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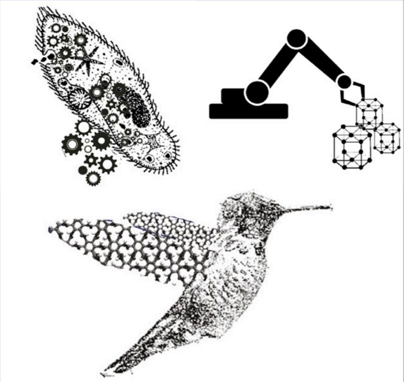

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Hygromorphic living materials for shape changing

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3.1 Introduction

In recent years, as a subfield of biomechanics, natural transformational mechanisms have been studied, from observing the phenomenon in the early 20th century to understanding the underlying mechanisms assisted by advanced scientific equipment currently. Due to the better understanding of those material behaviors and structures, the development of synthetic transformable materials inspired by those moving organisms has become an emerging field. However, most of the development is still constrained within the biological and material science community; scientists have been suggesting how those transformable materials can be used for future biomedical devices or aircraft, but application development is still limited; their major research focus so far is to develop materials, not to design applications with those materials.

3.2 Hygromorphs in nature

Living organisms (with plants as the main focus of this chapter) can generate motions and deformations in response to various environmental stimuli. The Power of Movement in Plants, Volume 27 in The Works of Charles Darwin, describes in detail how plants move in response to light and gravity. More recently, Burgert and Fratzl categorized actuation systems in plants and fungi into four groups: cell growth, turgor pressure, cohesion force, and cell wall swelling. Each type has different mechanisms and different engineering lessons to teach [1].

Another thorough investigation into the physical limits and design principles of plant motion was presented by Skotheim and Mahadevan [2]. In their paper they presented a spatial-temporal map, to group plant motion into three categories: swelling/shrinking, snap-buckling dominated, and explosive fracture dominated.

Under the context of robotics development, this map is very informative, since robotic design is also connected to both temporal and dimensional scales. For a specific scenario, we could choose the corresponding natural mechanisms to study. From the map, we can tell that swelling/shrinking based plant motion is the biggest but also the slowest group, and the time needed for a transformation to finish varies from tens of microseconds to days. For a motion type that is not sensitive to timing, or that requires slow reaction, a swelling/shrinking based material mechanism is ideal; similarly, if we look for faster shape changes, we should study snap-buckling dominated phenomena or explosive fracture dominated phenomena. For both phenomena, prestored stress energy exists in the tissue. While snap-buckling is a pure topological change, explosive fracture actually involves tissue tearing. A lot of desert plants use explosive fracture to disperse their seeds.

In this chapter, we focus on investigating swelling/shrinking based plant motion.

3.2.1 Nature's hydraulic shape change: Hygromorph

Reyssat and Mahadevan gave a definition of hygromorphs, which refers to objects that respond to environmental humidity by changing their shape [3]. In the same paper, they studied pine cones as an example of hygromorphs and implemented a bilayer composite to mimic the behavior of pine cones with manmade materials. All the swelling/shrinking phenomena described in the aforementioned spatial-temporal map for plant and fungal movements are defined as hygromorphs. It is a widely abundant and adapted technique nature uses for transformation.

Many natural materials respond to changes in environmental humidity. The phenomenon has been observed and studied at different scales, from organic molecules to the entire organ and systems.

3.2.2 Historical study and adaptation of natural hygromorphs

We have a long history of using natural hygromorphic materials, perhaps inspired by simple observation and life experiences. The sensor and actuator component within one of the oldest analogue hygrometers is a human hair. The length of a human hair increases by 2%–2.5% when the relative humidity changes from 0% to 100%. There are variations made of plant fiber and animal gut. A folk art "weather house" follows a similar mechanism.

Wood shrinking and swelling due to relative humidity in the environment was observed earlier in human history as well. Indeed, shrinking and swelling of wood have been very tricky problems for furniture designers and construction engineers. Warping of tree trunks and warping of wooden floors and furniture have been issues to tackle. The swelling and shrinking are not uniform across all wood plants. In wood work, three types of distortion can be induced depending on the shape of the board and the orientation of the wood cells: cupping, checking, and radial cracking.

3.2.3 Mechanisms of hygromorphs explained through case studies

We can observe a pattern in terms of how each organism is studied: behavioral observation, structure and mechanism analysis, simulation, and lessons. Each organism may be studied over decades by several generations of scientists. Earlier study focus on behavioral observation; with more advanced instruments and understanding, study of material structure across scale enables us to understand the plant behaviors.

3.2.3.1 Pine cone: Bending induced by a bilayer structure with differentiated microfibril distributions

Here we talk about how the distribution of nanofibrils inside the cell wall can affect the bending of a pine cone scale. Although there are still a few structural hierarchies between nanofibrils and pine cone scales, including macrofibrils, primary cell wall, cell wall and cell, the literature study tends to simply skip those hierarchies. This is because the structural constraints that really matter are the orientation and distribu- tion of the microfibrils, and all the other parts of the cells are simplified into a soft matrix.

A change in the relative humidity causes a closed, tightly packed cone to open grad- ually. Study shows that the transformation is due to the bilayer structure of the indi- vidual scale that changes conformation when the environmental humidity is changed. The deformation mostly happens at a small region close to where the scale is attached to the center of the pine cone [3,4].

The mechanisms can be explained microscopically. In the primary cell wall, there is cellulose as the rigid scaffold, and pectin and hemicellulose form the soft matrix (polysaccharides). Cellulose contains bundles of microfibrils, and the orientation of the microfibril bundles determines the orientation of the rigid scaffold inside the pri- mary cell wall. When relative humidity increases, the soft matrix will absorb water and swell and the rigid scaffold stays the same. The rigid scaffold also functions as a constraint and prevents the matrix from swelling along the longitudinal direction of the microfibrils.

