

# Bio-inspired Design of Intelligent Materials

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## ABSTRACT

Several examples of sensors and actuators inherent in biological species are reviewed with emphasis on their mechanisms for a given set of stimuli. Examples include, action plants (Venus flytrap, Cucumber tendrils) and bamboo, and algae. Based on these examples and their mechanisms, we designed artificial actuators, FGM piezo actuators and electroactive polymer actuators.

**Keywords:** Bio-inspired design, intelligent materials, action plants, functionally graded microstructure, bamboo, Venus flytrap, electroactive polymers, actuators, sensors.

## 1. INTRODUCTION

Biological systems are ideal adaptive structures with smart sensing capabilities. The knowledge gained from studying biological mechanisms are key input for designing adaptive structures and intelligent materials.

Biological systems adapted and perfected the design and functioning of their structures during thousands of years of evolution in a changing and increasingly more complex, competitive and challenging world. It is therefore smart in itself to study, understand and adopt nature's time-tested principles and mechanisms to the design of adaptive structures and intelligent materials. Here we focus on autonomous and locally controlled responses, which do not require or the remote control by a central nervous system. We look at three kinds of mechanisms. First, the principles of touch and light sensing in plants and single-celled algae will be examined for their applicability to trigger, modify and control actuation mechanisms. Second, the study of various actuators in plants provides a wide set of alternative choices to create novel, energy-conservative actuation mechanisms in intelligent materials. Third, the comparison of biological, filament-based muscles and artificial, polymer gel-based actuators provides the means to develop and test alternative explanations of the mechanics of muscle contraction and to find the causes or conditions causing the superior speed in natural systems.

## 2. SENSING MECHANISMS

### *Mechano-sensing in plants*

Mechano-sensing can be used to trigger actuations in response to signals ranging from direct touch to friction due to increased flow rates and the underlying principles apply to the initiation of smooth docking systems or speed-related surface changes (see below). In plants and animals, most epidermal (i.e. skin) cells are capable of sensing mechanical touch to which they respond with a complex electric signal. When an improved sensing of mechanic touch is essential for the functioning of an organ, the sensitivity is enhanced by surface extrusions in the form of either *sensory hairs* (Fig. 1(a),(b); found e.g. on the upper side of the leaf pair of the Venus flytrap and the lower part of leaf joints of *Mimosa pudica*) or *sensory papillae* (Fig. 2; found at the surface of tendrils in some *Cucurbita* and *Passiflora* species). Instead of distributing it over many cells, these structures focus the touching force to act on the surface area of only one cell – the sensor cell – and so amplify the emerging hydraulic pressure. In the case of the Venus flytrap, bending of the sensory hair is confined to a horizontally positioned layer of cells (“the joint”) which interrupts an otherwise consistently vertical

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cell arrangement (see Fig. 1(b)). The peripheral vertical cells just below the bending zone experience an increased pressure, which they convert into an electrical receptor potential. These cells are the genuine mechanosensors in the system designed to transform the mechanical signal into a hydraulic signal, the pressure signal into a receptor potential which - when strong enough - is then transmitted to the rest of the leaf cells in the form of an action potential. Note that the mechanic stimulus is transmitted by the hair structure to the mechano-sensing cell, which is hence protected from direct contact with the touching body (insect).

Touch sensitivity can be amplified further by the design of the sensor cell itself. If thin patches (tactile pits) interrupt the normal thick wall of a cell, a touch-induced pressure pulse causes a particularly large stretching of the plasma membrane covering these flexible and yielding pits. Tactile pits are found in the walls of the sensor cells in the trigger hairs of the flytrap (see Fig. 1(c)) but also in the leaf surfaces of normal plants like e.g. *Bryonia dioica* [1,2]. Stretch-activated ion channels in the pit membrane open and the passing ions cause an electric signal in the form of a depolarization (i.e. the voltage between the inner and outer surface of the membrane drops). This local electric signal in the sensor cells (Fig. 1(c)) is called receptor potential (Fig. 1(d)), which - if exceeding a certain threshold - causes an action potential in the neighbor cells below from where it propagates to the actuator. Action potentials in plants differ from those in animals by their ionic mechanism (major current carrying the depolarization is Cl<sup>-</sup>) and also by the fact that their transmission is not confined to specialized nerve cells [3,4].

