Liquid RF Antennas, Electronics and Sensors: A Modeling Challenge

Anya Traille and Manos M. Tentzeris

School of ECE, Georgia Tech, Atlanta, GA 30332-250, USA

Abstract

In this paper we present a novel approach for the modeling of multi-phase liquid RF electronics and sensors problems. The deployment of level-set based multi-phase simulation could potentially lead to the development of a new generation of computationally efficient approaches that could bridge the gap between Maxwell and solid/liquid-interface equations. Numerous examples of liquid antennas and multi-phase wireless biosensors will be presented at the conference to verify the accuracy and validity of the above approach in a variety of liquid radio-frequency wearable, implantable and printable topologies.

1.Introduction

Lately, there has been a significant effort to build miniaturized biosensors that can monitor the effect of proteins, aminoacids and DNA, while an ever increasing number of 3D RF modules [1] include flexible microfluidic or nanofluidic channels, that commonly carry heat-abducting liquids. In addition, numerous implantable RF devices utilize liquid antennas [2], while inkjet-printable batteries require the deposition of semi-liquid conductive gels. Plus, many electromechanical-coupled phenomena, such as particle dynamics, cell dynamics electrophoresis and dielectrophoresis are recently being employed for biotechnology and environmental science.

In addition, portable health systems for continuous, real-time monitoring of bio-signals must be compact, wearable, biocompatible and reliable for individuals in high-risk environments or with health conditions. Bio-sensors collect physiological data such as skin temperature, water content, ECG (electrocardiogram), respiration, heart rate, pulse, blood pressure, power exerted and movement and can transmit this information via Bluetooth or cable to a portable unit for further processing and evaluation. Most mobile health monitoring systems have significant limitations due to various reasons. Particular forms of diagnosis that require the sensors to be placed in various locations of the body and then connected together using wires suffer from significant interference limiting their performance and making real time continuous monitoring ineffective. Other systems that do provide real-time continuous monitoring are not designed to transmit physiological data immediately and continuously to locations other than to a portable unit worn by the individual for their own awareness and the ones which do transmit are subject to the unreliability of GPS indoors and other environments.

Various solutions have been proposed to be used as a nonconventional radiator which would provide a more efficient radiation and could overcome these limitations. One such solution is an antenna made out of liquid instead of metal [3]. While metallic antennas are quite effective in the air, they exhibit a sharp dielectric contrast to human tissue (mostly consisting of ionized water) which complicates matching and limits efficiency. A conventional metal antenna placed flush into human skin will induce a surface wave within the tissue causing most of the power to be wasted within the body rather than being radiated outwards. Human tissue has a very high dielectric constant, consists of varying amounts of salt and is very conductive, making it an insufficient environment for a metallic antenna to operate adequately. The vulnerability of dielectrically submerged metals to corrosion and ion deposition enhances the problem of noise and interference. In addition to electrical properties, mechanical properties such as shape manipulation of metallic antennas is limited due to the risk of defects (air gaps), which would introduce unwanted resonances and altered impedance.

An antenna consisting of liquid that nearly mimics the skin would eliminate the problem of power loss and interference and radiate more efficiently. The use of glass or plastic to enclose the liquid would make it corrosion resistant as well as bio-compatible when implanted nearby or underneath human tissue as well as eliminate the sharp dielectric interfaces that complicate matching. Liquid dielectrics would solve the problem of air gaps permitting shape manipulation and improvements in electromagnetic coupling between probe and dielectric to eliminate the problem of matching. This technology would enable the development of biocompatible, implantable, compact antennas for the condition monitoring of prosthetic devices and transplanted organs. Encapsulating the proposed liquids antennas in flexible plastic will make them conformable to various clothes allowing for the effective remote real-time biomonitoring. They could also be used for the implementation of broadband/multiband portable antennas for submarine/diving communications with a significantly smaller physical size than the conventional metal antennas.

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Antennas used for wearable applications or for underwater use have experienced a number of difficulties in the past:

- Matching Complications & Efficiency Limitations are a problem in metallic antennas because exhibit a sharp dielectric contrast to human tissue, mostly consisting of ionized water.
- Unwanted Resonances, & Altered Impedances prevent shape manipulation of metallic antennas due to defects (such as air gaps)
- Noise & Interference is an issue with dielectrically submerged metals due to corrosion and ion deposition.

