Design and manufacturing of mimosa pudica inspired smart window and analysis of scale dependent constraints

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Abstract. Bio-inspired design is the practice where the form, function and behaviour of natural entities at different scales used for developing sustainable technologies. During this process, scaling up and miniaturization play an important role. The successful implementation or achievement of bio-inspired features in engineering systems depends on the scale at which the inspiration is taken. Hence the constraint analysis in scale up and miniaturization of bio-inspired design is an important aspect to study. The work take up the mimosa pudica as a bio-inspiration for smart window technology, analyze w.r.t its micro and macroscale design features. Unlike the other works, the macroscale features of mimosa pudica are taken as inspiration and microscale phenomena (Water molecular flow based turgor pressure etc.) are replaced with macroscale viable phenomena (electronics and sensors..). The macro feature inspired smart window is demonstrated with multiple working states. Further, the constraint analysis in the scaling up process of bio-inspired smart window is presented. The analysis indicates the advantages w.r.t accuracy and responding time at the cost of high power consumption and also posts the requirements to achieve the trade-off. This work also emphasizes on the significance of scale based design & constraint analysis, and importance of scale in bio-inspired engineering.

1. Introduction
Bio-inspired design or biomimicry is the area where solutions are created by taking inspiration from nature. The field is emerging with fast pace by providing innovative solutions [1]. In the same lines mimosa pudica is the plant that closes its petals against the stimulus. The stimulus can be touch, light, vibration and heat. This plant design inspired scientists and engineers for years to engineer structures such as thermally adaptive building coverings, Tactile sensors, flexible pressure sensors, water/ethanol foldable origami materials, smart fabrics, self-powered smart phones, osmosis based artificial muscle [2] etc.
Where the inspirations are taken at micro level, such as surface micro texture (pressure sensing), osmosis (artificial muscle) [3], fluid flowing against water vapour (origami materials) etc. Previously movements and displacements have been kinematically analysed and amplified [4]. As far as design is concerned the macro scale features such as mechanical folding of petals, touch [5], light [6] and vibration sensing, organising the bio-clock, photosynthesis management etc. inspires in individually and collectively too. The macro scale inspired full-fledged technologies are mostly not attempted.

On the other hand the concept of smart window has significance for engineers due to its applications in different systems such as agro forms, aircraft, buildings, and marine. But the careful observations of smart window technologies, it is observable that most of the technologies focus on the light [7-8] and heat control and self-cleaning, where the window completely isolates the internal environment from external. Till date mimosa pudica inspirations have been analysed for massive applications in robotics for soft touch [9]. However, there are no windows that control light, noise; air/oxygen at same time gives the advantage of intelligent operation and this application has not been explored yet. Further, the mimosa pudica / bio-inspired smart windows are attempted from micro-scale inspiration such as self-cleaning window (lotus texturing), mechanochromic window (Jellyfish inspired), adaptive stiffness material [10] (spatial distribution of microscopic constituents) etc. Further correlations between photosynthesis and respiration in response to changes in electric signals have been explored microscopically [11]. Specifically the windows used in building technology, agro forms, and old age homes, health care centres etc. demand the smart windows with light, vibration (noise), dust, oxygen, rain based state changes, with easy operation strategy.

The requirement can be met by taking the macroscopic feature based inspiration from mimosa pudica for comprehensive design of smart window. These works presents the design analysis of mimosa pudica in terms of micro and macroscale features and apply the macro inspiration to design the smart window. The macro features inspires different states of operation of the window are demonstrated. Further, the impact of scaling up of the macro features to smart window technology are analyzed and constraints are indicated.

2. Results and discussion

2.1. Scale based design analysis of mimosa pudica

The mimosa pudica plant belongs to Fabaceae family where the plant movements are significant and of interest for engineers. The internal microstructure of the plant from pelvous to tip post different phenomena that are supporting the macro features. The multi cellular organism of the part having water in their cells transmits the water from tip portion to pulvinus portion by stimulation [12].

The small leaflets grow off the midrib as a collection from mimosa pudica plant, constituting about 15 to 20 pairs across the midrib. It is observed that vein and the midrib of each leaflet lie at an angle ranging from 25° to 85° between As a result, this angle decreases to between 15° to 25° when the leaflets sense touch [13].