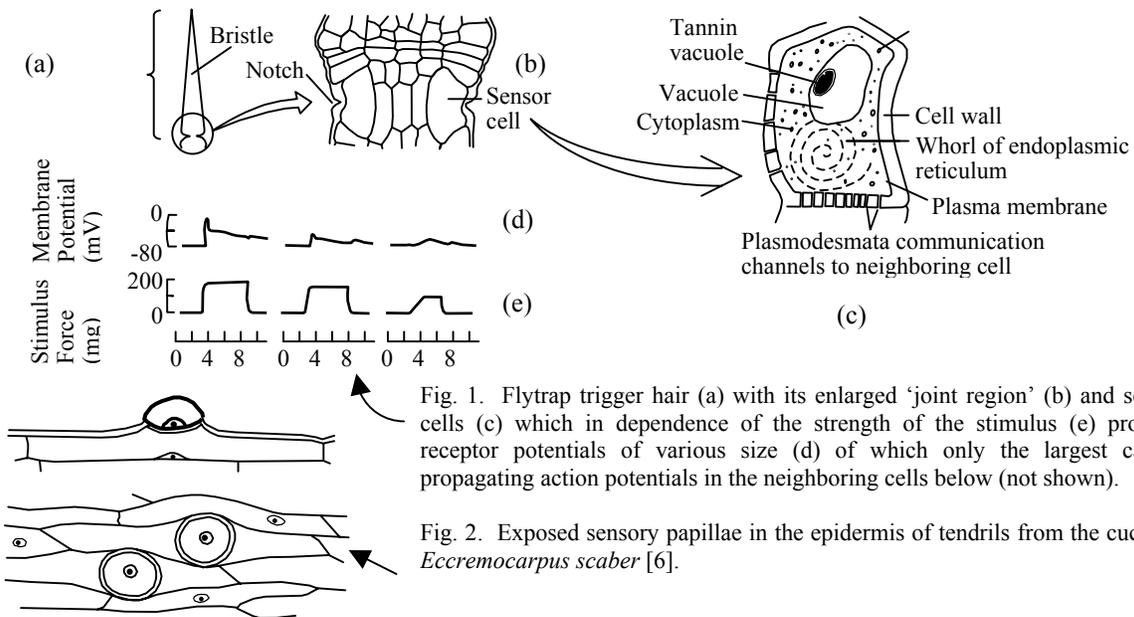


Fig. 1. Flytrap trigger hair (a) with its enlarged 'joint region' (b) and sensor cells (c) which in dependence of the strength of the stimulus (e) produce receptor potentials of various size (d) of which only the largest causes propagating action potentials in the neighboring cells below (not shown).

Fig. 2. Exposed sensory papillae in the epidermis of tendrils from the cucurbit *Eccremocarpus scaber* [6].

Another important example for touch sensitivity is that of tendrils. Like in hairs of the Venus flytrap touch sensitivity supersedes that of a human finger. Some, but not all, tendrils have special, pimple-shaped cells, which protrude from the epidermis surface (see Fig. 2). These tactile papillae are the mechanosensors and convert the mechanical touch into an electric receptor potential [2] which then triggers a propagating action potential in sympastically well-connected cell neighbors [5], a process which results in the coiling of the tendril (see below). Similar pimple-shaped mechanosensors are found also at the surfaces of touch-responsive stamens in the corn flower *Centaurea*, *Berberis*, *Opuntia* and *Portulaca* [2,6] as well as in the touch-responsive stigma in monkeyflowers of the genus *Mimulus*.

### Light reception and reflectance in plants, algae and fish skin

Photosensing occurs at increasing levels of sophistication, one of which range from the simple establishing of changes in light intensity over the determination of light direction to shape recognition, stereo and color vision. An important achievement is to determine the changing direction of light and to respond to it. Directional photoreceptors (called

eyespot or stigmata) were first developed in green algae, single-celled organisms equipped with a flagellate engine that provides them with a high mobility and allows them to bring their photosynthesizing body into an optimal light environment (Fig. 3(a)) as well as to back away from harmful UV radiation (Fig. 3(b)). In the eyespot single to multiple layers of carotenoid-colored vesicles with a high refractive index alternate with clear cytoplasmic layers (Fig. 3(c)). They are arranged as a small flat-to-parabolic disc antenna that is oriented towards the motion-actuating photosensor (often a rhodopsin) located in the plasmamembrane (Fig. 3(c)). Depending on the direction of the incoming light, the eyespot disc either screens the photoreceptor or reflects a light pulse with an optimally adopted wavelength back to the receptor. This function of the eyespot is not simply based on light absorption by the carotenoid pigments but uses the alternating refraction indexes of the pigmented and transparent layers (which each have the thickness of a quarter of the wavelength of the maximal absorption of the photosensor pigment) to reflect the light by constructive interference, the same principle used in interference mirrors, Fig. 4 [7,8]. Depending on the intensity and wavelength of the perceived light, the rhodopsin photosensor increases the cytoplasmic calcium level by opening calcium channels in the plasmamembrane. Photosynthetically active radiation causes a small, but blue and UV light a steep calcium influx. The resulting changes in cytoplasmic calcium have a crucial effect on the flagella movement. Below  $10^{-6}$  M  $\text{Ca}^{++}$  the flagellate algae swim forward, at higher cytoplasmic concentrations the power stroke of the flagella is reversed and the cells backs away from the light source (Fig. 3(a)(b)).

