Biomimicking of physiology with micro embedded systems for tree infusion

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KEYWORDS

Tree Diagnosis,
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Micro Needles,
Micro Capillaries,
Biocides,
Tree Injection,
Micro Fluidics,
MEMS Pumps.

ABSTRACT

The aim of project is to bridge the plant engineering with micro/nano era to promote sustainable environment and tree health. This projects promotes resource and chemical accountability, more hands on yield and metabolisms and paves for a new future in tree health diagnosis in Horticulture, Ornamental trees, Urban trees and commercial trees like Malabar neem, teak, eucalyptus etc for timber and rubber. The concept is to hack the hydraulic physiological process of trees to induce water, minerals, growth hormones, biocides and any other chemical solutions prompting tree health with almost noninvasive and zero environmental hazards. The pumping process is bio mimicked with MEMS pumping motor or actuator with necessary sensor plugins embedded into Drug delivery using MEMS in humans is already trending the concept is adapted to tree diagnosis. Micro needle or capillary tubes shunted either to lateral roots or to cambium part of bark as per the solution to be infused. An entire model kit for micro infusion is to be designed for automated and pumping at tree flow rates in a least invasive way. In this paper we propose a biomimicking hydraulic pumping model with MEMS shunted with micro needles/Capillaries to maintain steady flow for several hours.

1. Introduction

The growing population, diminishing resources of land and water, increasing food markets and land cultivated for decades have already lost the natural fixated minerals and currently relied on fertilizers even to inhibit growth. Protecting fruit trees from disease and insect pests is an essential part of an horticulture production system apart from other abiotic stress. Trees with several meters of height are difficult to apply Foliar sprays or soil mixing methods due to large quantities being sprayed, less absorbing levels and causes environmental pollution. Tree diagnosis is a ever trending problem with less risky methods and efficient treatments are to developed not only for health but also to have hands on yields. The size scales of tree anatomy is in correlation with the MEMS devices which offer a novel way of solving this problem. The plant physiology which is highly mathematically modeled and physical sciences are thoroughly established can be mimicked, designed and simulated in many Multiphysics software's Like COMSOL, ANSYS, MATLAB.

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2. Tree Diagnosis Methods

Profitability in domestic fruit markets requires meeting high food quality standards, often through the judicious use of crop protection materials, including pesticides. Technological advances in agriculture in the last half century have allowed farmers to grow and protect their crops more efficiently. Integrated pest management (IPM) is an economic and environmentally sensitive technique for pest control, and plays an important role in tree fruit production. Effective use of pesticides in an IPM program requires precise delivery of selected materials to the crop canopy. Conventional air blast sprayers have been very effective for increasing crop, yields, and profits, however the negative impacts can be considerable and limited progress has been made to improve application strategies. Conventional spray methods do not represent a well rounded IPM program , which is an economic and environmentally sensitive technique for pest control. Non-economical issues include soil compaction, pest resistance, and many non-target effects such as environmental hazards, negative impacts on beneficial insects, health concerns caused by worker/ public exposure. Pesticides are a major expense and inefficiently applied with only 0.1% of the pesticide making contact with the target. Tree injection targeting the trunk part of tree has minimal environmental effects and Foliar spray, Paint patches, Soil Mixing are close alternatives available but sprays and paints are less effective and cause serious air pollution. Soil mixing is restricted by tree absorbing index of root hairs, symplast transports and cortex by the fertilizer composition.

Trunk Injection Disadvantages

Disrupt Functional transport: Columns of occluded xylem and killed barks are wounded resulting upto 40% of transport system blockage. Different species ability to restore from wounds and most cases causes many xylem vessels are damaged and tree metabolisms are affected. Drilling for injections allows air into the sapwood, disrupting translocation and reducing chemical effectiveness.

Infections: More prone to diseases in wound areas as easily affected by bacteria, fungi and insects.

Food contamination: The injection is pressurized to pass through entire vascular bundles which consists of food transporting phloem and absorbs into food resulting in fruit/crop poisoning.

Invasive method: Drilling wounds cause permanent damage. Repeated drilling can seriously impact tree vitality. Lack of expertise for procedure can result in death of tee which have high impacts considering the resources and years spent on the tree.

As per the new infusion concept the root of the tree is hacked and any solutions from nutrients to growth hormones can be pumped in least invasive and environmentally friendly way. Multiple treatments can be made without injuring the tree and metabolisms are not disturbed as the pumping is done at tree flow rates. Not only to solve these adverse conditions but to promote metabolisms and control various stages of tree, where minerals play a vital role which can be supplemented in least invasive way. The phenomenon that embraces the distinct tree responses to sudden physical stress or mutation of intakes popularly termed as Physiological Shock can be inhibited by infusing the minerals or hormones which triggers the tree responses. The concept seems promising for horticulture and tree level applications promoting not only health but also functionality of trees.

