

The Venus Flytrap as a model for a biomimetic material with built-in sensors and actuators

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Abstract

In the present paper a model is presented for the dynamic response of a family (Droseraceae) of carnivorous plants such as the Venus Flytrap (*Dionaea Muscipula Ellis*) and the Waterwheel Plant (*Aldrovanda Vesiculosa*) to external dynamic disturbances. The goal of the present investigation is to apply such modelling to the molecular design of biomimetic materials with sensors and actuators. In modelling the dynamic response of such plants (or their flowers, to be exact) to external disturbances it is worth noting that these plants are capable of trapping and capturing their prey, usually small insects and flies, by the stimulation of a number of built-in trigger hairs or whisker-type sensors, which may be electro-elastic. The trapping and capturing action is quite muscular in the sense that, for example in the case of the Venus Flytrap, the flower, which is in the form of twin-lobed leaf blades closes quite quickly, upon stimulation of its trigger hairs, to trap the prey. These petals or valves are normally held ajar like an open spring trap. A victim entering the compass of the valves trips a trigger mechanism, whereupon the valves snap together with often surprising speed like a pair of jaws, and the victim is securely held within. The Venus Flytrap and Waterwheel Plant are closely related, though the former is terrestrial while the latter is aquatic. They belong to the same family as the Sundews (Droseraceae). The purpose of the present paper is to present a model for such intelligent structures with built-in sensors and muscular actuators in the hope of being able to fabricate similar intelligent materials (biomimetics) and intelligent structures for practical applications. Another remarkable property of the Venus Flytrap is that it is indeed possible to spring the trap without touching the trigger hairs – by repeated rubbing or scratching of the surface of the lobes for example – but the insect always does so by touching one or more trigger hairs. Based on a number of experimental observations in our laboratory we present a model for sensing and actuation of the Venus Flytrap. Our model is based on redistribution of ions and in particular Ca^{2+} and H^+ ions in the tissue volumes. Generation of action potential simulation of trigger whiskers creates an ionic membrane type depolarization wave that propagates throughout the flower tissues.

Keywords: Biomimetic sensors; Built-in sensors; Venus Flytrap

1. Introduction

Intelligent material systems and structures, including biomimetic ones, have become important in recent years due to some potential engineering applications. Accordingly, based on such materials, structures and their integration with appropriate sensors and actuators, novel applications, useful for a large number of engineering applications have emerged. The field of intelligent botanical structures is another field of interest to explore.

The Venus Flytrap (*Dionaea Muscipula Ellis*) possesses an active trapping mechanism to capture insects. In this family of intelligent botanical plants there are also other examples, such as the Waterwheel Plant, that basically perform the same trapping mechanisms of wandering food materials in a liquid environment. Sibaoka [1] and Fagerberg and Allain

[2] have presented a quantitative study of tissue dynamics during closure in the traps of the Venus Flytrap. Thus, in the present paper a model is presented for the dynamic response of a family (Droseraceae) of carnivorous plants such as the Venus Flytrap and the Waterwheel Plant (*Aldrovanda Vesiculosa*). These plants are capable of trapping and capturing their prey, usually small insects and flies, by the stimulation of a number of built-in trigger hairs or whisker-type sensors which are electro-elastic (Fig. 1).

Williams and Mozingo [3] and Jacobson [4] have discussed the fine structure of the trigger hair and the effect of the ionic environment on its response in the Venus Flytrap. The trapping and capturing action is quite muscular in the sense that, for example in the case of the Venus Flytrap, the flower, which is in the form of twin-lobed leaf blades, closes quite quickly upon stimulation of its trigger hairs to trap the prey. These petals or valves are normally held ajar like an open spring trap. A victim entering the compass of the valves

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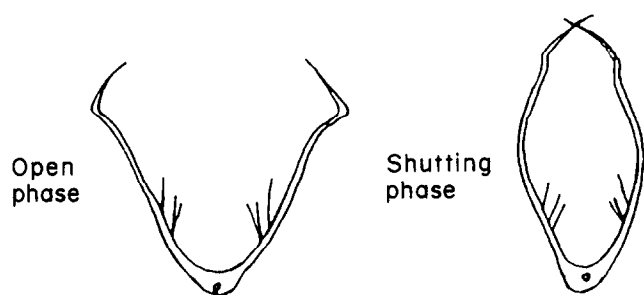


Fig. 1. Stages in the closing of the traps in the Venus Flytrap.