For a pine cone scale, the transformable tissue can be divided into two layers consisting of two different cell types: the outer layer is composed of sclerids (20–30 μm diameter, 80–120 μm long), and the inner layer is composed of fibers (8–12 μm diameter, 150–200 μm long) [5]. Although two cell types are roughly made of the same ratios of material components, the orientations of the rigid scaffold (microfibrils) are different. In sclerids (inner layer), the microfibrils are wound around the cell allowing it to elongate when damp. In fibers, the microfibrils are oriented along the cell and prevent it from elongating when damp. The pine cone scale tissue therefore functions as a bilayer strip and bends in response to humidity change.

3.2.3.2 Erodium awns: Coiling induced by a single layer structure with differentiated microfibril distributions

Similar to the pine cone scales introduced before, here we again talk about how the distribution of nanofibrils inside the cell wall can affect the transformation of the plant’s part, in this case the erodium awn. Although there are still a few structural hier- archies between nanofibrils and pine cone scales including macrofibrils, primary cell wall, cell wall and cell, the structural constraints that really matter are the orientation and distribution of the microfibrils, and all the other parts of the cells are simplified into a soft matrix.

A single layer cell with anisotropic microfibril distribution can induce coiling.

This is a common mechanism of a group of grass awns.

Seed self-burial through hygromorphic transformation is commonly observed and well studied in plant awns, which have a long tail and a seed at the tip. Hygromorphic self-burial has been observed in black oat grass (*Stipa avenacea*), wiregrass (*Aristida tuberculosa*), musky heron's bill (*Erodium moschatum*) and pinweed (*Erodium cicutarium*) [6–10].

Evangelista et al. captured the process of *Erodium cicutarium* awn transformation and accurately modeled the behavior geometrically [9]. The awn stays straight before it detaches from the main body of the plant. Due to the prestored elastic energy, the awn tail forms a helix after it is detached from the plants. The hygromophic phenomenon happens during the seeding process of the awn: the awn unwinds itself when it is wet, and slowly rewinds during the drying process. If on sandy soil, the unwinding process will help the awn to settle in gaps of the sand and orient the awn in the right direction for seeding. After a few iterations of winding and unwinding, the seed will be eventually drilled into the soil. In addition, it is observed that the seed is surrounded by stiff hair-like barbs that help the seed to hold into the ground once seeding is started [6]. As a result, the alternate wetting and drying of the awn won't withdraw the seed easily.

From the perspective of designing a responsive and shape-changing material, it is a beautiful response. Since seed germination is most effective when there is enough water, these grass awns have designed their own responsiveness and caused their seeding process to occur when the environmental conditions are beneficial.

Scientists did not stop at observing the phenomenon. They studied the material structures on a microscopic scale and tried to understand the fundamental mechanisms. With limited imaging techniques back in 1990, Murbach was able to observe the anisotropic fiber alignments inside the awn cells of *Stipa avenacea*, after treating the cell with caustic potash and glycerine. He described the "striations quite well marked, passing obliquely across the cell." The orientation of the striations[1] was opposite on the opposite side of the cell. The spiral cellulose structure inside the cell wall expanded and shrunk in response to the change in humidity and generated the hygro- scopic torsion.

More recent publications [11,12] have explained the mechanisms more thoroughly. Unlike common bilayer hygromorphic structures, the helical transformation is achieved by cells of a single layer. Like other plant cell walls, the cell wall contains a swellable matrix and stiff cellulose microfibrils. The microfibrils form a helical scaffold. When the cell wall dries, the matrix contracts against the cellulose microfibril scaffold and forms a spiral. More interestingly, the authors pointed out that, while the hypothetical constant microfibril angle (MFA) can induce twist, the actual chang- ing MFA will cause both bend and twist—a helix as a combination effect.

[1] Later study showed that the observed striations were microfibrils inside the plant cell wall.

3.2.3.3 Selaginella lepidophylla: Curling induced by a graded lignin distribution

Unlike the pine cones and grass awns introduced before, literature studying Selaginella lepidophylla has paid attention to its lignin[2] distribution rather than microfibril distribution. My guess is that microfibril distribution is more or less the same across the stem of *Selaginella lepidophylla*.

In 1980, Eickmeier described the stem movement of *Selaginella lepidophylla* [13]. *Selaginella lepidophylla*, commonly called fake rose of Jericho, is an ancient plant native to the Chihuahuan desert (Mexico and United States). It shows a dramatic curling and uncurling in response to plant hydration. Early literature was able to elucidate that the movements of the tissues are physical rather than biophysical. Such movement depends on the hygroscopic capacities of the tissues [14,15]. It is commonly described as a "resurrection plant" as it turns green when it absorbs water and opens up. Very recently Rafsanjani et al. were able to identify the mechanisms for the different transformation behaviors between the inner and outer stems; in addition, they were able to simulate the transformations and generate variations of similar behaviors with a computational model [16].

In this paper [16], Rafsanjani et al. observed that both inner and outer stems were flattened when hydrated. Upon dehydration, the outer stems bent into a circular ring in a relatively short time, whereas the inner ones curled into a spiral slowly. In their paper, two questions were answered: Why do the stems curl? And, why do the inner stems curl differently as compared to the outer stems?

The stem of *S. lepidophylla* is composed of a ring layer of cortical tissue and an inner vascular bundle. The transformation is due to the lignin distribution within the cells that form the cortical tissue. Microscope images showed that the cells are smaller and more densely packed on the abaxial (away from the center of the plant axis) side than the adaxial side, which means there is more lignin on the outside than the inside of a stem. During the stem transformation, lignin is considered the passive component and other soft matrix materials within the cortical tissues are considered active components. As the more active side (adaxial side) swells and shrinks, the stem flattens and curls, respectively.