3. Tree Physiology and Anatomy

The current application focuses on tree hydraulic physiology and vascular system anatomy which are to be bio mimicked at root level. The movement of fluids throughout the tree's vascular system is called translocation. Water moves from the soil to the tree, into the atmosphere, and back into the soil. Water in plants forms a continuous water column and depends on high cohesive forces to carry a flow of water throughout the plant as per cohesion adhesion theory [1]. The roots are primary for any intake for trees which grabbed our interest to replicate its physiology. The lateral roots, large xylem vessels (LXV) and Root Stem junction (R-S) are studied and observed to be key anatomical parameters for the design. The lateral roots merge into the main root and for any given tree of certain age there are at an average of about tens to hundreds of these roots which can be hacked to pump the biocides and solutions.

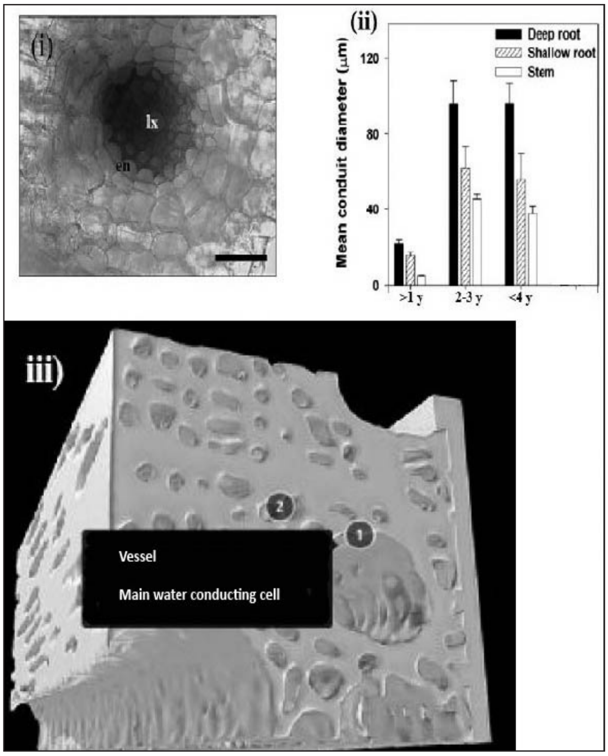


Fig. 1. i) Lateral root under light microscope (lxv) is the large xylem vessel with ranging from 50µm-2mm based on species, ii) Xylem conduit diameters in deep roots, shallow roots and stems of different ages of growth in Red oak [yale], iii) 3D model of Red Oak tree with main conducting vessel.

The anatomic constraints are limited to the micro needle or micro capillary tube shunted into the root vessels and the MEMS motor or actuator which is seated at the other end which is out of the root of this micro setup need not adapt to exact size ranges. As per the physiology is which is key for the MEMS design to mimic the micro fluidic parameters which influence micro hydrodynamic properties of flow rates [1-10 m/hr] and pressures supporting wide range of viscosities of various solutions that are to be infused at low Reynolds numbers [0.01-0.23]. From the point of view of fluid mechanics, the flow of water in the plant xylem is a three-dimensional unsteady incompressible flow, speed of transport is determined by the transpiration pull and xylem transport resistance in the tube together. The pumping pressures are to be maintained till the solution is diffused into the main root or R-S junction, the later lifting is done by natural translocation process of tree. The challenge, of course, is that anything that breaks the integrity of xylem walls has the potential to form embolism or changes in pressure distribution (Rockwell, Wheeler, and Holbrook, (2014); Jansen, Schuldt, and Choat, (2015)). Three major techniques are used (Boyer, (1995)): (1) pressure chamber (Scholanderetal., (1965)), (2) psychrometers (Boyer and Knipling, (1965)), and (3) tensiometers. These methods give accurate estimates of xylem tensions as shown in their ability to capture the gradient in gravitational potential in tall trees (Scholander et al., 1965), when measured at night (no transpiration), or on material in which xylem tensions have been experimentally generated using a centrifuge.

i)

