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Real-time tracking of metallic treatment probe in interstitial thermal therapy

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Abstract

In this paper, we propose an inverse scattering method with compressive sensing to image and track the metallic ablation probe during the interstitial thermal therapy. The contrast source inversion (CSI) method is used to solve the inverse scattering problem, which determines the location of the probe by utilizing the scattered field data produced by the contrast source current at the probe surface. A fast spectral gradient-projection method is used to solve the linear inverse problem with sparsity constraints and reconstructs the surface profile of the metallic probe. The proposed method will first be validated numerically by imaging a PEC probe in a realistic interstitial thermal therapy model, and then be validated experimentally with a vector network analyzer based inverse scattering measurement system.

1. Introduction

In recent years, thermal ablation has seen increased used in the treatment of various diseases. In the case of thermal ablation using an ablation probe, magnetic resonance (MR), X-ray computed tomography (CT) and ultrasound were used to guide the probe to the treatment region and monitor its movement. However, the high expenses and complexity of the MR and the harmful ionizing nature of X-ray CT has limited their clinical usage. The more widely used ultrasound guided system has a relatively lower cost, however, it is a hand-held device and can only generate a 2D monitoring image which provides limited information. In this paper, we propose a microwave-based treatment probe tracking method, which uses the scattered field generated by the contrast source of the metallic probe to reconstruct the 3D shape and location of the probe during thermal therapy. The contrast source inversion (CSI) method [1] is used to solve the linear inverse scattering problem. A fast spectral gradient-projection method is used to the solve the local optimization problem with sparsity constraint. The proposed microwave probe tracking method is validated first by imaging a PEC probe in a realistic interstitial thermal therapy numerical model, and then be validated with a vector network analyzer (VNA) based inverse scattering measurement system.

2. Method

In solving the inverse scattering problem for probe tracking, the scattered electric field is often measured in the form of scattering parameters (S-parameters) by the VNA. The volume integral equation (VIE) [2] is used to link the contrast source of the metallic probe to the measured scattered S-parameters, which can be written as:

$$S_{m,n}^{scat}(\omega) = k_b^2 \int O(\boldsymbol{r}')\boldsymbol{G}_{m,n}(\boldsymbol{r}',\ \omega) \cdot \boldsymbol{E_n}(\boldsymbol{r}',\omega) dV' \quad (1)$$

where $\boldsymbol{r}'$ is the position vector in the imaging region, $\boldsymbol{E_n}$ is the total field in the imaging region due to transmitter $\boldsymbol{n}$, k_b is the lossless background wavenumber, and O is the dielectric contrast function, which can be written as:

$$O(\boldsymbol{r}') = \Delta\epsilon(\boldsymbol{r}') + \frac{\Delta\sigma(\boldsymbol{r}')}{j\omega\epsilon_b} \quad (2)$$

where $\Delta\epsilon(\boldsymbol{r})$ and $\Delta\sigma(r)$ are the contrast permittivity and conductivity with regard to the imaging background. The vector $\boldsymbol{G}_{m,n}$ is the waveport numerical vector Green's function [2] which links the total electric fields in the monitoring region excited by the transmitting antenna $\boldsymbol{n}$ to the S-parameters measured at the antenna $\boldsymbol{m}$ with an arbitrary inhomogeneous imaging background.

In solving this inverse scattering problem, the CSI method is used which solves for the contrast source. The contrast source is defined as the product of the material contrast and total electric field in the imaging region. The contrast source in the imaging region generated by exciting transmitting antenna $\boldsymbol{n}$ can be written as,

$$\boldsymbol{x_n}(\boldsymbol{r}',\omega) = \boldsymbol{O}(\boldsymbol{r}') \cdot \boldsymbol{E_n}(\boldsymbol{r}',\omega) \quad (3)$$

where $\boldsymbol{r}'$ is the position vector of the imaging region**.** By only solving for the contrast source, the nonlinear inverse scattering problem is reduced to a linear problem, which can be written as,

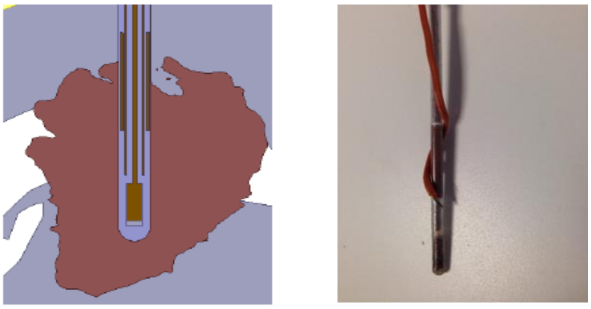
$$\boldsymbol{y} = \overline{\boldsymbol{A}}\boldsymbol{x} \quad (4)$$

where vector $\mathbf{y}$ is the scattered S-parameters, matrix $\overline{\boldsymbol{A}}$ contains the waveport numerical Green's function and the background wavenumber, and $\boldsymbol{x}$ is the contrast source vector.