For the outer stem, we can consider that the lignin distribution from the base to the tip of the stem is even. As a result, the outer stem curls into an arc. For the inner stem, the lignin distribution varies from the base to the tip of the stem. The uneven lignification of the cells across the stem causes the inner stem to curl into a spiral with uneven bending angles. In the later computational model, the authors were able to capture the curling variations due to the lignin distribution. The intermediate transformation states were simulated as well.

From a material composition perspective, *S. lepidophylla* is different from pine cones and grass awns, as the passive components are considered as 1D (particles, or very short fibers) rather than 2D (long fibers).

[2]Lignin is a constituent of the cell walls of almost all dry land plant cell walls. It is the second most abundant natural polymer in the world, surpassed only by cellulose. It is distributed in between cellulose bundles. Source: https://en.wikipedia.org/wiki/Lignin.

3.2.4 Summary of hygromorphs

Hygromorphic plants and microorganisms can be categorized in different ways. In order to better describe or understand hygromorphs from morphological and temporal perspectives, we map the aforementioned cases into a spatial-temporal space. From Fig. 3.1, we see that hygromorphic actuation induces different types of spatial transformations, including bending, 2D coiling, 3D coiling, drilling, volume changing, and folding. While some actuation reaches an equilibrium within seconds, the others take minutes or hours. Another way to understand and categorize hygromorphic behaviors is based on actuation mechanisms. On a higher level, there are two types of material structures that can induce hygromorphic shape changes: isotropic material and anisotropic material. For anisotropic material, we observe three submechanisms: fiber orientation, cellular organization, and lignin distribution (Fig. 3.2).

3.2.5 Design lessons and opportunities

3.2.5.1 Electrical signal-free actuation

Most of the current shape-changing interfaces still rely on electrical signals: sensing and actuation have to be powered by electricity, while the trigger of the reaction has to be sent in the form of an electrical signal. By default, information is assumed to be sent via an electrical signal. For natural responsive materials, interaction can happen without any electrical signal–triggered stimulus. This thesis will demonstrate that, in my cases, an electricity-free interface can be more efficient and effective.

3.2.5.2 Hierarchical structure

It has been copiously reported that natural organisms are composed of hierarchical structures. Macroscopic functions and performance are determined by microscopic material composition and hierarchical material structures. Well-engineered and hierarchical transformable architecture in nature serves as an inspiration for our hybrid systems. A pine cone orients its actuators (fibrils composed of cellulose) differently on the upper and bottom sides of the scale in order to achieve transformation and dis- perse seeds. Wheat awns use similar anisotropic strategies; however, they differentiate their fibril orientations from the outside to the inner part of the awns. This thesis tries to demonstrate that looking into biological actuating systems can inspire the architectural design of a synthetic material system.

3.2.5.3 Coupling of sensing and actuation

In a common physical interactive system, there are sensors for sensing input and converting the input stimuli into digital signals. In addition, there are embedded microcontrollers to receive the digital signals and compute output based on a certain logic. Finally, actuators generate certain output based on the control signals coming from the microcontrollers.

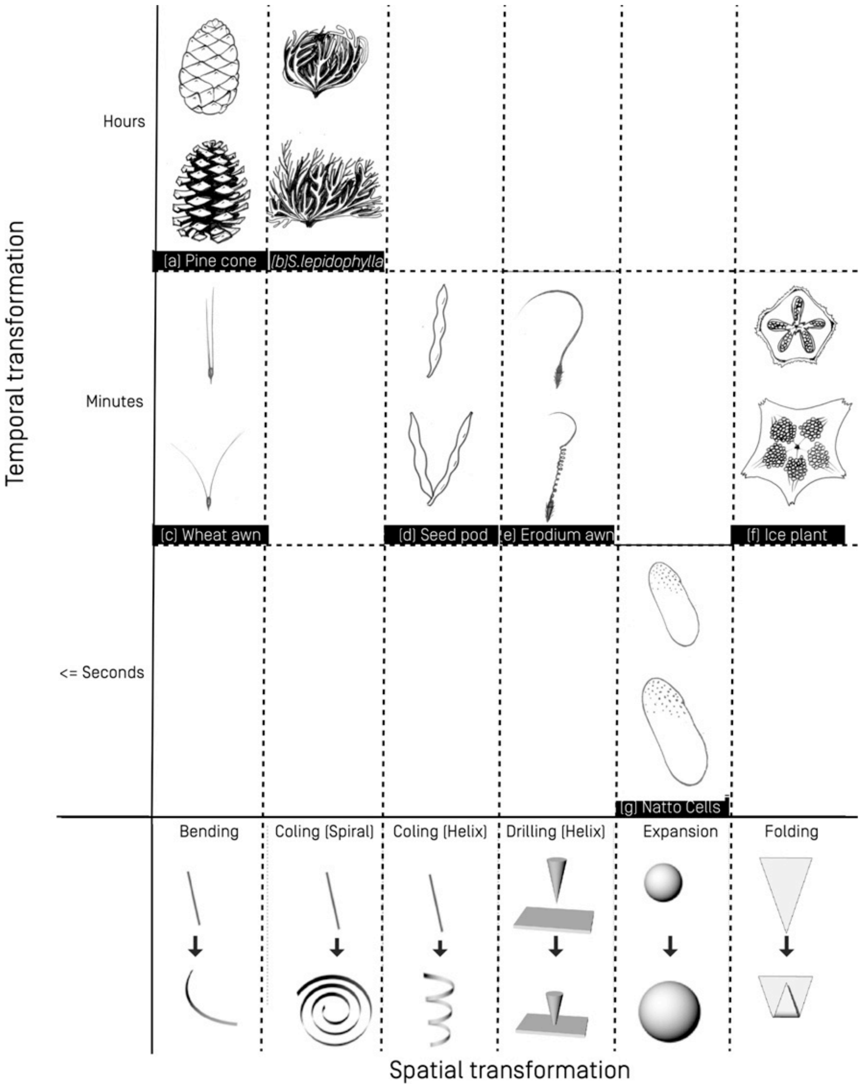

Fig. 3.1 The spatial and temporal map of hygromorphic actuation in plants and microorganisms. (A) Pine cone scales bend during a duration of hours. (B) *S. lepidophylla* coils into spirals during a duration of hours. (C) Wheat awns bend during a duration of a few minutes. (D) Chiral seed pods coil into a helix during a duration of minutes. (E) Erodium awns drill into a helix during a duration of minutes. (F) Ice plant seed pods unfold during a duration of minutes. (G) Living bacteria, natto cells, expand and contract within subseconds.

