RADAR Spine Imaging based on an Inhomogeneous Medium Focussing Algorithm

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ABSTRACT

In this paper we propose an inhomogeneous medium focussing algorithm for UWB RADAR imaging of the human spine. The advantage of microwave imaging over conventional x-ray imaging in this specific application is the comparatively low exposure to radiation enabling possibly repetitive imaging of patients who are not viable for x-ray exposure. The proposed focussing algorithm is based on the general solution of the electromagnetic wave equation and called General Solution based RADAR imaging (GSRI). Compared to conventional methods the GSRI yields good results in the estimation of shape and position of the measured target. The viability of the approach and the performance are demonstrated on simulated data and measured data for a variety of measurement setups including an imaging of the human spine.

Categories and Subject Descriptors

F.2 [**ANALYSIS OF ALGORITHMS AND PROBLEM COMPLEXITY**]: General

Keywords

RADAR Body Imaging, ROC, GPR, Human Spine RADAR Imaging

1. INTRODUCTION

The RADAR imaging system measurement set-up is as figure(1). The system is consisted by antennas array, signal processing system and a monitor. During the measurement processing, different antennas in the antenna array are selected as transmits and receiver separately. They transmit the electromagnetic wave towards the human body and collects the reflected electromagnetic (EM) wave by the human body. The received data is saved and processed by signal processing system. The processed and focused RADAR images about human spine are finally shown on the monitor. It can be found the RADAR imaging system is very flexible.

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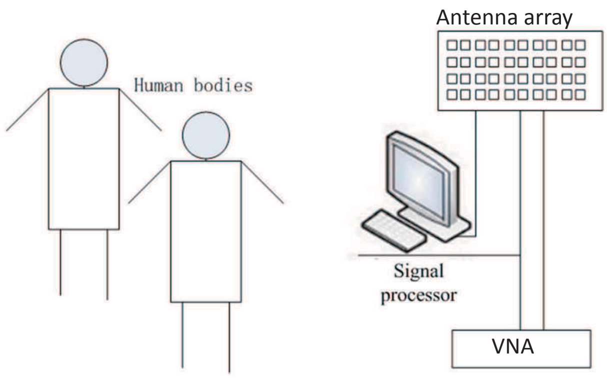

Figure 1: RADAR imaging system measurement set-up

Because it is an open system, multi-body RADAR imaging can be achieved by one measurement. The RADAR imaging system is very simple. The cost of the system is not high. Furthermore, the UWB signal is applied by the system, the electromagnetic wave radiation effect on human body is low. In this paper, we propose the general solution based RADAR imaging algorithm(GSRI). As general solution including the particular solution and the homogeneous PDE solution, the GSRI algorithm is consist of the integration way imaging algorithm and differential way imaging algorithm. The differential way RADAR imaging algorithm is applied on the inhomogeneous area for detecting the layers of the inhomogeneous material. For each layer, the integration way imaging algorithm is applied for detecting the scattering targets in the layer. Combining the image for each layer, the whole focused inhomogeneous material RADAR image is finally obtained.

2. THE THEORY OF THE RADAR IMAGING ALGORITHM

The RADAR imaging is just one application of the electromagnetic theory on practical systems. The theoretical concepts of electromagnetic field can be described by Maxwells equations and EM wave equation. The EM wave equation in frequency domain (Helmholtz equation) can be rewritten as:

$$(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial y^2}+\omega^2\mu\hat{\varepsilon})U(x,y,z,\omega)=S(x,y,z,\omega) \quad (1)$$

where μ and ε are the is the permeability and the complexed permittivity of the medium EM wave propagating through, respectively. $U(x,z,y,\omega)$ expresses EM field. $S(x,y,y,\omega)$ denotes the EM source in frequency domain. Equation (1) is exactly an inhomogeneous second order PDE. The solution consist of two parts, the particular solution and the solution of the corresponded homogeneous equation. The objective of the RADAR imaging processing is exactly as to reconstruct the EM scattering sources $S(x,y,z,\omega)$ through the RADAR received EM scattering field $U(x,y,z,\omega)$.