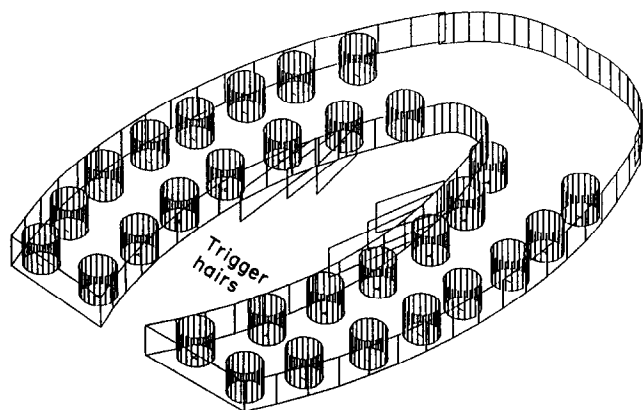


Fig. 2. Folding of traps due to an imposed action potential.

trips a trigger mechanism, whereupon the valves snap together with often surprising speed like a pair of jaws, and the victim is securely held within. The Venus Flytrap and Waterwheel Plant are closely related, though the former is terrestrial while the latter is aquatic. They belong to the same family as the Sundews (*Droseraceae*). The purpose of the present paper is to present a model for such intelligent structures with built-in sensors and muscular actuators in the hope of being able to fabricate similar intelligent structures for practical applications. Another remarkable property of the Venus Flytrap is that it is possible to spring the trap without touching the trigger hairs – by repeated rubbing or scratching of the surface of the lobes for example – but the insect always does so by touching one or more trigger hairs. Based on a number of experimental observations in our laboratory we present a model for sensing and actuation of the Venus Flytrap. Our model is based on redistribution of ions and in particular Ca^{2+} and H^+ ions in the tissue volumes. Our model is similar to that of Hodick and Sievers [5,6]. Generation of action potential simulation of the trigger whiskers creates an ionic membrane type depolarization wave that propagates throughout the flower tissues. In the following section we present a mechanism for folding of the two lobes of the Venus flytrap due to the imposition of an electric field created by the action potential generated by the movement of the trigger hairs. The possibility of transformation of such plants to other forms of matter has been discussed by Karlsson and Pate [7].

In connection with the present paper there are applications of electrically activated ionic polymeric gel muscles as discussed by Shahinpoor [8–11]. These findings clearly indicate that the short-term response of an ionic medium to an imposed electric field is the migration of unbound counterions in the cell network and the impingement of solvent ions on the surface of the cell network. It is the surplus or deficiency of such ions which determines the osmotic pressure, free volume and deformation or folding (trapping). In the following sections a model is offered for the trapping of a Venus Flytrap flower along its crux subject to a transverse electric field gradient.

2. The trapping mechanism in the presence of an electric field

Suppose that a Venus Flytrap flower takes the form of a two-lobed trap margin and tynes such that the actual bending mechanism is in the form of a thin straight strip of an ionic cell of length L , thickness t^* and height h , is bent into a curved strip (Fig. 2) by an imposed voltage gradient across its thickness t^* . It is assumed that initially the trap is in a natural bending stress free state equilibrated with some ionic concentration. Now, referring to Fig. 3, note that the strain ϵ (defined as the ratio of the actual incremental deformation (δl) to the initial length (l_0)) is given by

$$\epsilon = \epsilon_c + \kappa_E \eta = \lambda - 1 \quad (1)$$

where ϵ_c is the strain along the neutral central line (the line through the centres of the areas of all cross-sections), κ_E is the curvature of the strip due to the presence of an action potential, λ is the stretch and η is a cross-section variable (Fig. 3) such that $-C \leq \eta \leq C$, $t^* = 2C$, where t^* is the thickness of the trap.