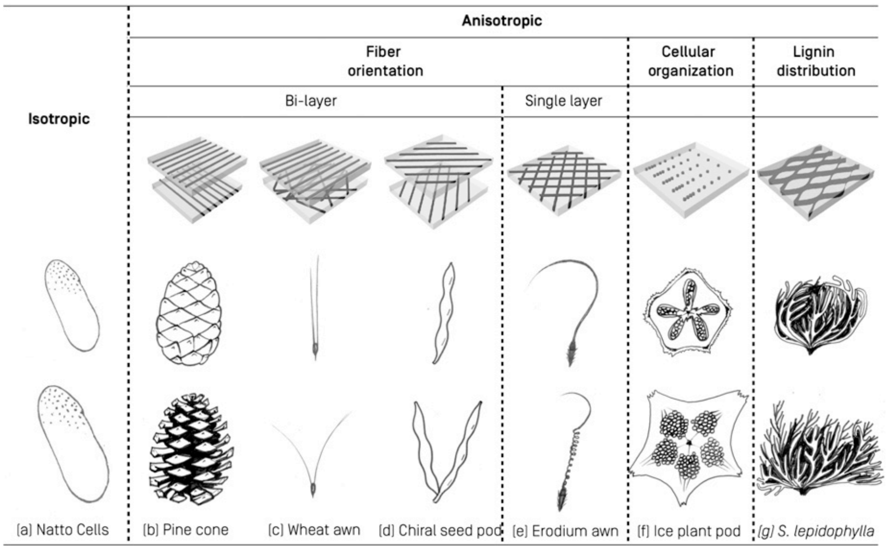

Fig. 3.2 The categorization of hygromorphic plants and microorganisms based on the actuation mechanisms. (A) Living bacteria, natto cells, expand and contract within subseconds. (B) Pine cone scales bend during a duration of hours. (C) Wheat awns bend during a duration of a few minutes. (D) Chiral seed pods coil into a helix during a duration of minutes. (E) Erodium awns drill into a helix during a duration of minutes. (F) Ice plant seed pods unfold during a duration of minutes. (G) *S. lepidophylla* coils into spirals during a duration of hours.

However, actuation systems in nature often have coupled sensing and actuation through material computation. In the case of hygromorphic behaviors in plants, the plant tissue senses the changes in relative humidity and responds with shape changes. The sensing and actuation come from the same material system. It is a highly integrated and efficient interactive system and fulfills the adaptive demands of plants for survival.

3.2.5.4 Fibril distribution, cellular organization, and lignin ratio

While each plant cell has roughly the same structure, hygromorphic transformations can be determined by different structural rules. For example, the pine cone scale bends because of the anisotropic fibril distribution, while the ice plant seed capsule unfolds due to the cellular organization, in which case the fibril distribution plays a less important role compared to the case of the pine cone. In addition, the transformation of *S. lepidophylla* is due to the heterogeneous distribution of lignin.

In the following section, when we talk about the design strategy of shape-changing composites, we introduce the concept of a shape-changing matrix composite (Fig. 3.4). Under this framework, the distributed fibril can be considered as a one-dimensional dispersion phase, the cellular distribution as a three-dimensional dispersion phase, and the lignin distribution as an isotropic dispersion without dimensions (points).

3.2.5.5 Programmability

It is intriguing to observe the programmability of behaviors from hygromorphic plants. In the case of *S. lepidophylla*, it uses material composition to program its bending curvature. In the case of the ice plant seed pod, it unfolds only when the relative humidity reaches a certain threshold. Those conditional behaviors were programmed with logic through the structure and composition of materials.

3.2.5.6 Structural assistance

Plants transform for a reason: the survival of the current generation or the next generations. In this chapter, we introduced two hygromorphic plants that transform for seed dispersion, i.e., erodium awns and wheat awns. Although their transformation mechanisms are different, they share common structural components—microbristles, or micro- barbs. These bristles help to prevent the awns from moving upwards during the transformation circles. So the only direction the awns can move is pointing down, once the bottoms of the awns are embedded into the soil. The combination of the microbristle structure and the coiling motion turned some grass awns into active botanical ratchets.

This teaches us that to design for function is to think about the design problem holistically. Structural components can be very helpful for the major shape-changing motions.

3.2.5.7 Lens of evolution and interaction

Nature not only teaches us science and mechanisms, but also teaches us interaction and design. Interaction is about action and reaction. Evolution tries to accomplish the same task for the purpose of survival. For example, hygromorphic plant tissues sense the environmental stimuli, relative humidity, or water gradient, and respond with shape changes. The shape changes correspond to certain purposes, including seed releasing, seed dispersal, or maximum growth. Such natural behaviors have high level design indications for autonomous robotic systems as well.

3.3 Shape-changing matrix composite

In order to design shape-changing composite material, we have to identify the shape-changing unit and the composite material structure. We introduce two concepts, a shape-changing material unit (SCMUnit) and a shape-changing matrix composite (SCMC). An SCMUnit and an SCMC have a recursive relationship. An SCMC comprises the matrix phase and the dispersion phase. For either the matrix phase or the dispersion phase, it can comprise an active unit (namely, an SCMUnit) or an inert unit. Each SCMunit can be made out of an SCMC structure. This SCMC model was inspired by pioneer work in ways of modeling composite material design, especially composite material [17], particle composite [18], matrix composite [19], functional graded materials [20,21], and fiber and grain models [22]. We try to customize a model to explain the fundamental building blocks of a shape-changing composite, especially bio-inspired hygromorph composites.

