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Hybrid Sensor Configurations

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29.1 Introduction

Designers and scientists utilize similar methodologies to fulfill their curiosities [1]. They both, for instance, observe natural phenomena to ask profound questions about processes. Either may utilize approaches that are bottom-up, where questions about natural phenomena lead to design innovations, or top-down, where design problems necessitate the understanding of nature. These may be, respectively, called biomimetics or bioinspiration.

Animals and plants utilize a range of fibers, slimes, glues, surfaces, coatings, weapons, armory, and colorations, with many (e.g. spider/insect silk, barnacle cement, hagfish slime, geckos toes, and armadillo and turtle shell) outperforming most of the synthetic equivalents manufactured to date [2–6]. Designers and engineers are accordingly keen to understand the principles underlying such products in order to mimic their structure and function in design [7–10]. These endeavors are driving the increasingly rapid growth of the field of biomimetics [10–14] and cocreation beyond species boundaries [15]. This chapter will discuss research that considers design ecologies, collaborating with nonhuman agents to create organic and inorganic material-based hybrid sensor configurations. Two case studies are presented, one harnessing plant electrophysiological signals and the other leveraging state-change properties of natural protein and cellulose materials. Design becomes a practice of crafting natural forces, where one element acting or reacting against another is considered in terms of its material agency [16] and solutions take their shape eloquently with minimal material or energy, fostering mutualistic rather than parasitic relationships.

Organic and Inorganic Materials Based Sensors, First Edition.
Edited by Sangita Das, Sabu Thomas, and Partha Pratim Das.

For design to facilitate change that addresses real sustainability, we must change the way we design and manufacture products. Value systems must include those beyond purely economic ones [17]. The current system consists of exploitative mechanisms of empty repetition, which need to be replaced with mechanisms based on the living systems [18], i.e. autopoietic networks, consisting of collectives of processes and relations of components of production. In autopoietic networks, the sum of all parts is greater than the whole, and the relationships are dynamic rather than static [18]. The current imbalance or ecological disequilibrium that has resulted from a period of intense industrialization threatens the sustainability of human life on the planet. An ecosystem-thinking approach to designing sensors involves broadening the existing value systems to include the ecologies of the environment as well as social relations and subjectivity. Guattari calls this ethicopolitical articulation "ecosophy" [17]. Rather than perpetuating models that merely treat symptoms, e.g. cleaning up pollution, we must move to design autopoietically, i.e. mimic the organizational structures of living systems that have the autoreproductive capacity to adapt and renew themselves constantly.

29.2 Sensor Systems

29.2.1 Wearable Sensors

Wearable sensors are becoming increasingly ubiquitous and intuitive, hidden away within the structures of our textiles, on, in, and around our bodies, and woven into the built environments we inhabit. They exist in interactive zones, the body providing them with mobility and, hence, their frame of reference changes as they enter new environments. Moist media is a term that posits a view of technological tools and media combining to form moist living ecosystems – coherent networks at a biological level [19]. From this perspective, sensors and materials could be described as promiscuous and intertwined [20]. In the same way that the membrane of a cell has the capacity to stabilize the environment within its walls [21], and future textiles will embody hybrid sensors and mimic the complexity of natural ecosystems to be reactive and aware [14]. Wearable hybrid sensors have the capacity to behave as embedded speckled computing arrays, gleaning data as they move around the environment, and acting as nodes in data clouds that intelligently predict behaviors to stabilize system imbalances back to equilibrium. At the same time, they may embody microecologies around the body and react locally to environmental changes [22].