Quick folding of leaves is achieved by change in turgor pressure. Turgor pressure is the amount of water pressure in the cell that is pushing up against the cell wall. When there is a lot of water pushing against the cell wall the turgor pressure is high, and cell is rigid. When water moves out of the cell, the turgor pressure decreases and the cell becomes flaccid. Osmosis is a phenomenon were water moves in and out of the cell associated with. Whenever there is an unequal concentration of sodium and potassium ions which act as solutes in the cells, across the membrane, the mechanism of osmosis takes place. Hence, there will be flow of Water from the solution with the higher concentration of solutes to the lower concentration, until equilibrium between the two sides is reached.

There are two type of cells in which the concentration of potassium and sodium ions change upon sense of touch, namely flexor and extensor cells within the mimosa pudica pulvinus [14-15]. The pulvinus
is the “hinge-like” area of the plant where the leaflet connects to the midrib, and the midrib connects to the stem. Water flows from the extensor cells present on the top to flexor cells situated at bottom pulvinus. This flow of water caused by a change in the concentration of chloride and potassium ions causes out of the extensor cells, makes them soft. On the other hand, the flow of water into the flexor cells, makes them turgid, and this mechanism in turn causes folding of leaflets.

It is observed that the leaves fold in about a time period of 4-5 seconds, whereas the unfolding can take anywhere between 10 secs-60secs. The time taken by the leaves to remain closed is defined as hiding time [16]. It is believed that the unfolding time is a result of behavioural adjustments that the plant makes over time in response to different kinds of stimuli. Younger, softer leaves are usually preferred by Herbivores.

It is concluded that when younger leaves were repeatedly exposed to stimuli that are non-damaging in condition, the folding of younger leaves took place completely, but it is observed that the time taken to unfold decreased than the time for complete folding. However, in case of the, older leaves only partial folding of leaves was observed, with same time to unfold. Thus it can be inferred that the plant is able to modulate its behaviour to optimize protection, energy production (photosynthesis), and energy expenditure shown in figure 1 (folding and unfolding).

![Figure 1](image_url)

**Figure 1.** The scale based features of the mimosa pudica at macro and micro scales. (a) Micro scale features, (b) macro scale features.

3. **Sensors coding states and flow chart of working**

Mimosa pudica has been taken as an inspiration for plant intelligence [17-18] previously and hence the smart window has been Arduino coded with an analogy with response to touch, light and rain. As shown in Figure 2, 3 different states coded and flow chart describing working of sensors are presented.
Figure 2. The different states coded in smart window inspired by the macro features of the Mimosa pudica plant.

Figure 3. The different states coded in smart window inspired by the macro Features of the Mimosa Pudica plant.
4. Experimental setup design and fabrication

4.1. Macro feature inspired smart window fabrication

The setup consists of 1) Three louver type glass surfaces which respond to human touch 2) Wooden outer frame 3) Louver motion mechanism (Figure 4). Referring to Figure 4-d, the louver type window is finalized because it provides maximum ventilation. For detection of touch on glass panes, Piezo sensors are used. Two piezo sensors are attached at the back of the glass pane on either side and the output of sensors is observed on touch of glass panes by finger. Therefore, an IR grid is placed just above the glass pane to detect presence of finger. The finger obstructs signal from a specific IR TX to IR RX in the grid indicating the presence of finger. This sensor detects touch on the panes. The rain and sunlight sensor are placed on the outer surface of window frame and glass panes close automatically during rain and at night. All the windows are operated by a single rod, which moves up and down to open and close the louvers. This rod is moved by a rack and pinion mechanism connected to a gear, which in turn is connected to a motor. This motor is operated based on the signals given to it by the microcontroller, which in turn gets signals from the IR sensor. The supporting racks for holding the glass panes have been additively manufactured from the PLA (Poly Lactic Acid) filament using filament extrusion process using ANYCUBIC 3D printer (Figure 5).
The outer body of the final prototype is made using 10mm thick plywood sheet. Plywood was opted as it can be easily machined and is less expensive. The touch sensitive louvers are held by to wooden vertical columns resembling walls in real life scenario. The louvers connected by a common link- which enables rotation of all louvers. A DC motor is positioned on one of the wooden vertical columns which drive the mechanism. Sensors for detecting daylight and rainfall are positioned on top of the inclined surface of the frame shown in figure 6 and 7.