In this paper, a 1.9GHz metallic ablation probe [3] shown in Figure 1 is used to perform the thermal therapy. Because the ablation probe is metallic, the total electric field within its metal body is always zero. Thus, the entries in the contrast source vector is only non-zero at the surface of the metallic probe, which should yield a sparse solution. We formulate the linear contrast source inversion as a lasso problem [4] with a least squares error function plus a sparsity constraint, which is written as,

$$J(\boldsymbol{x}) = \left|\left|\boldsymbol{y} - \overline{\boldsymbol{A}}\boldsymbol{x}\right|\right|_2 + \lambda\left|\left|\boldsymbol{x}\right|\right|_1 \tag{5}$$

where $J(\boldsymbol{x})$ is the cost function, and λ is a regularization parameter. A fast spectral projected-gradient method [5] is utilized to solve for this lasso problem and generate a sparse solution for the contrast source at the surface of the probe. Then the 3D profile and the location of the probe can be reconstructed. During the reconstruction process, GPU parallel computing is utilized to accelerate the solving of the linear inverse problem, which would provide a refresh rate at 1 frame/second.



a b

Figure 1. (a) Probe inserted into human brain model, (b) metallic ablation probe used in probe tracking experiment.

3. Numerical Simulation

The proposed microwave probe tracking method is first validated numerically by imaging the probe inserted in a realistic human head phantom, which is shown in Figure 2. The human head phantom is derived from the Visible Human Project of NIH [6]. An imaging cavity with the size $15 \times 25 \times 15\ cm^3$ is used to contain the head phantom and collect the scattering data of the probe. The imaging cavity consists of 96 rectangular patching antennas working at 880MHz, while 48 of them will be used as the transmitters and the other 48 as receivers. The finite difference time domain method (FDTD) is used to simulate the scattered S-parameters produced by the contrast source of the probe. In simulation, the metallic probe is assumed to be PEC. The shape and the location of the metallic probe will be reconstructed by solving the linear contrast source inversion problem.

4. Experimental validation

The proposed probe tracking method is also validated experimentally with our in-house developed VNA based inverse scattering measurement system. The imaging cavity consists of 36 patch antennas working at 900MHz, while 18 of them is used as transmitters and other 18 as receivers. The patch antennas are connected to the 2 port VNA through a switching matrix, which creates the 324 measurement paths with different T/R antenna pairs. The

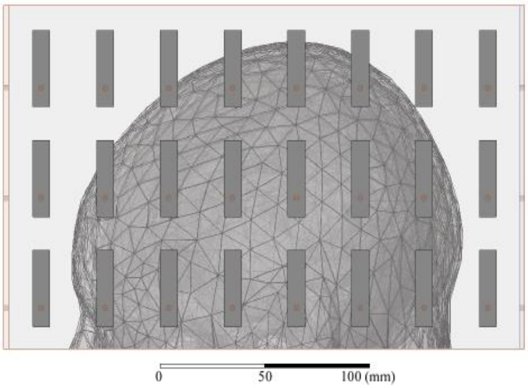


Figure 2. Square imaging cavity surrounding realistic numerical human head model

imaging cavity is filled with emulsion mimicking the dielectric property of human brain. Matlab is used to control the measurement system and process the inversion. Imaging results will be provided with the ablation probe put at different locations within the imaging cavity.

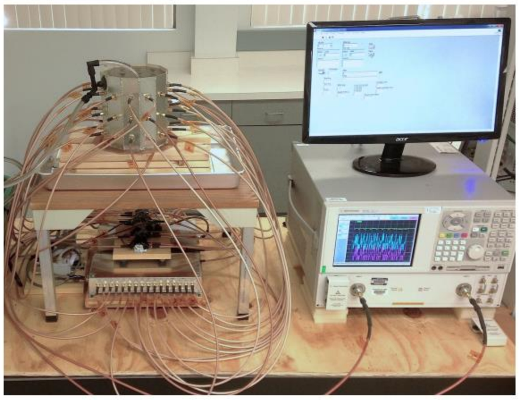


Figure 3. VNA-based inverse scattering measurement system

5. Summary

We propose a CSI based microwave imaging method to track the metallic ablation probe during thermal therapy. As the contrast source only exist on the surface of the metallic probe, compressive sensing is used to add sparsity constraint to the problem. A sparse solution of the formulated lasso problem is obtained with the spectral projected gradient method. The proposed ablation probe tracking method is first validated in simulation with a realistic interstitial thermal therapy model, and then validated experimentally with an in-house developed VNA-based microwave inverse scattering measurement system.

6. References

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