29.2.2 Biological Sensors

Taking a close look at biological systems provides inspiration for the production of advanced sensor technologies [23]. Indeed, living things need to accurately receive and interpret the stimuli from their environment to make informed choices. The cost of utilizing false information or failing to interpret correct information may be fatal. As such, biological receptors as the components of nerves and nervous systems, or other cellular response processes (e.g. stomatal processes [23]), are extremely efficient and accurate at detecting and interpreting stimuli and eliciting a mechanical or chemical response. Plants possess a high degree of sentience, processing, and communication skills, as well as learning capacity, as a means of adapting to environmental challenges [24–32]. Plants can monitor their own growth and nutritional status, they detect environmentally born light, moisture, chemicals, and pollutants, and behave accordingly. Some, such as the Venus flytrap, can move body parts in a way that resembles animal movement and even do simple math [33]. The communities of plants are distributed, sustainable, and have the capacity to sense multiple aspects of the environment. Transgenic and genetically modified plants are bred to sense environmental genotoxicity with the advantage that they can be customized to be more sensitive to specific pollutants [34]. Recent technological advancements, such as machine learning and cloud computing, have opened the field of plant sentience to interpret plant physiological communication along mycorrhizal networks in real-time [35]. There is a growing interest in leveraging the capacity of plants as organic pervasive wireless biosensor networks for monitoring the environment [30, 36]. For example, plant data networks via electromyography (EMG) sensors have been used as predetection systems for environmental hazards, such as earthquakes [37].

29.2.3 Macromolecular Sensors

Cellular processes are multidimensional and complex, so creating artificial cells can be thwart with difficulties (but see [38] for a successful example). In many animals, their secretions act as the extended phenotypes (i.e. the products of gene expression beyond the body). Insect and spider silk, mussel byssus, and hagfish slime being some prime examples [13, 39–41]. Since these extended phenotypes are made of functional biological materials that are naturally secreted by the animal, they provide more simplistic but equally efficient and effective mechanistic functional models to inspire the development of sensor technologies [10, 12, 42, 43].

29.3 Molecular Mechanisms

29.3.1 Spider Silk Supercontraction

Spider major ampullate (MA) (or dragline) silk has extreme strength and toughness, biocompatibility, and antibacterial properties, and it is derived from water and protein. Accordingly, it is of interest for biomimetics research as industries seek to find more environmentally friendly textiles and fabrics [7, 10, 12, 44–46]. It also has the following: (i) high conductivity of heat, light, and sound [47–51], (ii) a capacity to conduct vibratory stimuli, (iii) an ability to recover from compressive or tactile stimulation [52, 53], and (iv) capacity to change its material property from strong and stiff to rubbery on exposure to water or a similar polar (i.e. partially charged) liquid solvent; a phenomenon called supercontraction [54–57] (Figure 29.1).

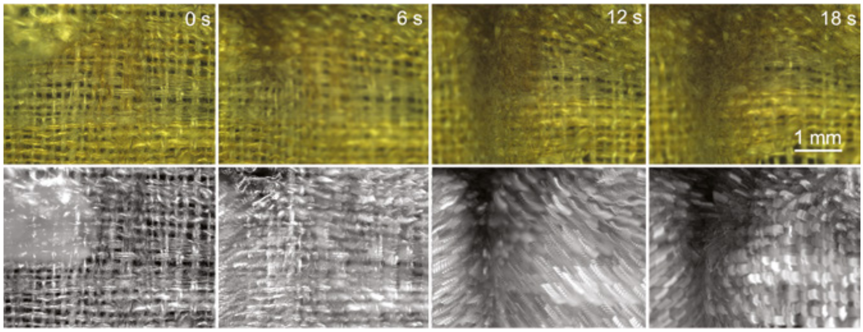

Figure 29.1 Spiders silk hydrophillic supercontraction timelapse. Source: Video: https://youtu.be/kXC2mHK9atA; Flanagan, Hosseini.

The magnitude of many of these properties can be highly variable. This variability may be a means to cater to the functional needs of the spider or an adaptation to variable environments [58–60]. What this means is that if we were to understand the mechanisms by which environments or circumstances are able to switch on particular properties in spider silk, we might be able to harness them to create new lightweight and environmentally benign sensors for incorporation into functional wearables or useful devices. The properties of MA silk come about as a consequence of the molecular structure of the silk proteins, which comprises proteins stacked into layers of pleated sheets, the so-called crystalline region, interspersed with proteins that form a range of structures, including random and β-coils, α-helices, and 310 helices. This region is referred to as the amorphous region, although it technically has a morphology [58]. We see that the effects of variation in the crystalline and amorphous region play out when spiders are placed on different diets [61] or when they are exposed to noxious chemicals [62]. These environments induce silk tensile, acoustic, and other properties to vary through on-the-fly variations in the silk's crystallinity and/or amorphous region density and alignment [58, 63–66].