3.3.1 Shape-changing material unit

In order to design shape-changing interfaces with responsive materials, we have to first identify the SCMUnit.

Although the macroscopic hygromorphic behavior is always determined by the microscopic material composition and structure, from an interaction design perspective, there is always a starting material or a starting unit, which is called the "material" during the design process. For example, wood can be used based on different starting units: wood barks, wood veneer, and cellulose fibers. Hygromorphic behaviors can be observed and utilized on different unit scales. For example, the warping of a wooden floor is due to the hygromorphic behavior of wood barks; a hygromorphic pavilion is designed from wooden veneers and responds to the natural environmental conditions [23]; while a hygromorphic chair is 3D printed from filaments comprising cellulose powders extracted from wood tissues.

It is critical to identify the starting unit of a material to study, because designers who would like to build responsive pavilions out of wood veneer perhaps do not need to study the hygromorphic behavior of the wood cellular components. Instead, the hygromorphic behavior at the veneer scale is more relevant. We call such a unit an SCMUnit.

3.3.2 Shape-changing matrix composite

An SCMC is composite material with at least two material elements, one being a continuous *matrix phase* and the other being a *dispersed phase* (Fig. 3.3). SCMC is a special type of composite material. The unique characteristic of SCMC as compared with other composite materials is that either the dispersion phase or the matrix phase has to be made of SCMUnits. SCMC can dynamically change physical properties under certain stimuli.

The *matrix phase* is one continuous isotropic material, which has its own form and size. The *dispersed phase* can be divided into four types based on its form factor: isotropic unit (no connectivity), fiber (1D connectivity), surface (2D connectivity), and volume (3D connectivity). An isotropic unit can be described in terms of size, density, and distribution; all the other form factors can be described in terms of form, size, orientation, density, and distribution (Fig. 3.3).

An SCMC can be further categorized by the types of combinations between the matrix phase and the dispersion phase: the active matrix phase containing shape changing material units (SCMUnits) combining with the inert dispersion phase, or the inert matrix phase combining with the active dispersion phase composed of SCMUnits.

This SCMC model can be used to describe natural hygromorphic transformation composites. Fig. 3.4 shows five variations of an SCMC from nature: (A) erodium awn cell wall; (B) pinecone scale tissue; (C) ice plant seed pod; (D) outer stem of *Selaginella lepidophylla*; (E) inner stem of *S. lepidophylla*.

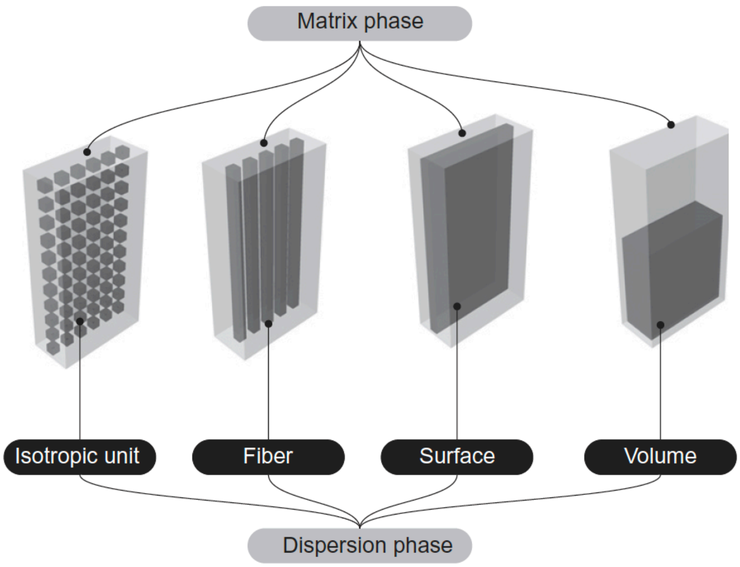

Fig. 3.3 An SCMC is composite material with at least two material elements, one being a continuous matrix phase and the other being a dispersed phase. Either of these two material elements must be composed of SCMUnits. The *matrix phase* is one continuous isotropic material, which has its own form and size. The *dispersed phase* can be divided into four types based on its form factor: isotropic unit (no connectivity), fiber (2D connectivity), surface (2D connectivity) and volume (3D connectivity).