Parameters	Phloem	Xylem	Human aorta
Velocity u (m/s)	10^{-4}	10^{-3}	4×10^{-1}
Radius a (m)	10^{-5}	10^{-4}	1.5×10^{-2}
Viscosity η (Pa s)	2×10^{-3}	10^{-3}	3×10^{-3}
Density ρ (kg/m^3)	$\sim 10^3$	$\sim 10^3$	$\sim 10^3$
Reynolds number ($Re = \rho u a/\eta$)	5×10^{-4}	10^{-1}	2×10^3
Péclet number ($Pe = ua/D$)	2	2×10^2	1.2×10^7
Schmidt number ($Sc = \eta/\rho D$)	4×10^3	2×10^3	6×10^3

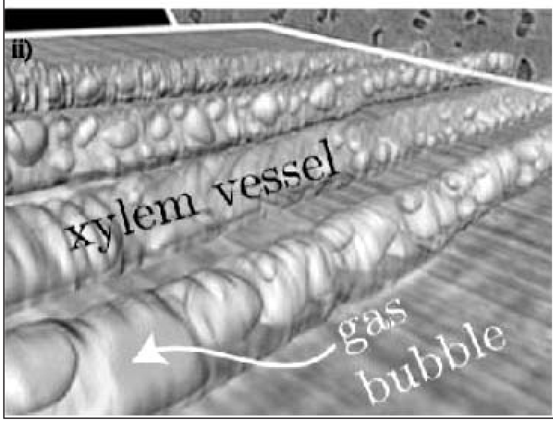


Fig. 2. i)Physiological parameters across various bio tissues, ii) The gas bubble formed in conduit which can lead to embolism due to breakage in water column by insufficient pressure gradient observed in both x-ray tomography and MRI (Brodersen et al., 2010; Zwieniecki, Melcher, and Ahrens, (2013)).

Poiseuille's law applies to cylindrical tubes which explains flow of liquid and velocity of flow. In Poiseuille's law, we are concerned with the volume flowing per unit time and area, often represented by J_v and called flux. For flow in a cylinder of radius r, and hence area πr2, J_v is.

$$v/\pi r^2 = J_v = -(r^2/8\eta)\, \partial P/\partial X \qquad (1.1)$$

where J_v has units of length/time, V = rate of volume movement (in units of cm^3/s), r = radius of the capillary tube (cm), h = viscosity of the solution (poise), $-(\partial P/\partial X)$ = the negative gradient of the hydrostatic pressure. We use a density for the sap in the xylem of 1 g/cm^3 (same as water at 20 C). We now change the units of density to dyn-s^2/cm^4. We find the Reynolds number, Re, for diffuse porous wood with a radius of 20 µm for the vessel members and a velocity of sap flow of 0.1 cm/s to be

$$Re = (\rho J_v r)/\eta \qquad (1.2)$$

Re =0.02(unitless)

For a ring-porous tree with a radius of 100 µm for the vessel members and a velocity of sap flow of 1 cm/s, Re is 1(unitless). Using same analysis Nobel's (1974, 1983, 1991, 2005, 2009) analysis determining the pressure gradient in different parts of the pathway that water takes as it crosses a root. Let us assume the same J_v that we used previously ($J_{v=}$ 0.1 cm/s). The pressure gradient in the cell walls is from (1.1)

$$J_v = -(r^2/8\eta)\, \partial P/\partial X$$

$$0.1\ cm/s = -(5 \times 10^{7)2}/8(0.010\ dyn\text{-}s^2/\ cm^{2)}\ \partial P/\partial X$$

$$\partial P/\partial X = -3.2 \times 10^6\ bars/m$$

A $(\partial P/\partial X)$ of only 0.2 bar/m is needed for the same J_v in the vessel member having a radius of 20 µm. These pressures and forces are to be calculated across various species of +trees which are the design parameters of MEMS model.

4. Proposed Model

The drug delivery systems adopted in human diagnosis are studied and microfluidic parameters which vary from human anatomy to plant anatomy. The pumping of wide range of viscous fluids depending on the biocides, nutrients or growth hormones solutions at variable flow rates depending on specie of tree. The proposed model with shunting part into root and pumping part seated at the end of micro infused parts of needles or capillary tubes with a control system to regulate the flow rates and dosages.

1) Infusion parts : The infusion parts are those shunted into root and diffuse the solution from pumping parts without fracturing. The micro machined hollow microneedles can be fabricated, which can serve the purpose of extraction and insertion of micro volumes of fluids with minimal invasion of tissue and materials are chose to provide tensile strength and biocompatibility with plant tissues like silicon or bio polymers.

   A compressive buckling force acts on the micro-needle in the axial direction. The maximum buckling force, which the micro needle can withstand without breaking is given by

   $F_{MaxBuck} = \pi^2 YI/L^2$,

   Y= Young's modulus, I= Geometric moment of inertia, L= Needle length.