29.3.2 Microbial Cellulose Weaving

Microbial cellulose is an exopolysaccharide produced by various species of bacteria, such as those of the genera Gluconacetobacter (formerly Acetobacter), Agrobacterium, Aerobacter, Achromobacter, Azotobacter, Rhizobium, Sarcina, and Salmonella. The production of cellulose from Acetobacter xylinum was first reported in 1886 by A. J. Brown. He observed that the resting cells of Acetobacter produced cellulose in the presence of oxygen and glucose. Bacterial cellulose (BC) is one of the stiffest and purest organic materials produced through fermentation by bacteria called Acetobacter xylinum. BC has a three-dimensional (3-D) structure of bundled and entangled cellulose microfibers with a nanoscale diameter and several micrometer lengths. The high mechanical properties, surface area, and water holding capacity of BC show its potential for biomedical applications, such as wound dressing, artificial skin, blood vessels, remarkable tensile properties, tissue engineering, and even textile manufacturing. The cellulose production of bacteria depends on the fermentation conditions and culture medium compositions, such as temperature, dissolved oxygen content, pH, and culturing method. The chemical composition of the culture plays an essential factor as the main carbon source affecting cellulose microfiber yield. Hence, optimizing culture conditions and nutrient components helps to improve bacterial productivity and overall BC yield.

29.3.3 Plant Electrophysiology

Electrophysiological signaling is one of the several ways a plant communicates and is predominantly used to coordinate activities between different parts of the plant, much as the nervous system of humans and other animals. These signals can easily be harvested using EMG sensors. These signals are context-dependent and subject to change over time, for example, something that elicits a response at one particular time may not do so at another, so working with it requires developing sensitivities toward the plants on an individual level. Recent technological advances allow simple deciphering of the signals, such as environmental stress from heat, light, or wind; draught; pathogens; insect infestations; and nutrient deficiencies, see for example www.phytlsigns.com.

29.4 Hybrid Sensor Configurations

29.4.1 Hybrid Sensor – Spider Silk/Cellulose

In the case study presented here, we leverage the hydrophobic and hydrophilic properties of natural materials to construct fabrics that are reactive to environmental factors. Two material polarities, i.e. spider silk's supercontractive response to submersion in polar liquids and cellulose's superexpansive water holding response, are combined within textile structures. The textiles are able to sense and react independently and as such have decision-making capacity. We conducted a series of experiments to prototype components for reactive materials: materials that can sense the environment and respond.

Fermentation of BC: The growth medium was made by mixing coconut water (Cocobella, Indonesia) with sucrose (Black and Gold, Australia) at a concentration of 10% w/v and ammonium phosphate monobasic (Sigma- Aldrich, Australia) at a concentration of 0.5% w/v. The fresh growth medium was then mixed with 30% w/v of the preculture solution Acetobacter xylinum, provided by Nourishme Organics, Australia. The solution was incubated at a room temperature for seven days. Cellulose pellicles that are formed at the air–liquid interface of the culture were harvested and rinsed under water for 10 minutes, followed by soaking in 2% w/v sodium hydroxide (NaOH, Chem Supply Pty Ltd., Australia) overnight to kill the bacteria and remove other impurities.

Microbial cellulose weaving: BC producing bacteria migrate from a low concentration of food to a high concentration. As a result, bacteria can sense a vast range of

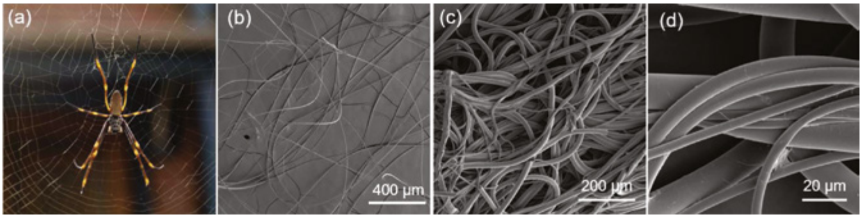

Figure 29.2 (a) Nephila plumipes spider. Source: https://australian.museum/learn/animals/%20spiders/golden-orb-weaving-spiders/; fotofritz16/Adobe stock. (b–d) Scanning electron microscopy (SEM) of spider silk in dry (b) and wet conditions (c and d). Source: Image credit b-d, Hosseini ©2021