**Figure 6.** The positions of rain, sunlight, piezoelectric sensors and Infrared Grid (IR) in the experimental setup.

**Figure 7.** A view of the Vertical column and Common link.
### Table 1 Functional Inspiration Based on macro features of touch me not plant and analogy to engineering based features.

| Mimosa pudica features                                                                 | Engineering functional features                                                                 |
|----------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Mimosa pudica shows sensitivity to touch by change of ion gradients, and leaves remain fold for 4-5 seconds and then open. | Glass surfaces (windows) have been designed to respond to which responds to human touch, with integrated piezo electric and IR grid sensors to induce opening and closing of the smart window. |
| There is change of angle from 25° to 15° of leaves when they are touched.               | The windows folding in response to touch, from angle of 90° to 0° from open to close position. |
| The plant is able to moderate its behavior to maximize protection, energy production (photosynthesis), and energy expenditure (folding and unfolding), by folding time of 4-5 seconds. | The smart window is sensitive to touch, rain and light with rapid response time approximately 2 secs to optimize time for working. |
| The leaves of the mimosa pudica plant emerge as a pattern from the midrib, and sense of touch on single leaf causes the all the other leaves connected to the midrib to get folded. | The glass windows motion mechanism is such that on touching any portion on any louver the entire louver setup rotates up to certain degrees in a particular direction. To achieve this, the easiest and the most efficient way is to connect all the three louver through a single common link and connect a motor to one of the louver. When the electronic system senses a touch, motor is activated and the complete louver setup rotates |

## 5. Scale based constraint analysis

### Table 2. The comparison among the mimosa pudica, smart window and traditional window w.r.t different measurable physical parameters [19].

| Parameters                              | Mimosa pudica | Smart window | Traditional window(manual) |
|-----------------------------------------|---------------|--------------|----------------------------|
| Response time(complete closing)         | 4 secs        | 2 secs       | No automatic closing       |
| Response time(complete opening)         | 5 secs        | 2 secs       | No automatic opening       |
| Threshold voltage and charge for closing | 1.3–1.5 volts and 2–10 μC of leaflets for opening / closing | 1.2-1.3 volts, 200mA | No power consumption       |
6. Real life applications
The smart window with macro scale features inspired from mimosa pudica responds to touch, light and rain (water droplets) in table 1 and 2. In skyscrapers and buildings, which have numerous glass windows and each one has to be operated manually which can consume large amount of precious time and can be tiresome. In addition, opening and closing of conventional windows can be a burdensome job for the physically challenged individuals. Furthermore, during rainfall, rainwater may enter into the residential areas or offices if the windows are not shut. This smart window responds to human touch. The window opens and closes by itself when just touched upon its glass surface, saving time and energy for humans. Additionally, this smart window is capable of detecting rainfall and daylight. Just like in case of mimosa pudica where touch of one leaflet leads to rapid closing of all leaflets attached to midrib, the smart windows are connected by louver mechanism such that touch of single window, leads to movement of all other windows, leading to energy conservation in actuating all windows individually one by one.

7. Conclusion
Thus a smart window sensitive to light, touch and rain was fabricated with inspiration from mimosa pudica. The inspiration from macro scale features of touch me not plant such as sensitivity to light, rain and power can significantly decrease human time and effort to close windows in applications such as skyscrapers and buildings, which have numerous glass windows and each one has to be operated manually which can consume large amount of precious time and can be tiresome. In addition, opening and closing of conventional windows can be a burdensome job for the physically challenged individuals. Furthermore, during rainfall, rainwater may enter into the residential areas or offices if the windows are not shut. This smart window responds to human touch. The window opens and closes by itself when just touched upon its glass surface, saving time and energy for humans. Additionally, this smart window is capable of detecting rainfall and daylight. Just like in case of mimosa pudica where touch of one leaflet leads to rapid closing of all leaflets attached to midrib, the smart windows are connected by louver mechanism such that touch of single window, leads to movement of all other windows, leading to energy conservation in actuating all windows individually one by one.