Owing to the presence of an action potential an electrical voltage gradient will be created across the thickness t^* of the traps, which are bent into a curved strip by a non-uniform distribution of fixed as well as mobile ions in the trap cells. Note that an electric field gradient may be imposed across the

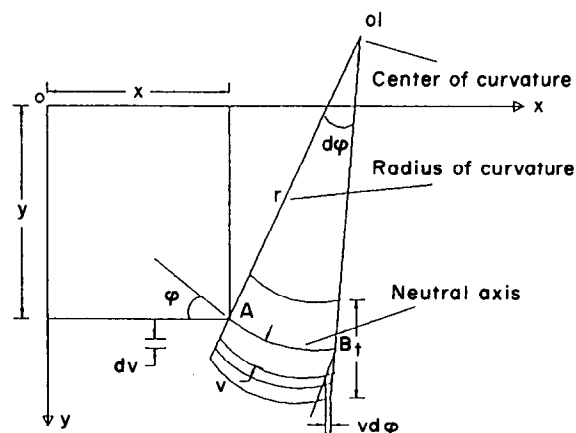


Fig. 3. Geometry of micro-bending of trap cells in the Venus Flytrap.

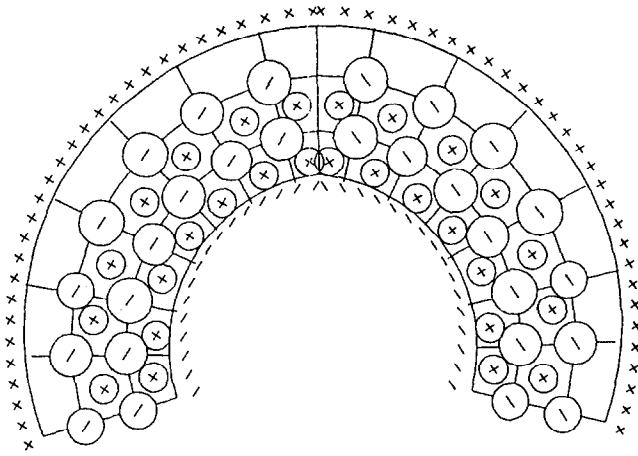


Fig. 4. A possible charge redistribution configuration in trap cells.

thickness of the traps by the triggered action potential. One may also consider a situation in which the action potential causes the ionic membranes of the trap cells to redistribute their surface pores and allow the internal hydrogen ions (H^+) to exit the trap cells on one side and cause a differential osmotic pressure across the trap cells, and thus induce bending. In this paper the former mechanism is considered rather than the latter.

If the trap cells possess a capacitance C_t and a resistance R_t , Kirchhoff's law can be written in the following form:

$$v = C_t^{-1}Q + R_t \dot{Q} \longleftrightarrow \dot{Q} = i \quad (2)$$

where v is the voltage across the thickness of the trap and Q is the charge accumulated in the trap cells, \dot{Q} being the current i through the trap across its thickness. Eq. (3) can be readily solved to yield

$$Q = C_t v [1 - \exp((-t/R_t C_t))] \quad (3)$$

assuming that at $t=0$, $Q=0$. Eq. (3) relates the voltage drop across the thickness of the trap to the charge accumulated, which eventually causes the trap to fold. The triggering of the fingers (sensors) causes an action potential to be unleashed to create a voltage gradient across the thickness of the twin lobes. The imposed voltage gradient across the thickness of the trap forces the internal fixed and mobile ions to redistribute, as shown in Fig. 4.

The proposed theoretical development considers the spatial distributions of cations and anions within the trap cells before and after the application of an action potential, which is assumed to set up an electric field across the trap cells. The model will then derive exact expressions relating the deformation characteristics of the trap as a function of electric field strength or voltage gradient, trap dimensions and physical parameters such as the diffusivities of cations (D_{TM}) and anions (D_{TP}), elastic modulus E , temperature T , charge concentration of cations (C_{TM}) and anions (C_{TP}), and the resistance R_t and capacitance C_t of the trap cells.

Let us now assume that there exists an electric field across the thickness t of the trap cells such that on the positive side or the anode side the strain is ϵ_+ and on the negative or

cathode side the strain is ϵ_- . Now it is obvious from Eq. (1) that

$$\epsilon_+ = \epsilon_c + \kappa_E C \quad (4)$$

$$\epsilon_- = \epsilon_c - \kappa_E C \quad (5)$$

where $C = (1/2)t^*$, such that $-C \leq \eta \leq C$, and t^* is the thickness of the trap cells. Now, from Eqs. (1), (4) and (5):

$$\epsilon_+ - \epsilon_- = 2\kappa_E C \quad (6)$$

Note that $\epsilon = \lambda - 1$, where λ , or stretch, is defined as the ratio of the current length of an element of the gel to the length of the same element in its natural state. Thus, it is clear that

$$\lambda_+ - \lambda_- = 2\kappa_E C \quad (7)$$

where κ_E is the total local curvature of the trap cells due to the pressure of a voltage gradient across the thickness of the trap cells.