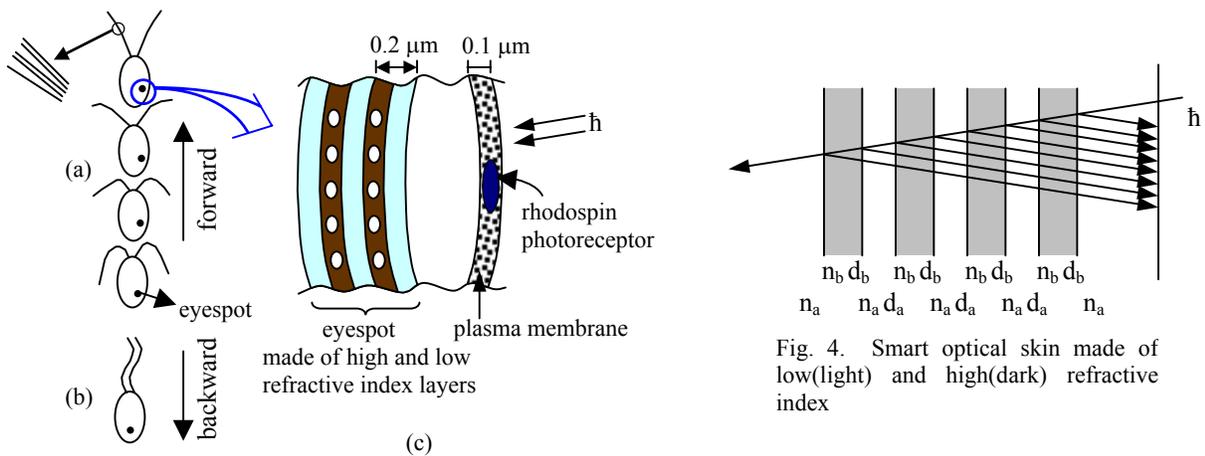


Fig. 3. An alga cell of *Chlamydomonas* swims forward using its flagella in a breast stroke-like motion (a). Under UV the flagella are tied parallel and being thrown forward which drives the cell backward (b). By constructive interference in the carotenoid/cytoplasm layers of the eyespot (c), where light is either screened out or filtered ( $\lambda/4$ ) and reflected back to the photoreceptor in the plasmamembrane (d).

The flagellum consists of a bundle of fused microtubuli and its beating movement involves the sliding of adjacent sets of microtubuli filaments against each other and is generated by activated dynein molecules (similar as actin movement along myosin filaments during muscle contraction, see below). Higher  $\text{Ca}^{++}$  levels are believed to change the anchoring of the flagella to a tighter, parallel formation which allows only backward movements [9].

Flagellate algae are one example for achieving directionality and improved performance of the photoreceptors by combining them with interference light filters. Another example is found in fishes and amphibians, which change their skin color when moving from the shade into the light. The males of Neon tetras and Killiefish have iridescent lateral stripes or spots, which change their color from blue-violet under low light to green, orange or red color under increased light intensities. These changes are local and autonomous responses and occur also in headless fishes. The reflected iridescent colors are produced by the constructive interference of light from stacks of thin alternating transparent layers with different refractive indexes. The fish skin has a layer of cells, called iridocytes, which are filled with iridophores or alternating layers of cytoplasm and guanine crystals. High illumination causes the photoreceptor rhodopsin to open sodium channels and the resulting accumulation of hydrated  $\text{Na}^+$  ions increases the thickness of the cytoplasmic layers and with it the wavelength of the reflected light and the color of the skin (camouflage). Alternatively, the light effect can be simulated by chemical drugs known to activate G protein-coupled receptors or by increasing cytoplasmic hydration

by perfusing a dilute sodium salt solution. [10]. Similarly, reflectance changes could be simulated by the swelling of a stack of gel layers with alternating refractive indices. Similar mechanisms work for the iridophore (here called melanophores) migration in the skin of *Xenopus* frogs, as well as for the light-regulated pupillary constriction [11].

### 3. Actuation mechanisms in plants

Also higher plants are able to determine the changing direction of light and to respond to it. This is demonstrated by the leaves of lupines that during the day follow the position of the sun like tracking antennas [12]. The responsible photoreceptor and actuation mechanism rests in an organ at the swollen base of the leaf stalk, the pulvinus.

Although plants can actuate movements using the biochemical machinery of actin-based myosin motors, e.g. in pea tendrils, [13] or more often of kinesin- and dynein-based microtubular motors [14-16] and hence show certain similarities to filament-based muscle movements, they developed original actuation mechanisms which cannot be found in animals. Because of their strong, fibrous and pressure-resistant cell walls, plant cells develop and maintain a high internal turgor pressure. Based on this feature plants developed a large variety of hydraulic actuation mechanisms or “plant muscles”. At least two different types of plant muscles exist: the grass blade-folding muscle (which has no scientific name) and the leaf-moving muscle, the so-called pulvinus.

*Leaf folding in grasses and Venus flytrap.* This is an actuation in which the grass changes the angle between the two symmetrical halves of their leaf blades. The purpose of blade folding is to keep the plant hydrated. It moves the leaf out of the path of direct illumination, and it drastically reduces transpiration by having the upper leaf surfaces covering each other. The movement is actuated in the upper epidermis by patches of thin-walled and large-sized cells which dehydrate and shrink much faster than the other cells. The volume loss of these motor cells creates a tension and subsequent folding or (if there are more than one patch of motor cells) rolling of the leaves. This process is completely reversible; a rehydration of the motor cells leads to a rapid unfolding of the leaf blade.

Leaf folding is also the basis for the rapid closure of a Venus flytrap normally caused by landing insects (Fig.5a and 5b). However, the folding mechanism is different. The closure of the leaf pair of the flytrap is caused by the rapid expansion of the outer epidermal cells of the leaf pair (Figs.5c and 5d) [17]. This is the fastest growth process known in plants [18], but it is not clear how this rapid actuation is achieved. After all, the expansion of leaf cells are thought to be mediated through lowering of the cell wall pH, which is loosening the cell walls to yield and expand to the internal turgor pressure [19]. To achieve the rapid expansion in the outer epidermis of the trap leaf would imply either unusual properties of this epidermis or the presence of a new type of actuation that differs from other leaves. This incredibly rapid mechanism invites further research.