environmental signals from the concentration of nutrients and toxins to oxygen levels, pH, osmolarity, and light intensity. Thus, controlling and engineering feeding methods can control bacterial motion by focusing their motion. Consequently, engineering the feeding source by moving it through the culture can direct bacterial motion and help to align the cellulose fibers produced.

Silking, spinning, and weaving spider silk: We have attempted to extrude spider silk proteins and produce regenerated fibers from a dope solution in the lab (as described by [7]). However, so far, the fibers have been too brittle to directly test.

For this experiment, we silked live spiders (Figure 29.2), drawing the silk around a glass tube attached to a mechanical rotor. This method produces approximately 10 mg in 4 hours (Figure 29.3). The silk fiber was hand spun using a small metal drop spindle. Two lengths of spun silk were then plied together to stabilize the twist. Spider silk was harvested from Argiope Keyserling (producing a white silk) and *Trichonephila Plumipes* (producing a yellow silk) and hand spun and woven into a plaid sample. The sample was tested to measure hydrophilic/supercontraction properties (see Figure 29.1).

Fermentation of BC–spider silk: Next, we examined the BC migration to spider silk, testing adhesion of protein to cellulose. Spider silk is hydrophobic and contracts when reaching water droplets; hence, it does so when silk is fully immersed in bacterial culture; spider silk is wrapped around a glass capillary with a diameter of 1 mm. Capillary is placed in the bacterial culture with two different modes, static culture and dynamic culture, for a week. Scanning electron microscopy (SEM): FEI Nova Nano SEM 450 FE-SEM at an accelerating voltage of 5.0 kV was used for SEM

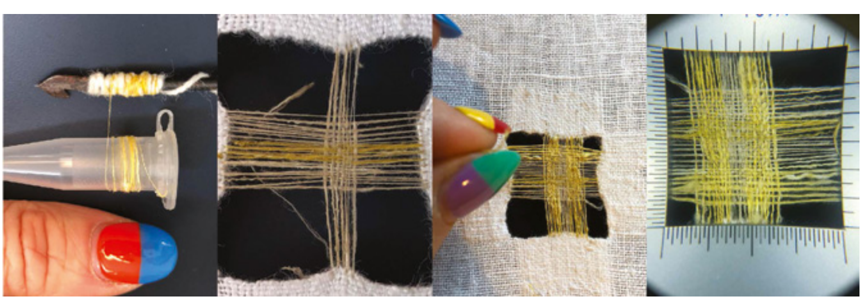

Figure 29.3 Spinning and weaving spider silk. Source: Image credit Flanagan ©2021.