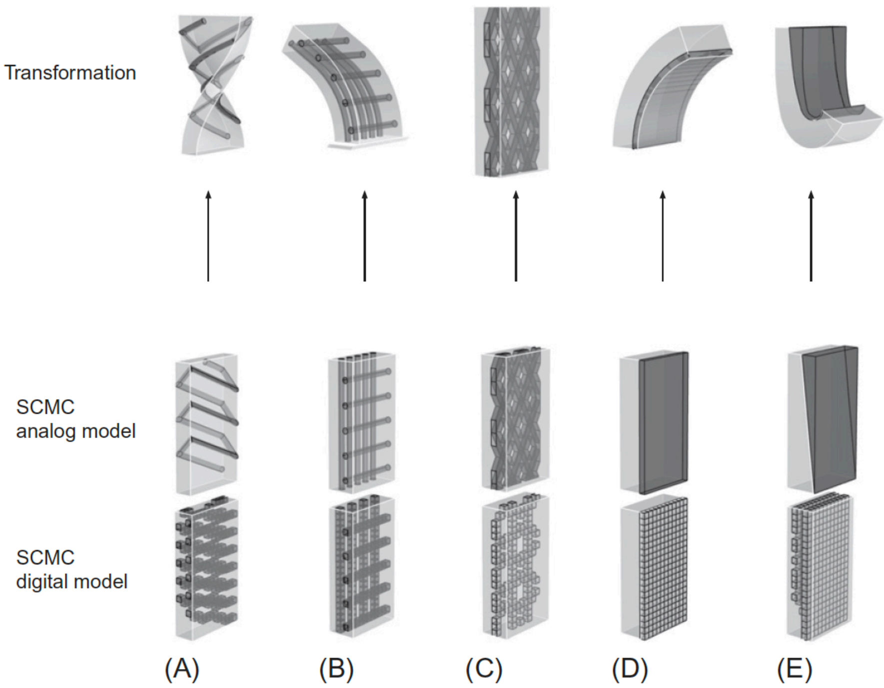

Fig. 3.4 Five variations of an SCMC from nature: (A) erodium awn cell wall; (B) pine cone scale tissue; (C) ice plant seed pod; (D) outer stem of *S. lepidophylla*; (E) inner stem of *S. lepidophylla*. The structures are chosen at different scales and different hierarchies

3.4 Shape-changing matrix composite: Hygromorphic bacteria

In this section, I will briefly describe a project I previously worked on as one example of the SCMC model introduced before. Together with a group of collaborators, I have participated in a series of publications introducing different aspects of the project, including mechanisms of the material [24], biotraceable and multifunctional aspects [24], composite material structure and applications [25], bioprinting tools [26], etc.

Looking at nature, from the wilting of flowers to the opening of fallen pine cones, biological sensors and actuators are omnipresent. Utilizing such mechanisms from nature, by way of integrating living organisms into design and engineering, has gained increasing interest among scientists and engineers [27,28]. One of the biggest advantages of such responsive systems is the integration of sensing and actuation in one material. In contrast, in engineered systems actuators and sensors are often decoupled. Customized sensors and actuators will be chosen to close an interaction loop. For example, in order to design a sweat-responsive garment, sweat and temperature sensors will typically be embedded at certain locations around the body. The sweat signals will be transmitted to a central computational unit, which will send out signals to activate the corresponding actuation through embedded, electrically triggered actuators.

In short, nature has engineered its own actuators, as well as the efficient material composition, geometry, and structure needed to utilize its actuators and achieve functional transformation. We recently published a series of papers [24–26], based on the natural phenomenon of cells' hygromorphic transformation, to introduce the living Bacillus subtilis natto cell as a humidity-sensitive nanoactuator.

The hygromorphic phenomenon of cells has been well studied, especially with regard to some plants, such as pine cones and wheat awns [1]. We observed similar hygromorphic behavior in the B. subtilis natto cell. By varying the relative humidity around the cells, the size of the cells can reversibly change.

3.4.1 Actuators grown rather than made

For robotics or other engineering applications that require actuation, we often use electromagnetic-based actuators. Ever since Tesla invented electromagnetic motors, the term "actuator" has been associated with electrical motors. It is inspiring to envisage a type of actuator that is grown rather than made, and cultured in a wet lab rather than manufactured in a factory. Using living cells as actuators involves several distinctive advantages: they are electronics-free, safe and edible, lack wires or tubes, and have quiet transformation, potential biological synthesis, self-reproduction, and liquid deposition flexibility.

3.4.2 SCMUnit: Bacteria

In a recent Science Advances paper we published [24], in order to quantify the transformation, we equipped an atomic force microscope (AFM) with a customized humidifier. We applied an air stream with controllable relative humidity addressing the cells to be measured directly. We performed the AFM measurements in the range of 15%–95% relative humidity. We observed a volume change of up to 40% when we adjusted the relative humidity from 15% to 95%. In this case, the bacteria is our smallest SCMUnit.

3.4.3 SCMC: Hierarchical composite structure

In order to translate the expansion and contraction of cells at the micron scale into visible transformation at the macroscale, we developed a biohybrid composite film. The composite film contains two layers: the cell layer and the substrate layer. The film can vary the bending curvature triggered by the relative humidity changes (Fig. 3.5). We obtain the composite film by applying a cell liquid solution to the substrate layer and vaporizing the water content. The ideal substrate material includes 0.2 mm-thick latex, 0.3 mil of Kapton, and 0.3 mil of PET. Details of these procedure were reported in the paper [25].

With biofilm providing the basic building blocks, we designed responsive struc- tures and transformations, which can be referenced when we try to achieve a certain shape change in the design of an active system. Transformation design is based on two bending primitives: curved bending is for more organic transformations, while angular bending is for more geometric transformations. To achieve a curving trans- formation, 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 in order to stabilize the structure and enhance the effect of a sharp fold. During the tests, we experimented with different folding primitives with the use of 0.2 mm latex substrates. Fig. 3.6 shows the folding

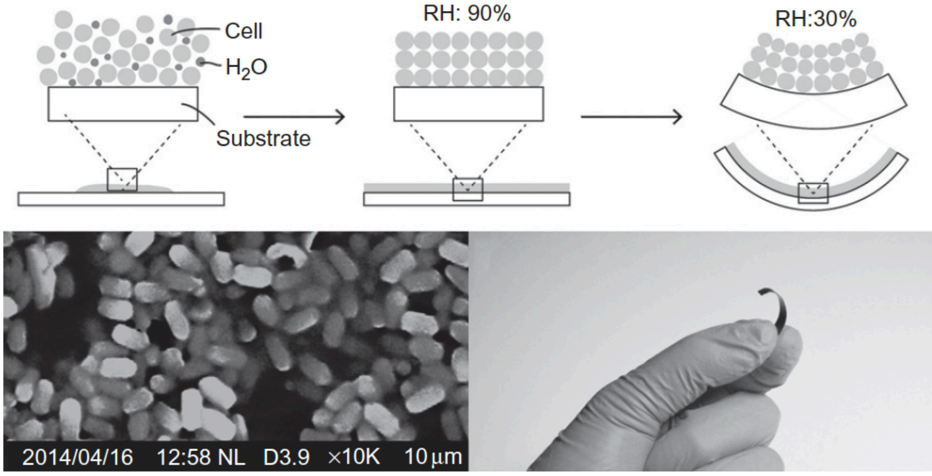

Fig. 3.5 (Top) Diagram of a bilayer structure of the biohybrid film. Cell solutions are deposited on top of an inert substrate. As the water vaporizes, the cells form a thin film on top of the substrate. The cell film expands and shrinks when the relative humidity changes in the environment, which causes the bilayer film to bend up and down in response to the changes. (Bottom left) SEM image of the cell film. (Bottom right) A sample of the bilayer biohybrid film.