Let us assume a non-linear constitutive equation for the trap cells such that the axial stress σ in traps is well modelled by the following equation:

$$\sigma = [E(C, pH, T)/3]f(\lambda) \quad (8)$$

where E is the Young's modulus of elasticity of the trap and is a function of the concentrations of solvent C and hydrogen and calcium ions in the trap cells as well as the absolute temperature T . Assume that due to the presence of an electrical voltage gradient across the thickness t^* of the trap the trap is bent into a curved strip by a non-uniform distribution of fixed as well as mobile ions (cations) in the trap cells.

Note from Fig. 2 that the trap cells acts like electrical circuits with resident capacitors and resistors. In particular, since the deformation of trap cells due to the influence of an imposed electric field is due to redistribution and shift of ions in the cells, the change in osmotic pressure Π associated with ion redistribution and concentration gradients should be considered. The bending deformation of the trap due to the presence of an action potential or an electric field can be described by Flory's theory of osmotic pressure, [12,13]. According to Flory's theory, the equilibrium volume V of a cell is determined by

$$\Pi_{\text{Network}}(V) + RT \sum_{i=1} (C_{i,t} - C_{i,s}) = 0 \quad (9)$$

where $\Pi_{\text{Network}}(V)$ is the osmotic pressure of a stress-free cell, R is the universal gas constant, T is the absolute temperature and $C_{i,t}$ and $C_{i,s}$ determine the ionic concentration of species i in the cell and its outer environment, respectively. The subscript i stands for mobile cations, M^+ , anions, P^- , hydrogen ions, H^+ , and hydroxyl ions, OH^- . If the trap cell also has electrical charges, there will be strong ionic concentration gradients on the boundaries of the cell and the surrounding solution which contribute to the osmotic pressure and thus expand or contract the upper or lower epidermis cells. Let us assume that the osmotic pressure in the epidermis

cells on the anode side is Π_1 and that of the cathode side is denoted by Π_2 . The difference $\Delta\Pi = (\Pi_1 - \Pi_2)$ causes the trap to bend such that the amount of bending is dependent on the difference between the stretches λ_+ and λ_- on the anode side and the cathode side, respectively. Then, based on Eq. (6), the stretches λ_+ and λ_- are related to the state of uniaxial stresses $\sigma_+ = \Pi_1$ and $\sigma_- = \Pi_2$, such that one has

$$\Pi_1 = (E_+/3)f(\lambda_+) \quad (10)$$

$$\Pi_2 = (E_-/3)f(\lambda_-) \quad (11)$$

where E_+ and E_- are the corresponding elastic moduli at the anode and the cathode sides of the trap epidermis cells, respectively. The idea here is to find explicit relations for Π_1 and Π_2 so that λ_+ and λ_- can be found from Eq. (10) and (11). One can then relate the resulting bending curvature κ_E to the difference $\lambda_+ - \lambda_-$ by Eq. (5). The epidermis cells and the surrounding aqueous solution are divided into three regions: the anode side A, the trap cell side T and the cathode side C. We further consider systems with only one kind of mobile cation (M^+) such as Ca^{+} . The imposed electric field forces the cations to move toward the cathode, causing abrupt concentration gradients across the boundaries. These cation concentrations are then given by:

$$C_{A,M}(t) = C_{A,M}(0)(1 - h_{TA,M}t) \quad (12)$$

$$C_{T,M}(t) = C_{T,M}(0)(1 - h_{TC,M}t) + C_{A,M}(0)(V_A/V_T) \times h_{TA,M}t - C_{A,M}(0)(V_A/V_T)h_{TA,M}h_{TC,M}t^2 \quad (13)$$

$$C_{C,M}(t) = C_{C,M}(0) + C_{T,M}(0)(V_T/V_C)h_{TC,M}t + C_{A,M}(0)(V_A/V_C)h_{TA,M}h_{TC,M}t^2 \quad (14)$$

where $h_{TA,M}$ and $h_{TC,M}$ are the cation transport rates across the T–A and T–C boundaries, respectively, V_A , V_T and V_C are the volumes of A, T and C parts, and t is the time of exposure to the electric field. The corresponding osmotic pressures $\Pi_{1,M}$ and $\Pi_{2,M}$ on the anode and the cathode boundaries of the trap cells due to redistribution of cations are then given by