High dielectric constant antennas date back to the 1930s. Ting and King determined in 1970 that dielectric filled tubes can resonate [4]. It was shown that conducting liquids and biological fluids could operate as antennas at microwave frequencies. According to reports from The Radio Amateur community, stimulating a column of salt water could produce a usable antenna. It was found that for salt water columns with a salinity in excess of 70 ppt, that at HF frequencies under 30 MHz, the resonant frequency was inversely proportional to salt solution column height. Bandwidths increased from 20-25% up to 50% with a radiation efficiency of 50-70%.

2. Level-Set Method

The modeling of the RF performance of these time-varying multi-phase structures, such as liquid antennas and multi-phase wireless sensors, requires the development of a new generation of multi-domain/multi-physics numerical simulators. Recently, level set method, proposed by Osher and Sethian [5],[6], has developed to be one of the most successful techniques for the expression of time-varying geometries. The idea of the level set method is to express a boundary (such as the interface of a charged volume that is submerged in a liquid) in an implicit form, as the zero level set of a high-dimensional function, and then trace the change of the boundary by the deformation of the embedded function; this implicit function both represents and evolves the boundary.

In a sense, the level set method is a technique to represent moving interfaces or boundaries using a fixed mesh. It is useful for problems where the computational domain is divided into two domains separated by an interface. The interface is represented by a certain level set of iso-contour of the level set function, which is a smooth step function that equals zero in a domain and one in the other. The physics interface solves the following equation in order to move the interface with the velocity field **u**

$$\frac{\partial \varphi}{\partial t} + \mathbf{u} \cdot \nabla \varphi = \gamma \nabla \cdot \left(\epsilon \nabla \varphi - \varphi(1-\varphi) \frac{\nabla \varphi}{|\nabla \varphi|} \right) \quad (1)$$

The terms on the left-hand side give the correct motion of the interface, while those on the right-hand side are necessary for numerical stability. The parameter, ε, determines the thickness of the region where ϕ goes smoothly from zero to one and is typically of the same order as the size of the elements of the mesh. By default, ε is constant within each domain and equals the largest value of the mesh size, h, within the domain. The parameter γ determines the amount of reinitialization or stabilization of the level set function. It needs to be tuned for each specific problem. If γ is too small, the thickness of the interface might not remain constant, and oscillations in may appear because of numerical instabilities. On the other hand, if γ is too large, the interface moves incorrectly. A suitable value for γ is the maximum magnitude of the velocity field $\mathbf{u}$. Before Eq.(1) can be solved, it is needed to initialize the level set function such that it varies smoothly from zero to one across the interface by letting ϕ to be zero on one side of the interface and one on the other, denoted as ϕ_o. Then solve

$$\frac{\partial \varphi}{\partial t} = \gamma \nabla \cdot \left(\epsilon \nabla \varphi - \varphi(1-\varphi) \frac{\nabla \varphi}{|\nabla \varphi|} \right) \quad (2)$$

using ϕ_o as the initial condition from t=0 to t~$5\varepsilon/\gamma$. The resulting ϕ is smooth across the interface and a suitable initial condition to the level set equation. The unit normal to the interface is given by $\boldsymbol{n} = \frac{\nabla \varphi}{|\nabla \varphi|}$ (at ϕ=0.5) and the curvature is defined as $k = -\nabla \cdot \mathbf{n}$ (at ϕ=0.5). These variables are available in the physics interface as the *interface normal* and *mean curvature*. The phase field method offers an attractive alternative to more established methods for solving multiphase flow problems. Instead of directly tracking the interface between two fluids, the interfacial layer is governed by a phase field variable, ϕ. The surface tension force is added to the Navier-Stokes equations as a body force by multiplying the chemical potential of the system by the gradient of the phase field variable. The evolution of the phase field variable is governed by the *Cahn-Hilliard equation*, which is a 4th-order PDE. The Phase Field interface decomposes the Cahn-Hilliard equation into two second-order PDEs. For the level set method, the fluid interface is simply convected with the flow field. The Cahn-Hilliard (C-H) equation, on the other hand, does not only convect the fluid interface, but it also ensures that the total energy of the system diminishes correctly. The Cahn-Hilliard equation PDE governing the phase field variable is given by:

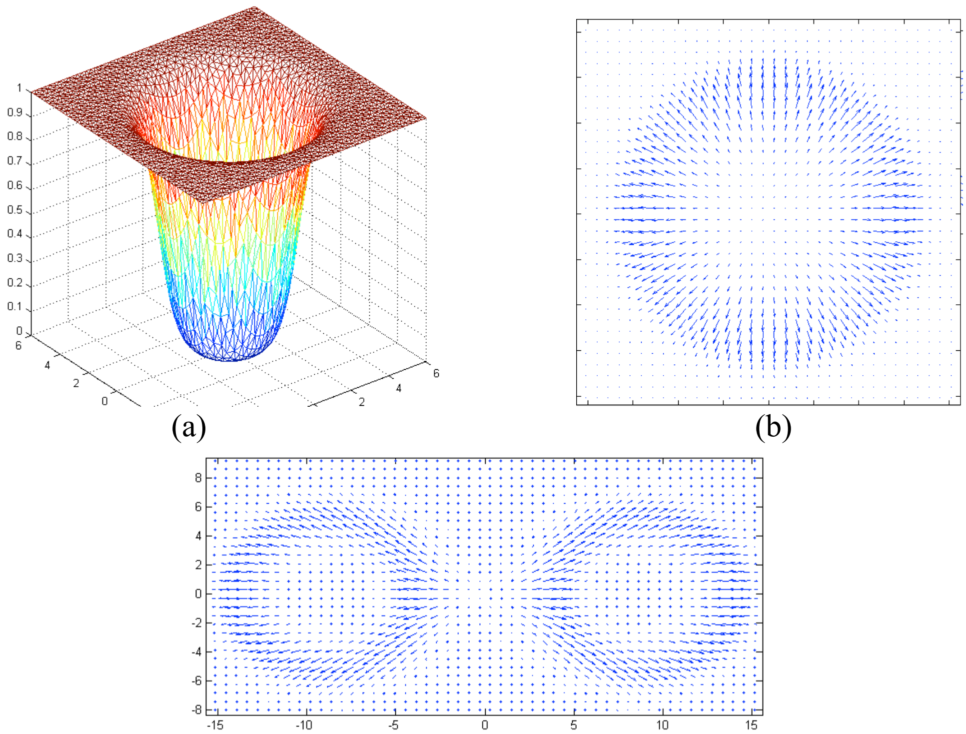
$$\frac{\partial \varphi}{\partial t} + \mathbf{u} \cdot \nabla \varphi = \nabla \cdot \gamma\, \nabla \mathrm{G} \qquad (3)$$

where G is the chemical potential and γ is the mobility, which determines the time scale of the Cahn-Hilliard diffusion and must be large enough to retain a constant interfacial thickness but small enough so that the convective terms are not overly damped. The quantity λ is the mixing energy density and ε is a capillary width that scales with the thickness of the interface. These two parameters are related to the surface tension coefficient, σ, through the equation: $\sigma = 2^{1.5}\, \lambda / (3\varepsilon)$ The C-H equation forces to take a value of 1 except in a very thin region on the fluid-fluid interface. The Phase Field interface splits Eq.(3) up into two second-order PDEs (4)-(5):

$$\frac{\partial \varphi}{\partial t} + \mathbf{u} \cdot \nabla \varphi = \nabla \cdot (\gamma\lambda\ /\epsilon\epsilon\,)\, \nabla \psi \qquad (4)$$

$$\psi = -\nabla \cdot (\epsilon\epsilon \nabla \varphi) + (\varphi\varphi - 1)\varphi \qquad (5)$$

Due to the different time constants of the Maxwell and the Cahn-Hilliard equation, the interface position determined by eqs. (4)-(5) is used to define the boundary conditions for 1,000-10,000 time-steps of the electromagnetic time-domain (e.g. FDTD/MRTD) simulations, that eventually define the electromagnetic force that acts as the new initial condition of the C-H equations. Various liquid antenna and sensor configurations will be presented at the conference verifying the validity of the above technique. Fig.1 shows an example of the level-set function implemented in Matlab for a charged particle or electrode submerged in water.



(c)

Fig.1 Examples for initializing level-set function in matlab to model a circular charged object submerged in water (a) Fixed olume charge density of charged object (b) Fixed volume charge gradient of charged object (c) Volume charge gradient of two charged objects of opposite polarity

3. Conclusions

The level-set technique is investigated as a computationally effective approach that can couple electromagnetics to microfluidics and multi-phase RF antenna and sensing structures. Combining this approach with time-domain electromagnetic simulators can enable multi-phase electromagnetic analysis for a variety of biomonitoring, implantable and wearable topologies. Furthermore, the capability of level-set techniques to accurately represent time-varying phase interfaces can be exploited in the future in the modeling and sensing of liquid/biological substances under the influence of electromagnetic fields as well as in the modeling of flexible inkjet-printed electronics.

4. Acknowledgments

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5. References

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