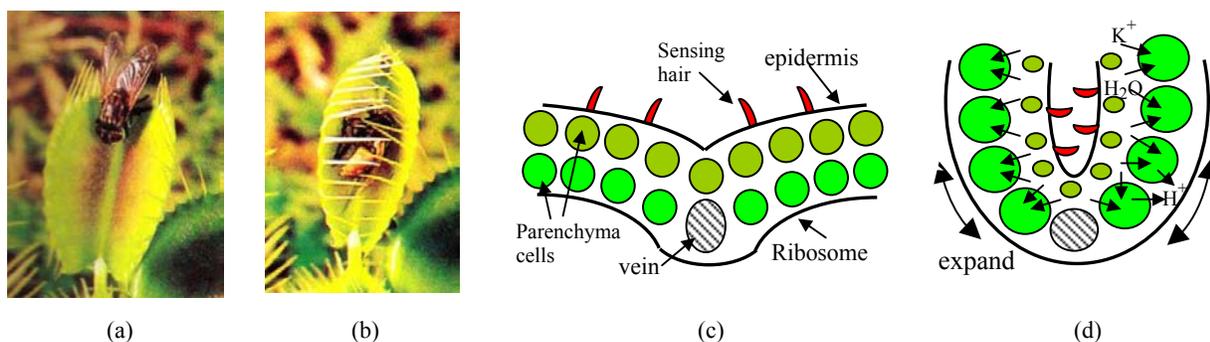


Fig. 5. Venus flytrap in action. When an insect touches the trigger hairs (a, c) the trap closes rapidly (b,d). The closure is caused by the rapid expansion growth of the outer leaf epidermis which must involve ion transport (d).

*Pulvinus-actuated leaf movements.* Pulvini are swollen parts at the base of leaf stalks or petioles which move leaves. Since pulvini can also house mechano- and photoreceptors [12,20], they are autonomous organs, which perform induced movements also when, detached from stem and leaf [21]. Anatomically all pulvini consist of thick-walled water-conducting vascular tissue surrounded by thin-walled motor cells which can undergo visible swelling and shrinking. In

analogy with animal joints, the motor cells on the lower site of the pulvinus are called flexor cells and on the upper site extensor cells. A lifting of the leaf is actuated by an increase in turgor pressure and volume caused by the uptake of  $K^+$  ions in the extensor cells. Upon darkness  $K^+$  channels in the extensor cells close but open in the flexor cells which loose turgor pressure and shrink, the pulvinus joint loses its rigidity and lets the leaf droop. In *Mimosa* pulvini like in animal muscles the flexor undergoes a measurable shortening upon stimulation by an action potential [21]. Its response can be triggered by touch, sudden darkness and the arrival of action potentials. Pulvini-based leaf movements occur in many plants of the bean family (*Fabaceae*), the fastest responses can be found in *Mimosa pudica*, and *Desmodium gyrans*. While most plants can move their leaves only up and down, lupines move them in any direction.

Recently Nakano [22] studied experimentally the size distribution of motor cells in the upper and lower parts of main pulvinus of *Mimosa pudica* before and after it is subjected to mechanical touch on the petiole, Fig. 6. The results of the motor cell size distribution are shown in Fig. 7 where (a) and (b) denote the case before and after the stimulus at the petiole. The darker color in Fig. 7 denoted the larger sized motor cells, thus a comparison between Fig. 7 (a) and (b), demonstrated clearly the shrinkage of the motor cells in the lower part of the main pulvinus and the turgor the upper part, resulting in a rapid bending of the petiole.

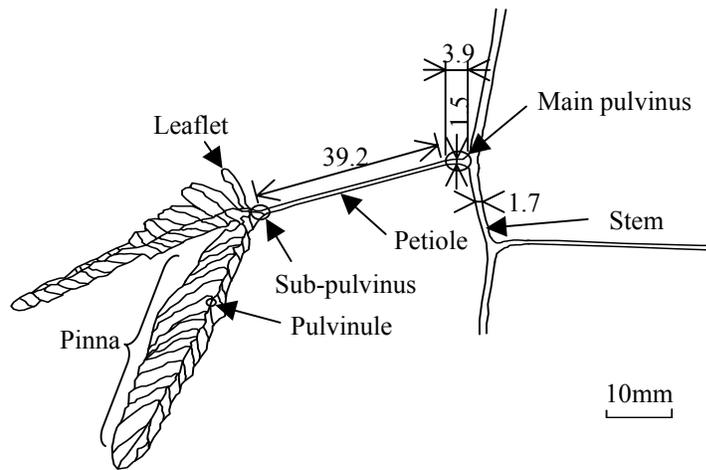


Fig. 6.