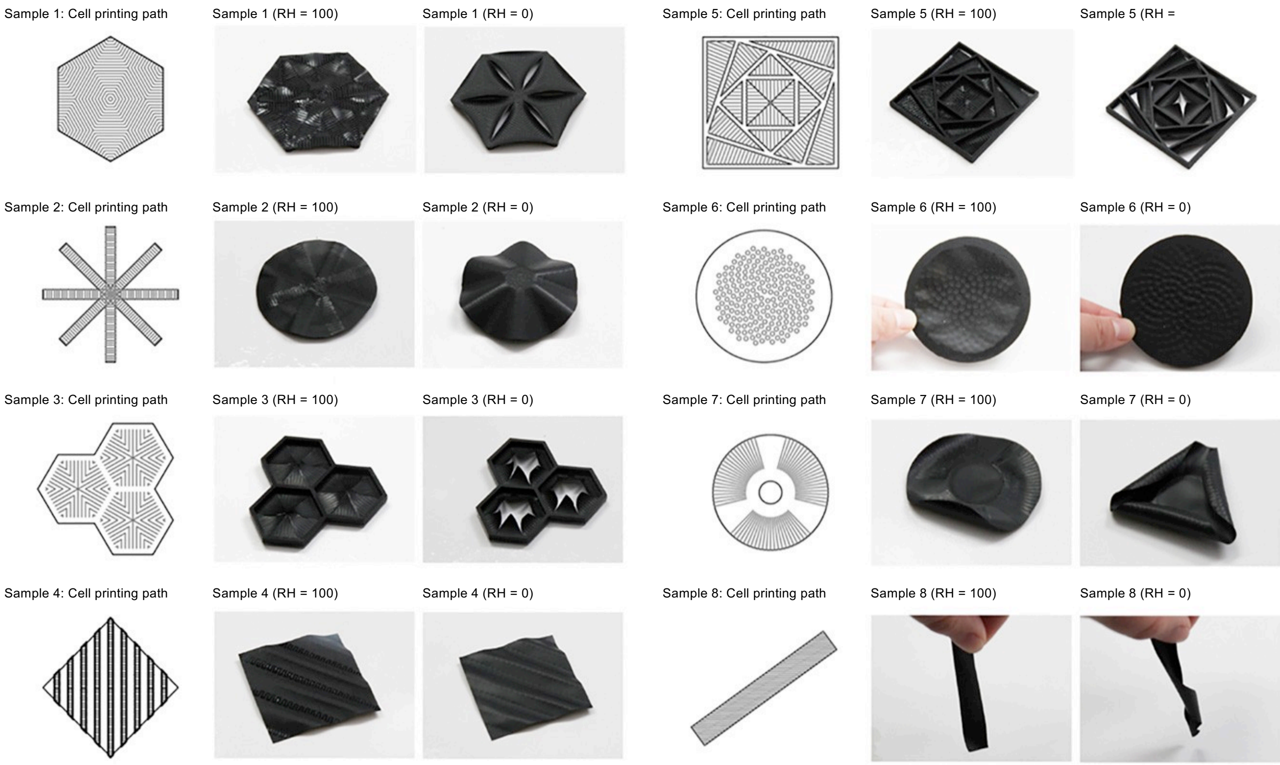

Fig. 3.6 Structural primitives with latex-cell hybrid films. The samples were prepared by Lining Yao, Guanyun Wang, and Ye Tao.

variations that were achieved with the latex-cell hybrid film. Compared to the Kapton-cell hybrid, the latex-cell hybrid has a smaller bending angle and a slower response time.

3.4.4 Applications

We developed a sweat-responsive fabric from this biohybrid material, which we have called Second Skin. Although the biohybrid material adheres to and functions best on thin elastomers, we hoped to design a garment with a common fabric. Eventually, we designed a fabric composite, with layered structures, to hold the transformative flap units in place. Fig. 3.7 shows the design of the layer composite fabric.

For a responsive garment, we hoped all the functional units would initially be flat and only curl when the user starts to sweat. However, since the bilayer structure curls naturally in ambient conditions (30%–70% relative humidity), it could not be used directly to develop the Second Skin application. In addition, the curling state makes the handling process challenging (e.g., cutting, shaping, and assembling). To solve those challenges, we developed a sandwich structure where cell layers were coated on both sides of a moisture-inert material. This structure allowed the film to respond only to a localized moisture gradient across the film, while ensuring the flatness of the film with balanced contractile forces on both sides in homogeneous environments (two sides exposed to the same condition). This biohybrid film with the sandwich structure is a robust fabric, which responds to body sweat and for which the bending degree can be adjusted and simulated by changing the thickness and elasticity of the middle supporting layer (Fig. 3.8).

Fig. 3.7 A close shot of Second Skin, with a macroscopic view of the biohybrid film, which reacts to sweaty skin.
Photograph by Rob Chron, 2016.

Fig. 3.8 Second Skin living garment.
Photograph by Rob Chron, 2016.

3.5 Conclusion

In this chapter, we discussed bio-inspired actuator design. We started with introducing a set of natural actuators, then gave a summary of the shape-changing matrix composite (SCMC) model, and ended with a case study of a hygromorphic composite actuator driven by bacteria. As we emphasize the unique advantages and characteristics of the natural actuators, we would like to point out that there are disadvantages as well. For example, natural actuators are often slow, hard to control, and tailored to very specific stimuli and responses. Depending on the targeted applications, actuation technology must be carefully chosen accordingly.