For example to respond to rain, sunlight hydroxipatite foams manufactured by gel casting mounted onto glass frames can be used. Gel casting [21] is a superior forming procedure and is advanced to tackle some of the restrictions of several complex-shape methods for instance injection moulding or pressing. Furthermore gel-casting process has remarkably become a potential research objective in ceramic forming area because of the elevated strength, great density, little cost, and machinable feature in forming of green bodies. Hydroxipatite/calcium foams embedded with sodium chloride solution mounted onto glass frames can witness a change in ion concentration due to moisture absorption/evaporation according to weather conditions and can actuate springs connected to glass window to pull/push the glass windows for closing, opening using minimal amount of force [22-23]. The advent of more such affordable manufacturing techniques like gel casting can only help in greater progression of bio inspired technologies to be applied to real world problems at affordable prices.
8. References

[1] Chatterjee S An approach towards plant electrical signal based external stimuli monitoring system Doctoral dissertation, University of Southampton

[2] Sinibaldi E, Argiolas A, Puleo GL and Mazzolai B 2014 Another lesson from plants: the forward osmosis-based actuator. PLoS one. 9

[3] Jensen EL, Dill LM and Cahill Jr JF Applying behavioral-ecological theory to plant defense: light-dependent movement in Mimosa pudica suggests a trade-off between predation risk and energetic reward The American Naturalist 177 377-81.

[4] Ismarrubie ZN, Goh HL, Masuri S and Yusoff H 2015 Bio-Mechanism Response of Mimosa Pudica against External Stimulation. InAdvanced Materials Research 1125 588-592

[5] Burkholder PR and Pratt R 1936 Leaf-movements of Mimosa pudica in relation to light American Journal of Botany 46-52

[6] Chang CL and Shie JL 2015 Design and implementation of a bionic mimosa robot with delicate leaf swing behavior Micromachines 6 42-62

[7] Soetedjo H, Haryadi B and Tasyantyo D 2015 Effect of Light Illumination on Leaves Movement of Mimosa pudica InApplied Mechanics and Materials 771 63-67

[8] Charpentier V, Hannequart P, Adriaenssens S, Baverel O, Viglino E and Eisenman S 2017 Kinematic amplification strategies in plants and engineering Smart Materials and Structures 16 063002

[9] Musah RA, Lesiak AD, Maron MJ, Cody RB and Edwards D, Fowble KL, Kane AJ, Long MC 2016 Mechanosensitivity below ground: Touch-sensitive smell-producing roots in the shy plant Mimosa pudica Plant physiology 170 1075-89

[10] Molecular Magic behind the “Touch me not” plant, Bhuvaneshwari Sampath, AU-KBC research centre, Anna University, Chennai

[11] Sinibaldi E, Puleo GL, Mattioli F, Mattoli V, Di Michele F, Beccai L, Tramacere F, Mancuso S and Mazzolai B 2013 Osmotic actuation modelling for innovative biorobotic solutions inspired by the plant kingdom Bioinspiration & biomimetics 8 025002

[12] Li S and Wang KW 2016 Plant-inspired adaptive structures and materials for morphing and actuation: a review Bioinspiration & biomimetics 12 011001

[13] Hoddinott J Rates of Translocation and Photosynthesis in Mimosa pudica L New Phytologist 79 269-72

[14] Reed-Guy S, Gehris C, Shi M and Blumstein DT 2017 Sensitive plant (Mimosa pudica) hiding time depends on individual and state PeerJ 5

[15] Mancuso S 2018 The revolutionary genius of plants: A new understanding of plant intelligence and behavior Simon and Schuster

[16] Barbara Mazzolai Smart technological solutions inspired from behaviour and adaptive strategies in plants Center for micro Barbara Mazzolai biorobotics, Istitutut italiano di tecnologia

[17] Trivedi D, Rahn CD, Kier WM and Walker ID 2008 Soft robotics: Biological inspiration, state of the art, and future research Applied bionics and biomechanics 5 99-117

[18] Trewavas A 2017 The foundations of plant intelligence Interface Focus 7 20160098

[19] Pavlovič A 2012 The effect of electrical signals on photosynthesis and respiration. InPlant electrophysiology 33-62

[20] Leaves fold in response to touch

[21] Seyedmajidi S, Seyedmajidi S, Alaghehmand H, Hajian-Tilaki K, Haghanifar S, Zabihi E, Rajabnia R and Seyedmajidi M 2018 Synthesis and characterization of hydroxyapatite/bioactive glass nanocomposite foam and fluorapatite/bioactive glass nanocomposite foam by gel casting method as cell scaffold for bone tissue Eurasian J Anal Chem. 13
[22] Patil HS and Vaijapurkar S 2007 Study of the geometry and folding pattern of leaves of Mimosa pudica *Journal of Bionic Engineering* 4 19-23

[23] Volkov AG, Foster JC, Ashby TA, Walker RK, Johnson JA and Markin VS 2010 Mimosa pudica: electrical and mechanical stimulation of plant movements *Plant, cell & environment* 33 163-73.