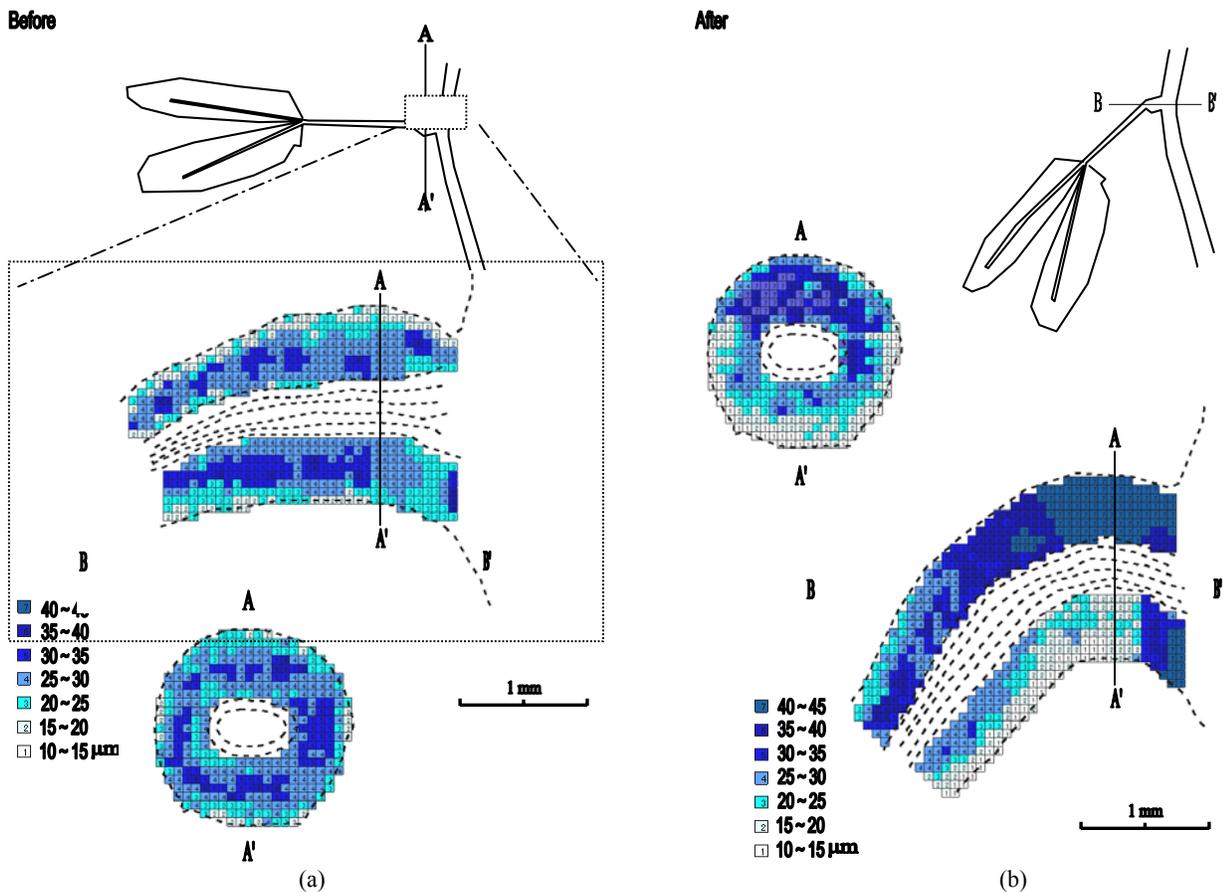


Fig. 7 Size distribution of motor cells in main pulvis of *Mimosa pudica* (a) before and (b) after the petiole is stimulated by touch.

*Tendrils-based attachment in climbing plants.* Some plants do not invest in strong stems but instead attach themselves to other structures with the help of tendrils. Some climbing plants like the wild mural vine *Parthenocissus tricuspidata* attach themselves even to walls to which the tendrils attach with knob-like adhesion discs. Tendrils like those of peas, cucumbers, and squashes are touch-sensitive organs. After the tendril tip found and looped around a solid support, the rest of the tendril undergoes a mysterious change in shape – it coils. Turning from a straight elongated cylinder into a shortened coil, the tendril pulls the climbing plant close to the mechanic support to which it remains flexibly but solidly attached (Fig. 8). To have cylindrical structures undergo such a rapid coiling is yet a process without parallel in the technical world. However, the first step in this direction is to understand how the tendril itself performs this action. Structural aspects of the mechanism, e.g. the role and expansion of the epidermis and mesophyll layers during the coiling process are widely unknown. To make matters more complex but also more exciting, actin as well as myosin fibers have been discovered in pea tendrils [13] and it is therefore possible that the actuation of tendril coiling involves both fiber-based biochemical motors and hydraulic mechanisms (plant muscles).

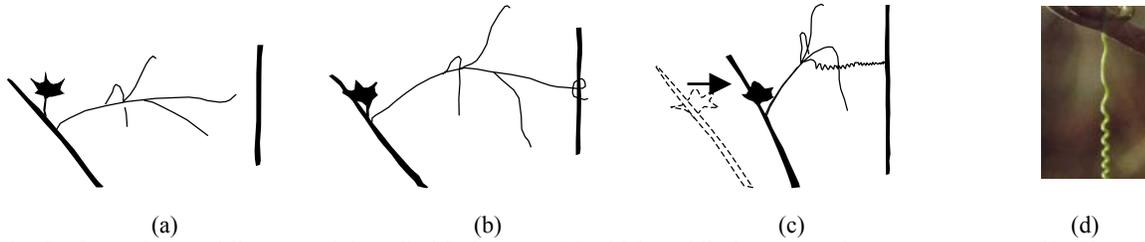


Fig. 8. Cucumber tendrils are straight cylindrical organs (a) which rapidly lobe around support structures (b). Then the tendril coils pulling the plant closer to the support (c). Since coiling starts from both ends there is a point of reversal X in the coil. Close-up photo of a portion (c), (d).