   The maximum free bending force that the micro-needle can withstand is given by

   $F_{MaxFreeBend} = \sigma_y I / cL$

   where, σ_y = yield stress of material and c= distance of the outermost edge of the micro needle from the neutral axis. After obtaining the anatomic and physiological parameters from above study the needle or capillary tube models and materials will be opted.

2. Mems Pumping : Need for controlled fluid flow, for various medical applications have motivated research in MEMS based micro pumps. Their various uses are in controlled biological fluid flow for Physiology analysis, lab-on-a-chip devices, micro-total analysis systems (µTAS), and drug delivery systems. The flow rates, pressure gradients, viscosities the physiological parameters are to be obtained from above and a suitable pumping system with a control system to regulate the flow rates across the day and night are to be designed.

   An electrostatic actuator model is opted as basic MEMS pumping system due to its size and flow rates correlation to the tree micro hydrodynamic parameters. The electrostatically actuated diaphragm pump consists of two chambers in series and three diffuser/ nozzle type elements to control the flow of fluid. Electric potentials applied at the electrodes cause vertical movement of the diaphragms and induces change of volume and fluid pressure in the pump chambers. There are no power limitations as the model resides externally and can be rooted with any supply. The design parameters are to be obtained from the plant anatomy and physiological study and the Infusion system is to be modeled.

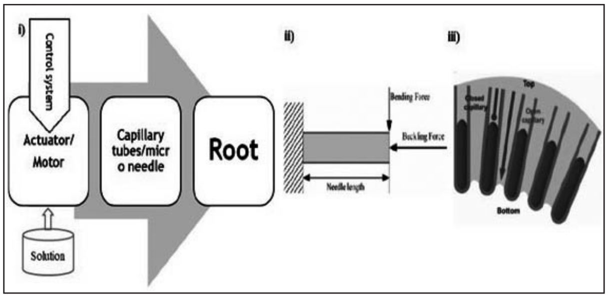
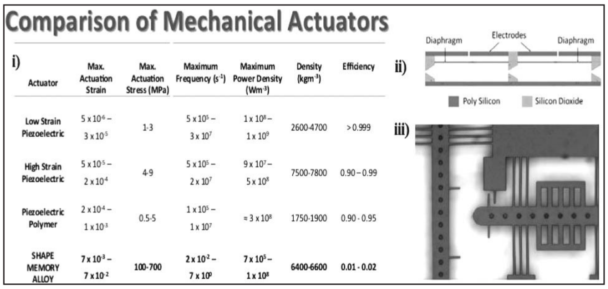


Fig. 3. i) The Basic model of the concept with shunting/ Infusing blocks, pumping and control blocks, ii) The micro needle as cantilever, iii) Micro capillaries to with osmotic potentials for fluid movements.



Actuator	Max. Actuation Strain	Max. Actuation Stress (MPa)	Maximum Frequency (s^{-1})	Maximum Power Density (Wm^{-3})	Density (kgm^{-3})	Efficiency
Low Strain Piezoelectric	5×10^{-6} – 3×10^{-5}	1-3	5×10^{5} – 3×10^{7}	1×10^{8} – 1×10^{9}	2600-4700	> 0.999
High Strain Piezoelectric	5×10^{-5} – 2×10^{-4}	4-9	5×10^{5} – 2×10^{7}	9×10^{7} – 5×10^{8}	7500-7800	0.90 – 0.99
Piezoelectric Polymer	2×10^{-4} – 1×10^{-3}	0.5-5	1×10^{5} – 1×10^{7}	$\approx 3 \times 10^{8}$	1750-1900	0.90 - 0.95
SHAPE MEMORY ALLOY	7×10^{-3} – 7×10^{-2}	100-700	2×10^{-2} – 7×10^{0}	7×10^{5} – 1×10^{8}	6400-6600	0.01 - 0.02

Fig. 4. i) Parametric details of various actuators, ii) Electrostatically actuated micro-pump, iii) Microscopic model of actuated micro pump.

5. Conclusion

The proposed model can not only be applied for pest control but also become a solution major

Horticulture problem and also betterment of yields. The plant parameters are currently being studied at field level and non invasive studies like radiography and other acoustic methods to study physiological parameters. The microfluidic flow of tree sap relies on atmospheric parameters which effects the transpiration and flow from roots to leaves. But due to these natural cohesion-tension models there is less stress on the MEMS pumping system which need not provide pumping pressures all across the tree but confined to pumping till the R-S junction. The scope offered by this concept is promising and will be implemented by bridging plant engineering to the MEMS era.

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