic interactions, and create different shape change configurations. One mentioned a control method for actively controlling the water on the film, by capillary principle. They also proposed a variety of manufacturing techniques to create

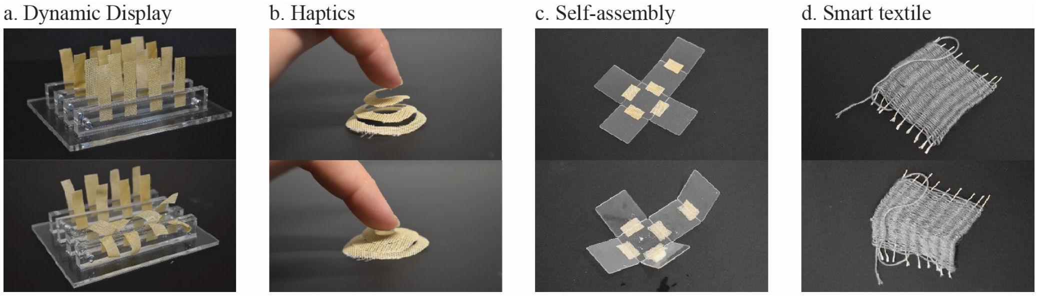

Figure 6: Early-stage prototypes of the four application possibilities.

diverse shape and application configurations and discussed fabrication methods. Screen printing was mentioned by a participant to apply chitosan coatings onto surfaces with precision. 3D printing was mentioned for creating 3D shapes, although the challenge of long drying times for the chitosan solution was acknowledged. Two mentioned traditional textile processes like yarn spinning, envisioning chitosan-infused textiles for innovative applications. To tackle the drying time issue in 3D printing, participants suggested exploring advanced drying technologies or experimenting with chitosan formulations optimized for quicker setting, paving the way for more efficient production of chitosan-based configurations.

6.3 Application Possibilities

Four application directions for chitosan films were derived from the MDD process as well as from the generative session.

6.3.1 Dynamic Display. Dynamic displays can provide feedback, present information in a visually appealing and contextually relevant manner, and guide users through complex tasks or processes. By dynamically adjusting the display, designers can highlight important information, provide visual cues, and assist users in achieving their goals more effectively. To demonstrate the dynamic display a 4x4 matrix was created consisting of strips of chitosan film mounted in clamps (fig. 6a). When humidity levels rise, the films bend in one direction. The bending of the films can create a visual sign.

6.3.2 Haptics. Haptics allow a device or system to provide tactile sensations to a user in response to their actions. Chitosan in the configuration of a spring allows for humidity adjustable force feedback. The spring stiffness depends on the elastic properties of the spring, when chitosan films are exposed to higher relative humidity, they become stiffer. This principle was demonstrated with a button consisting of a spiral spring cut from a sheet of chitosan with a round piece attached to the top (fig. 6b) whereby force feedback can be adjusted through changes in relative humidity.

6.3.3 Self-assembly. Self-assembly enables the creation of self-reconfigurable systems in soft robotics, where components autonomously reorganize to adapt to different tasks or environments. To demonstrate the self-assembly and foldability of the film, a cube of 0.5 mm thick acrylic plates was created (fig. 6c). When water is applied onto the surface the flat sheet will fold into the shape of a cube. Self-assembly is also possible using origami as the material is both stiff and allows for making folds.

6.3.4 Smart textile. Chitosan can be used as a component of a smart fabric. Instead of using electronics, chitosan can be used as a sensor and actuator. E.g., a thread coated with chitosan can be used to create garments with moisture-wicking properties. When the humidity levels rise, the thread can expand or change its shape, allowing the fabric to open and promote better airflow. Also, it can activate a fan or cooling mechanism to help regulate the wearer's body temperature. To demonstrate this, a woven textile was created (fig. 6d). When humidity levels rise, the textile transforms from flat to a curve-like shape.

7 DISCUSSION AND CONCLUSION

We introduced chitosan as a bio-degradable humidity responsive soft actuator in the context of sustainable soft robotics [11, 19] for Design-HCI. Our material development allows for reversible actions by creating biofilms that can work autonomously as both sensor and actuator. Chitosan is an abundant material, and we propose an accessible process for creating different shapes and configurations. Following discussions with designers and engineers from diverse backgrounds, we identified how chitosan actuators can enable interactivity in e.g., data physicalization, haptics, self-assembly and, wearables. The proposed responsive structures and transformations could contribute to more sustainable approaches of actuation in tangible interfaces through shape change as requested by Alexander et al. [2].

Achieving intricate configurations with chitosan poses challenges due to the complexities of the formation process. 3D printing and laser cutting are suggested a promising processes for exploring and realizing more intricate configurations in actuation. Although the percentage of chitosan solution decreases relative to the overall material, the actuation process becomes more difficult due to increased material weight. The adaptability and flexibility of textiles make them an ideal material platform for integration of sensing, actuation, and control as well as for interaction with the human body.

Challenges were identified in relation to fabrication, freedom of form, and response time. The films were produced using a manual casting process, but the current molds did not support consistent thickness throughout the drying process affecting the control accuracy. Future work could explore the possibility of creating flat structures by neutralizing the film with sodium hydroxide, thereby increasing the strength of the chitosan film as proposed by Fernandez et al. [7]. Secondly, chitosan presents challenges when shaping it into three-dimensional forms, making molding and 3D printing intricate tasks. Its development requires direct exposure to air and long drying times, limiting its actuation possibilities. Finally, chitosan films with a substrate have a relatively low response time, restricting the application possibilities to slow interactions. We proposed a set of potential applications based on expert sessions and observations throughout our research-through-design process. The multidisciplinary session ensured that not only design perspectives were considered but also mechanical, electrical, and experiential properties of the material. Building on work on bio-based [27], bio-degradable [25], and chitosan actuators [6] we developed a reversible actuation and manufacturing process that will allow designers to develop bio-degradable actuation in their interfaces, contributing to more sustainable approaches in Design-HCI. Future work will explore other biopolymers with e.g., cellulose towards expanding the library of sustainable actuation materials.

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