Sato and Umezaki [23] measured the mechanical properties of coiled tendrils of four different plants, pumpkin, snake gourd, sorrelvine and cucumber and the measured spring constant  $k$  are plotted as a function of elongation of the coiled tendrils, Fig. 9. Fig. 9 indicates that the values of  $k$  remain in the range of  $0.8 - 1.8 \times 10^{-2} \text{N/mm}^2$ .

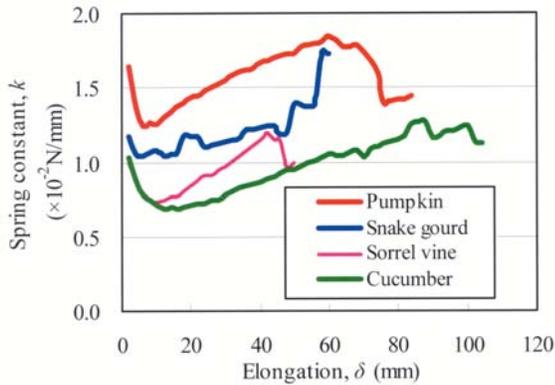


Fig. 9 Spring constant of coiled tendrils of pumpkin, snake gourd, sorrel vine and cucumber as a function of elongation [23].

#### 4. DESIGN OF ACTUATORS

Based on the mechanisms inherent in several action plants, we designed several actuators, cantilever beam made of electroactive polymers (EAP), bimorph type piezo-composite laminate with functionally graded microstructure (FGM), and spring actuators based on ferromagnetic SMA. These will be reviewed in the following

##### Electro-active and photo-active polymers

Electroactive polymers (EAP) and photo-active polymer (PAP) are emerging as a new actuator material. EAPs and PAPs can change their properties and/or shape upon applied electric field, pH change or photon injection, respectively. Fig. 10 illustrates the three-dimensional phase transformation diagram of a typical EAP or PAP.

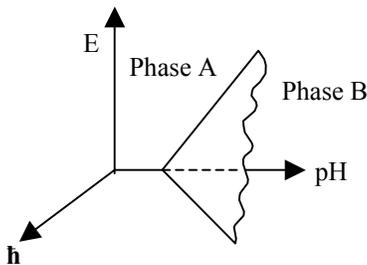


Fig. 10 3-D phase transformation diagram of a EAP or PAP where the phase change  $B \rightarrow A$  can be realized by a combination of increasing pH, electric field (E) and/or photon injection (h)

Please note that the phase transformation diagram of Fig. 10 has a similar phase-boundary as in the ferromagnetic shape memory alloy (SMA) except for stimuli for ferromagnetic SMA are stress, temperature and magnetic field. The order of strain induced in EAP is much larger than that of metal (such as FSMA) and ceramic (piezo) based actuator.

Due to the modest energy consumption, they can be best applied to the adaptive structure such as seagoing UAV and smart antenna that are very portable and low-cost. We have been working on the development of several types of EAP-hydro-gels such as amphoteric acrylamide gel [24] and Nafion [25] and ferroelectric gels [26] and photo-active gel actuator [27]. Despite the above attractive properties associated with EAP and PAP, there exist two technical challenges that remain to be solved, low speed of actuation and weak mechanical property.

The speed of diffusion in a hydrogel of EAP is irreversibly proportional to the diffusion distance which can be minimized by creating pores inside a gel. With this principle, we designed a faster response hydrogel. Fig. 11(a) shows one of our recent results [28] on the diffusion study of polymer gels where diffusion constant  $D$  is seen to increase with porosity of a porous gel. Among many hydrogels, solid electrolyte Nafion plate is the EAP that has been extensively studied. A typical Nafion with Pt or Au electrode exhibits forward and backward bending under a constant applied voltage (normally 1.5V to avoid electrolysis of water). This forward and backward motion may not affect adversely for the actuation of a Nafion based swimming fish in water., but it is not desired for applications of microelectronic switch where the displacement induced in the Nafion actuator is expected to remain constant. Recently we [25] designed a new Nafion actuator with Cu-Pt electrode which exhibit larger displacement than that of the Nafion with Pt or Au, and the induced displacement under a constant voltage (0.72V) remains constant after the initial relaxation, Fig. 12.

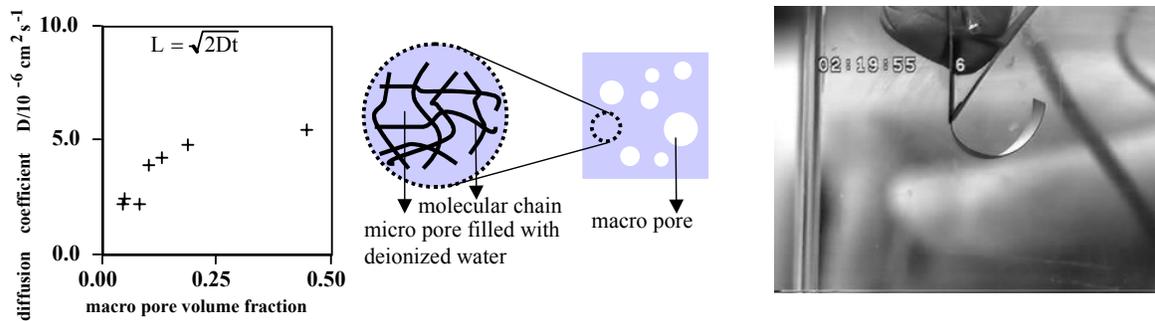


Fig. 11 Diffusion coefficient  $D$  as a function of porosity in an acrylamide gel [28] and actuation of Nafion EAP with Cu-Pt electrode [25].