References

[1] I. Burgert, P. Fratzl, Actuation systems in plants as prototypes for bioinspired devices, Philos. Trans. A: Math. Phys. Eng. Sci. 367 (1893) (2009) 1541–1557.
[2] J.M. Skotheim, L. Mahadevan, Physical limits and design principles for plant and fungal movements, Science 308 (5726) (2005) 1308–1310.
[3] E. Reyssat, L. Mahadevan, Hygromorphs: from pine cones to biomimetic bilayers, J. R. Soc. Interface 6 (39) (2009) 951–957.
[4] K. Song, E. Yeom, S.-J. Seo, K. Kim, H. Kim, J.-H. Lim, S. Joon Lee, Journey of water in pine cones, Sci. Rep. 5 (2015)9963.
[5] C. Dawson, J.F.V. Vincent, A.-M. Rocca, How pine cones open, Nature 390 (1997) 668.
[6] N.E. Stamp, Self-burial behaviour of erodium cicutarium seeds, J. Ecol. 72 (2) (1984) 611–620.
[7] B.S. Collins, G.R. Wein, Mass allocation and self-burial of Aristida tuberculosa florets, J. Torrey Bot. Soc. 124 (4) (1997) 306–311.
[8] N.E. Stamp, Efficacy of explosive vs. hygroscopic seed dispersal by an annual grassland species, Am. J. Bot. 76 (4) (1989) 555–561.
[9] D. Evangelista, S. Hotton, J. Dumais, The mechanics of explosive dispersal and self-burial in the seeds of the filaree, Erodium cicutarium (geraniaceae), J. Exp. Biol. 214 (4) (2011) 521–529.

[10] C. Pandolfi, D. Comparini, S. Mancuso, Self-burial Mechanism of Erodium cicutarium and Its Potential Application for Subsurface Exploration, Springer Berlin Heidelberg, Berlin, Heidelberg, 2012, pp. 384–385.
[11] Y. Abraham, C. Tamburu, E. Klein, J.W.C. Dunlop, P. Fratzl, U. Raviv, R. Elbaum, Tilted cellulose arrangement as a novel mechanism for hygroscopic coiling in the stork's bill awn, J. R. Soc. Interface 9 (69) (2012) 640–647.
[12] W. Jung, W. Kim, H.-Y. Kim, Self-burial mechanics of hygroscopically responsive awns, Integr. Comp. Biol. 54 (6) (2014) 1034–1042.
[13] Eickmeier, W. G, Photosynthetic recovery of resurrection spikemosses from different hydration regimes, Oecologia 46 (3) (1980) 380–385.
[14] J.C.T. Uphof, Physiological anatomy of xerophytic Selaginellas, New Phytol. 19 (5–6) (1920) 101–131.
[15] M.L.D. Sablon, Sur la r'eviviscence du Selaginella lepidophylla, Bull. Soc. Botan. Fr. 35 (2) (1888) 109–112.
[16] A. Rafsanjani, V. Brul'e, T.L. Western, D. Pasini, Hydro-responsive curling of the resurrection plant Selaginella lepidophylla, Sci. Rep. 5 (2015) 8064.
[17] D. Hull, T.W. Clyne, General introduction, in: An Introduction to Composite Materials, Cambridge University Press, Cambridge, 1996, pp. 1–8.
[18] R.M. German, Introduction, Springer International Publishing, Cham, 2016, pp. 1–22.
[19] F. Wikipedia, Metal Matrix Composite, https://en.wikipedia.org/wiki/Metalmatrixcomposite, 2017.
[20] V. Birman, L.W. Byrd, Modeling and analysis of functionally graded materials and structures, Appl. Mech. Rev. 60 (2007) 195–216.
[21] M. El-Wazery, A. El-Desouky, A review on functionally graded ceramic-metal materials, J. Mater. Environ. Sci. 6 (5) (2015) 1369–1376.
[22] N. Oxman, Material Based Design Computation (Ph.D. Thesis), Massachusetts Institute of Technology, Cambridge, MA, 2010.
[23] A. Menges, S. Reichert, Material capacity: embedded responsiveness, Archit. Des. 82 (2) (2012) 52–59.
[24] W. Wang, L. Yao, C.-Y. Cheng, T. Zhang, H. Atsumi, L. Wang, G. Wang, O. Anilionyte, H. Steiner, J. Ou, K. Zhou, C. Wawrousek, K. Petrecca, A.M. Belcher, R. Karnik, X. Zhao, D.I. Wang, H. Ishii, Harnessing the hygroscopic and biofluorescent behaviors of genetically tractable microbial cells to design biohybrid wearables, Sci. Adv. 3 (5) (2017) e1601984.
[25] L. Yao, J. Ou, G. Wang, C.-Y. Cheng, W. Wang, H. Steiner, H. Ishii, Bioprint: a liquid deposition printing system for natural actuators, 3D Print. Addit. Manuf. 2 (2015) 168–179.
[26] L. Yao, J. Ou, C.-Y. Cheng, H. Steiner, W. Wang, G. Wang, H. Ishii, Biologic: natto cells as nanoactuators for shape changing interfaces, Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15), ACM, New York, NY, 2015, pp. 1–10.
[27] X. Chen, D. Goodnight, Z. Gao, A.H. Cavusoglu, N. Sabharwal, M. DeLay, A. Driks, O. Sahin, Scaling up nanoscale water-driven energy conversion into evaporation-driven engines and generators, Nat. Commun. 6 (2015)7346.
[28] M. Ma, L. Guo, D.G. Anderson, R. Langer, Bio-inspired polymer composite actuator and generator driven by water gradients, Science 339 (6116) (2013) 186–189.

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