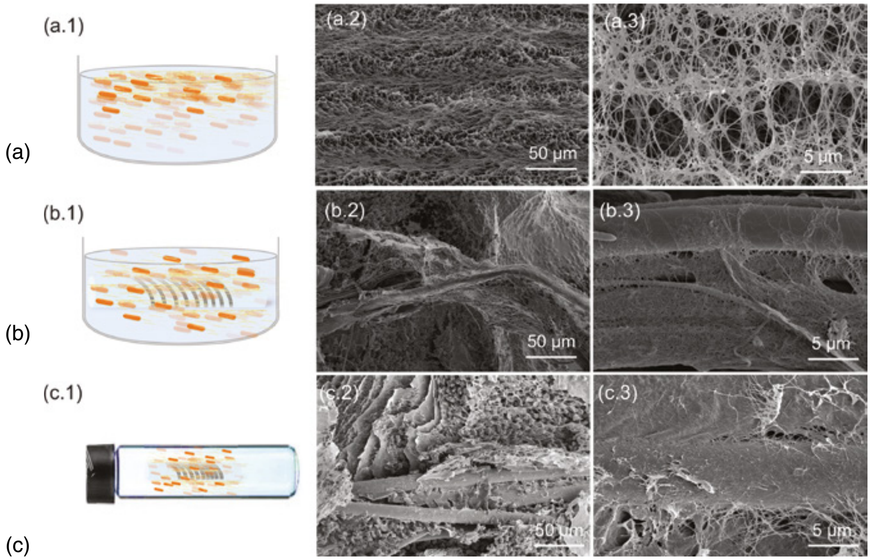

Figure 29.4 Spider silk and bacterial cellulose hybrid. (a) Cellulose, (b) Spider silk wrapping glass capillary in static culture, (c) Spider silk wrapping glass capillary in dynamic (rotating mode) bacterial culture. Source: Image credit Hosseini ©2021.

imaging of samples. Dehydrated samples were coated with Pt at a thickness of 30 nm, using Leica ACE600 sputter coater before SEM imaging (Figure 29.4).

Microbial cellulose + pectin strips: Microbial cellulose was cultured to create a network of filaments. The cellulose forms in a thick sponge and, when dried, it reduces to nanofilm sheet layers. We experimented with 3-D printing aqueous pectin onto the cellulose sheet. For this experiment, two samples of cellulose were stitched together. One was treated with pectin. The material was cut into strips and folded, so pectin was at the tips. When wet, the printed area returned to its swollen state and, subsequently, dried to thin layers (Figures 29.5 and 29.6).

Finally, we created a prototype organic sensor by weaving an even-count narrow-band from spider silk warp and cotton weft and inserted the cellulose/pectin strips as a pile weave. The result is a reactive sensor that morphs shape from flat to circular as the spider silk contracts and the cellulose/pectin expands.

Figure 29.5 Cellulose/pectin strips (stitched, cut, folded, dry, wet). Source: Image credit Flanagan ©2021.

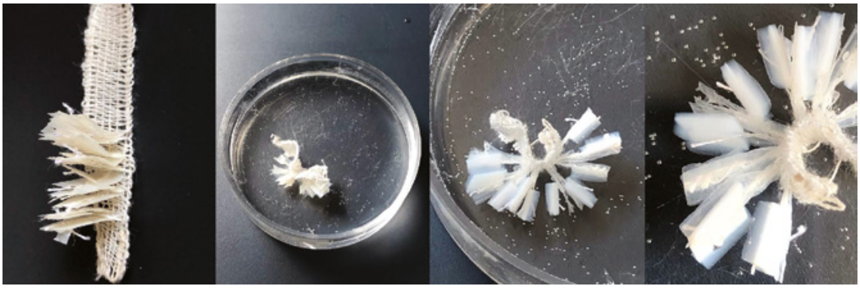

Figure 29.6 Organic sensor switch. Source: Video: https://youtu.be/aTE6fAVXWV0. Video credit Cognitive Textiles Flanagan ©2021.

29.4.2 Hybrid Sensor – Plant/Human

In this investigation, we augment plant sensing capabilities with digital technology to reveal their signals, i.e. we eavesdrop on the plants and mediate their language into something that humans can understand. Many nonwestern and, in particular, indigenous cultures are well aware of the intertwined relationship between humans and plants – that is, it establishes a sociotechnical space where plant–human collaborations can unfold. To this end, we have designed a symbiotic system based on a hybrid configuration of plant–human attributes (Figure 29.9). Plant's bioelectrochemical or electrophysiological signals are collected using EMG sensor pads connected to the plant's leaves. These are connected to a microprocessor and amplifier, and output as a sound file through a textile woven speaker. Following experiments sensing electrophysiological signals in trees, soft speakers mounted on the trees produced barely audible sounds (Figure 29.7).

Our team devised a mouth worn soft speaker by using the mouth cavity as a speaker box. We modeled and 3-D printed a prototype mouth ring from poly(lactic acid) (PLA) and wove the disk with cotton and a spiral of silver conductive thread, and suspended a magnet behind the speaker (Figure 29.8).

By amplifying plant electrophysiological signals using the mouth-cavity speaker box (the electrophysiology mouth ring), we aimed to replicate an empathetic relationships with nature. We expected to raise the awareness of plant sentience and plant–human power relations (Figure 29.9).