### Low-cost Antenna

The most flexible satellite to ground/airplane communication system is based on the phased-array antenna technology [Boeing Connexion Web Page]. A typical phased array antenna developed by Boeing Phased Array Group consists of  $16 \times 16$  elements, and each element has a small antenna, phase shifter, and amplifiers. The antenna beam steering is done by adjusting the phases of all elements and a very fast beam scanning which is required for a satellite to airplane link is feasible with this system. Unfortunately, the cost of the phased array antennas is related to the number of active elements and the present system is too expensive for many commercial/military applications. The ground station antennas designed for low-earth orbit satellites needs to track a satellite whose position is predictable and therefore fast beam steering is not essential. However, the cost of the antennas must be much less than the current phased array antenna so that it can be deployed for military missions.

The proposed reflector consists of many small reflectors and each reflector is attached to an EAP actuator which is controlled by a DC voltage. Unlike piezo materials, the physical displacement attainable with EAP is substantial (2 to 5 mm can be achieved) and therefore, it is suited for microwave applications. The driving voltage which depends on the materials can be high but the EAP actuators require very little power to operate.

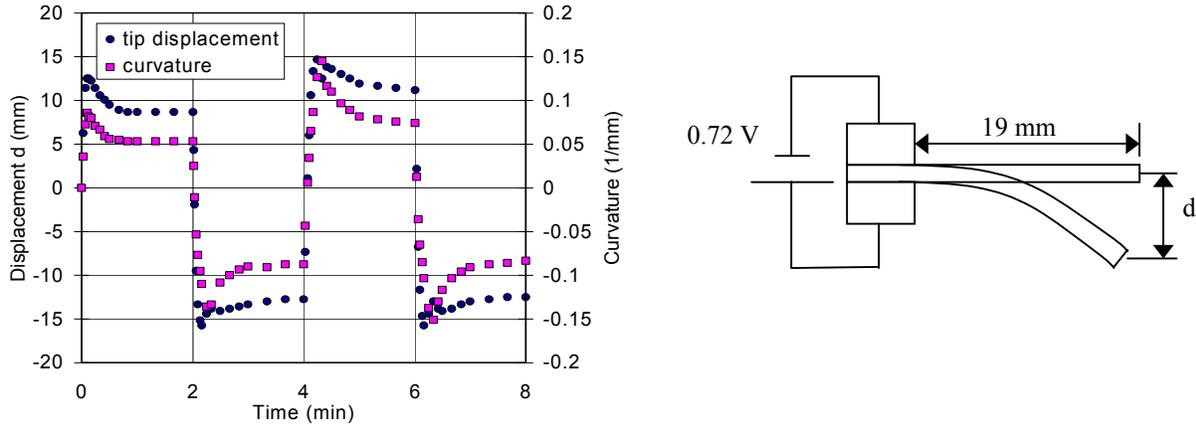


Fig. 12 Deformation of Nafion in electric field

### FGM-Piezo Actuator

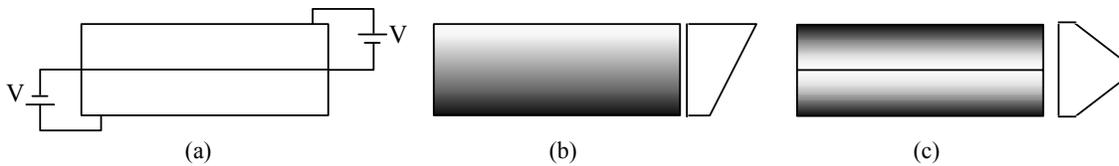


Fig. 13. Piezoelectric plate, (a) bimorph, (b) bimorph with one-sided FGM, (c) FGM bimorph.

Use of piezoelectric standard bimorph has been popular in achieving out-of-plane displacement, Fig. 13(a) where the top and bottom layers consist of identical piezoelectric material except for the polarity of the electrodes of the top and bottom layers being symmetric with respect to the mid-plane. Despite relatively large out-of-plane displacement the standard piezo-bimorph, however, suffers from large induced stress field at or around the interface (mid-plane) between the top and bottom layers. Wu et al. [29] proposed a piezoelectric actuator with one-sided FGM (so called rainbow-type FGM), Fig 13(b) where the electroelastic properties of laminate are graded from the top to bottom lamina smoothly. Even though the rainbow-type FGM piezo actuator exhibited much reduced stress field, its out-of-plane displacement is still smaller than that of the standard bimorph.

To overcome the above deficiencies associated with both standard and rainbow-type piezo actuators, we proposed a new piezo actuator, “FGM bimorph piezo actuator” which consists of laminae whose electroelastic properties are graded smoothly from top (or bottom) lamina toward the mid plane, Fig. 13(c), which can exhibit large out-of-plane deformation while minimizing the magnitude of induced stress field, thus, enhancing fatigue life.