$$\Pi_{1,M} = RT[C_{T,M}(t) - C_{A,M}(t)] \quad (15)$$

$$\Pi_{2,M} = RT[C_{T,M}(t) - C_{C,M}(t)] \quad (16)$$

Similarly, the anions P^- will be redistributed by migrating toward the anode. Since the whole system is neutral, water resolves into H^+ and OH^- to satisfy these redistributions of cations and anions by migrating towards the cathode and the anode electrodes, respectively. Therefore, the contribution to the osmotic pressures on the anode and the cathode sides due to these charge redistributions can similarly be calculated such that

$$\Pi_1 = \Pi_{1,M} + \Pi_{1,H} + \Pi_{1,OH} \quad (17)$$

$$\Pi_2 = \Pi_{2,M} + \Pi_{2,P} + \Pi_{2,H} + \Pi_{2,OH} \quad (18)$$

In summation form, Eqs. (17) and (18) can be written as

$$\Pi_1 = RT \sum_{i=1} [C_{T,i}(t) - C_{A,i}(t)] \quad i = M, P, H^+, OH^- \quad (19)$$

$$\Pi_2 = RT \sum_{i=1} [C_{T,i}(t) - C_{C,i}(t)] \quad i = M, P, H^+, OH^- \quad (20)$$

where

$$C_{A,i}(t) = C_{A,i}(0)(1 - h_{TA,i}t) \quad (21)$$

$$C_{T,i}(t) = C_{T,i}(0)(1 - h_{TC,i}t) + C_{A,i}(0) \times h_{TA,i}t - C_{A,i}(0)(V_A/V_T)h_{TA,i}h_{TC,i}t^2 \quad (22)$$

$$C_{C,i}(t) = C_{C,i}(0)(1 - C_{T,i}(0))(V_T/V_C)h_{TC,i}t + C_{A,i}(0)(V_A/V_C)h_{TA,i}h_{TC,i}t^2 \quad (23)$$

Due to charge neutrality the following relations also hold:

$$C_{k,M}(t) = C_{k,OH}(t) \quad k = A, T, C \quad (24)$$

$$C_{k,P}(t) = C_{k,H}(t) \quad k = A, T, C \quad (25)$$

Thus Eqs. (19) and (20) simplify to

$$\Pi_1 = 2RT \sum_{i=1} [C_{T,j}(t) - C_{A,j}(t)] \quad j = M, P \quad (26)$$

$$\Pi_2 = 2RT \sum_{i=1} [C_{T,j}(t) - C_{C,j}(t)] \quad j = M, P \quad (27)$$

As discussed before, these stresses will be related to the induced stretches λ_+ and λ_- on the anode and the cathode sides, respectively, by Eqs. (10) and (11). The resulting non-linear equations are then solved for λ_+ and λ_- to calculate the induced curvature κ_E such that

$$\kappa_E = [(\lambda_+ - \lambda_-)/t^*] \quad (28)$$

where t^* is the thickness of the trap cells. The total charge Q which relates the voltage v and other electrical parameters C_i and R_i to the curvature κ_E may be calculated by the following equation:

$$Q = V_T \sum_{j=1} C_{T,j} \quad \text{for } j = M, P \quad (29)$$

3. Conclusions

A simple theory for trapping deformation of the Venus Flytrap has been presented. This theory considers a finite strip of the trap cells. The proposed theoretical model for the bending deformation of epidermis cells in an electric field predicts the phenomenon of bending of the traps due to an induced action potential. The action potential may also redistribute cell membrane pores due to ionic interactions and thus cause internal H^+ ions to evacuate the trap cells on one side and induce bending. However, our preferred model considers the spatial distributions of cations and anions within the epider-

mis cell network before and after the application of an action potential or an electric field. The model predicted and derived exact expressions relating the deformation characteristics of the trap as a function of electric field strength or voltage gradient, trap dimensions and trap cell physical parameters, such as the diffusivities of cations (D_{TM}) and anions (D_{TP}), elastic modulus E , temperature T , charge concentration of cations (C_{TM}), charge concentration of anions (C_{TP}), and the resistance R_t and capacitance C_i of the trap cells. The similarity between these mechanisms and the dynamic response of ionic polymeric gels suggest that one may be able to design biomimetic materials from ionic polymeric gels with a similar response and dynamic characteristics with built-in sensors and actuators.

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