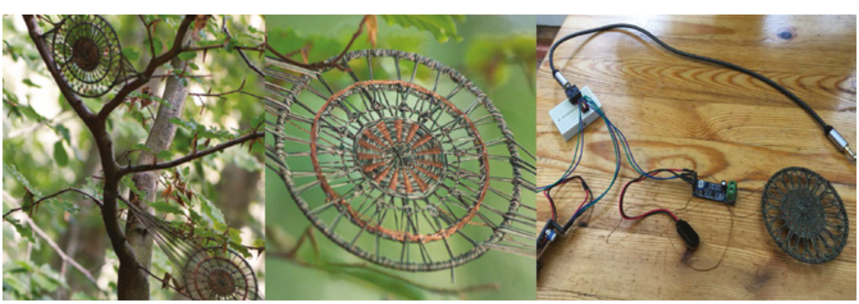

Figure 29.7 Plant bio-electro-physiological tree speakers. Source: Image credit Frankjaer ©2020.

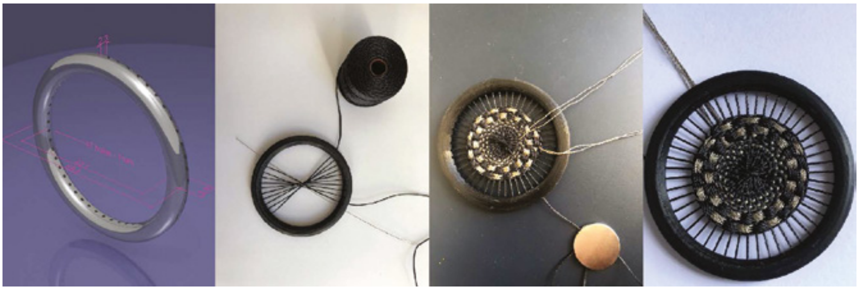

Figure 29.8 Plant bio-electro-physiological mouthring speaker prototype. Source: Image credit Flanagan ©2021.

Figure 29.9 Tree/mouthring interface. Source: Image credit Flanagan ©2021.

29.5 Future Work

At the Spider Silk Research Laboratory, we initiated new research to investigate the surface and structural properties of silk and are investigating incorporating these properties into new wearable fabrics (see [7]). We hereupon present some primary outputs of one of our programs, the development of a spider silk/cellulose/pectin hybrid material for applications as wearable sensors. Further iterations of the mouth ring will be produced to test the audio output capacity of a variety of conductive threads. The mouth ring frame will be cast in sterling silver and a variety of sizes. There is an integration of the plant electrophysiology mouth ring into a wider wearable system that engages with forest ecology and collection of plant data. The data will be compared with the libraries of recordings from Agri-Tech to search for patterns of similarity or uniqueness.

29.6 Critical and Speculative Futures

Developing human–plant interaction methodologies that engage other than human agencies as codesigners for future ecologies literally (and metaphorically) gives them a voice. Our aim is to implement this methodology and the prototypes described in this chapter to promote discussion around native species, where species diversity can ebb and flow with the mobility to migrate in reaction to seasonal and climatic trends. Moreover, by exploring the experience of plants, a life-form so divergent from our own that we barely recognize it as alive at all, we begin to see our own existence in a new light and question our relationship to the world we inhabit. This chapter promulgates embracing systems that are responsive and agile. Leveraging the agency and manufacturing capacity of biological organisms involve hybrid design and craft approaches driven by ecoperspectives rather than hierarchical system's thinking. Organic- and material-based sensors are smart materials that react to environmental changes and modify accordingly. Sensor configurations can be connected in speckled computing arrays worn by human agents in the environment or leverage the existing networks of plant sentient capabilities. By viewing design as collaborative with material entities, we are building ecologies of empathy for other-than-human entities. Our aim is to foster sustainable ecosophic design practices that function in futures of material resource scarcity.

Acknowledgment

MH acknowledges support by a UNSW Scientia PhD fellowship. PS acknowledges partial support from the Australian Government through the Australian Research Council's Discovery Projects funding scheme, Project DP190102614. 3D modeling M. Zavala-Baez.

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