To design higher performance piezo FGM actuators, we constructed a hierarchical modeling, (1) piezo composite model based on Eshelby’s method [30,31] and (2) laminate plate model [32,33]. The former model is to obtain the averaged electroelastic properties of each lamina while the latter is to predict the stress and displacement field in each lamina and the entire plate. These are two laminate plate models, one based on classical laminate theory (CLT) [32], the other on 2-D elasticity [33]. The 2-D elasticity model can predict the interlaminar shear stress which can not be obtained by CLT. The hierarchical model is used to design several types of FGM piezo actuators, which is stated below.

### Rainbow type FGM laminate with porous PZT

The cross section of Mohso-bamboo has functionally graded microstructure (FGM) so as to resist the bending of the bamboo due to strong wind by maximizing its bending rigidity while minimizing its weight. Fig. 14 shows the cross section of Mohso-bamboo [35].

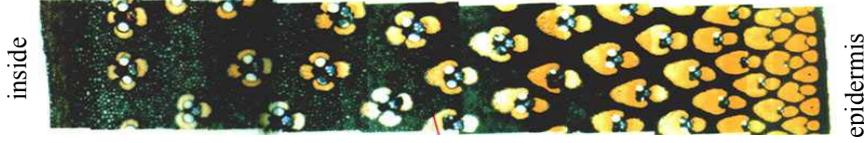


Fig. 14 Cross section of a Mohso-Bamboo along the radial direction (Nogata, 1997)

Inspired by this FGM structure in the Mohso-bamboo, we [34] designed a rainbow type FGM laminate with porous PZT. The rainbow type FGM laminate model is shown in Fig. 15(a) where the FGM layers are made through graded porosity according to

$$\left(1 - \frac{P_i}{P_n}\right) = \left(\frac{h_i}{h_n}\right)^m \quad (3)$$

Where,  $P_i$  and  $P_n$  are the porosity of  $i$ -th and top (dense) layers,  $h_i$  and  $h_n$  are the thickness from the bottom surface of the actuator. Each layer has the same thickness in the case of  $m=1$ , but the upper layers become thick or thin, if  $m$  is smaller or greater than unity.

By using the above power-law FGM with graded porosity and our CLT model, we obtained predicted curvatures as a function of power law factor  $m$ , the optimum  $m$  which provide the largest bending curvature is identified as  $m=1.92$ . Then we processed the FGM with  $m=1.92$  whose cross section is shown in Fig. 15(b).

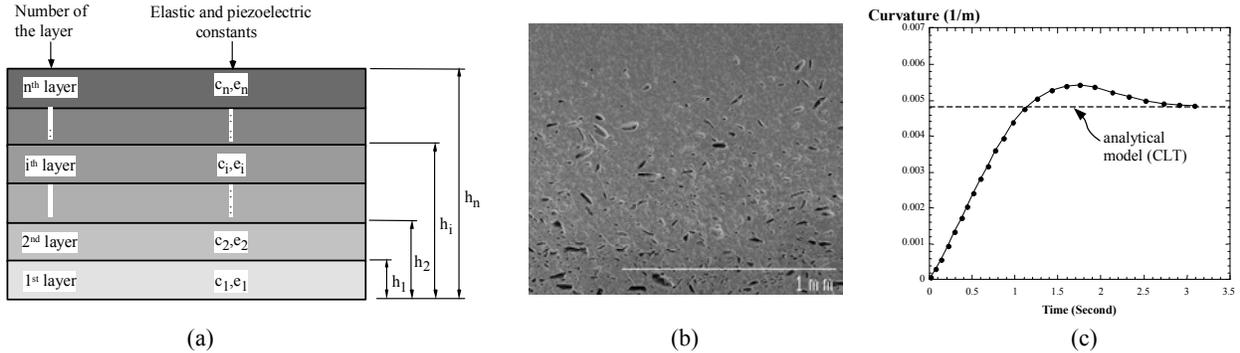


Fig. 15 (a) Schematic of FGM piezoelectric actuator composed of PZT graded porosity. (a) FGM laminate model, (b) SEM micrograph of the cross section of the FGM actuator, (c) measured displacement vs time curve, a good agreement with the predictions by our analytical modeling based on classical laminate theory (CLT) (Almajid et. al, 2001).

When a voltage of 100V was applied to the actuator, the curvature of the above FGM actuator was measured by using the electric strain gauges. Fig. 15(c) shows the curvature generated by the actuator as a function of time. The curvature increased gradually and showed a peak at 1.5 s, where the electric field across the thickness of the actuator reached at 100 V, and then decreased slowly with increasing time, due to pulse nature of piezoelectric actuators. The dotted line shows the expected curvature based on the calculations by our CLT and Equation (3) when the applied electric field is equal to 100 V, resulting in an excellent agreement. The peak curvature corresponds to the tip bending displacement of

6.5  $\mu\text{m}$  for the actuator of 12 mm in length. If the same electric field is applied to the PZT actuator designed by Zhu [36] the present FGM actuator will exhibit a much larger displacement.

## ACKNOWLEDGEMENTS

The present author is very thankful to Dr. R. Stahlburg, University of Washington for his stimulating discussion on actuation mechanisms in biology. This work was supported in part by a contract from NEDO/ RIMCOF agency, Japan in the area of smart materials and structures.

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