2.1 Particular solution imaging algorithm

Firstly, the particular solution and the particular solution based RADAR imaging algorithms(PSRI) are shortly discussed. In fact, solving directly inhomogeneous Helmholtz wave equation is very difficult and complicated when the material and boundary are complex. The particular solution of the inhomogeneous Helmholtz, which we discuss in this subsection, focuses only on solving the EM field in the case of non boundary surrounding the sources(homogeneous material,). In this case the permittivity ε and the permeability μ are independent on space variance x,y,z. It also means there is no refraction phenomenon during EM wave propagation. As well known, the particular solution U_p satisfy the inhomogeneous second order PDE equation (1). Therefore, we have:

$$\nabla^2 U_r(x,y,z,\omega)+\omega^2\mu\hat{\varepsilon}U_r(x,y,z,\omega)=S(x,y,z,\omega) \quad (2)$$

Basing on the fundamental solution and Poisson equation, the particular solution of the equation (2) can be expressed as:

$$U_p(x,y,z,\omega)=\iiint\frac{e^{-j\omega\sqrt{\hat{\varepsilon}\mu}r}}{4\pi r}S(x',y',z',\omega)dx'dy'dz' \quad (3)$$

where $r=\sqrt{(x-x')^2+(y-y')^2+(z-z')^2}$. Equation (3) relies that the EM field U_p is sum of the EM sources S with corresponded phase delay and attenuation. The phase delay and attenuation are determined by the straight line distance from EM field position to EM sources position. It must be noted that the particular solution is not like equation (3), when the permittivity ε and the permeability μ are space dependent. In the other words, the equation (3) does not satisfy the EM wave equation, when EM wave propagates through the inhomogeneous medium. In order to reconstruct the scattering sources $S(x,y,z,\omega)$, one easy way is as to compensate the phase delay of signals from scattering sources for each frequency point. The RADAR imaging processing can be formulated as:

$$S(x',y',z',\omega)=\iiint U_p(x,y,z,\omega)e^{-j\omega\sqrt{\hat{\varepsilon}\mu}r}dxdydz \quad (4)$$

Equation (4) shows an integration way to reconstruct the scattering sources(or to image the reflection objects). It should note that the integration way based RADAR imaging algorithms are available for homogeneous medium RADAR imaging. More detailed PSRI information is in our reference [4]

2.2 Homogeneous solution imaging algorithm

In this subsection the solution of the corresponded homogeneous Helmholtz wave equation and the homogeneous solution based RADAR imaging algorithm(HSRI) will be discussed. The solution of the corresponded homogeneous Helmholtz wave equation U_h satisfies the equation as:

$$\nabla^2 U_h(x,y,z,\omega)+\omega^2\mu\hat{\varepsilon}U_h(x,y,z,\omega)=0 \quad (5)$$

Because the source part(right part of the equation 5) is zero in the homogeneous equation, the solution of the homogeneous equation is available to reconstruct the EM field in the area without EM sources. According the variance reduction techniques and Fourier transform, the solution of the equation (5) in wavenumber-frequency domain can be expressed as:

$$\begin{aligned}U_h(z,k_x,k_y,\omega)=&U_0(z=0,k_x,k_y,\omega)\\&e^{-jz\sqrt{\omega^2\mu\hat{\varepsilon}-k_x^2-k_y^2}}\end{aligned} \quad (6)$$

where k_x and k_y are the wave numbers for EM wave in x and y direction separately. $U_0(z=0,k_x,k_y,\omega)$ is the EM field on $z=0$ plane in wave number frequency domain. The solution in space-frequency domain can be obtained by twice inverse Fourier transforming as:

$$U_i(x,y,z,\omega)=\mathscr{F}_{k_y}^{-1}(\mathscr{F}_{k_x}^{-1}(U_p(z,k_x,k_y,\omega))) \quad (7)$$

According to equation (6), the EM field in the wavenumber frequency domain can be obtained through the EM field extrapolation. The location of the RADAR is assigned as $z=0$ plane, then $U_0(z=0,k_x,k_y,\omega)$ can be achieved by space Fourier transforming the received EM field. Further the EM field in wavenumber frequency domain $U_h(z,k_x,k_y,\omega)$ can be obtained through the extrapolation of $U_0(z=0,k_x,k_y,\omega)$. For inhomogeneous medium RADAR imaging, the equation (6) is expressed by recursive way as:

$$\begin{aligned}U_h((i+1)\cdot\Delta z,k_x,k_y,\omega)=&U_0(i\cdot\Delta z,k_x,k_y,\omega)\\&e^{-j\Delta z\sqrt{\omega^2\mu\hat{\varepsilon}-k_x^2-k_y^2}}\end{aligned} \quad (8)$$

By recursively extrapolating the EM field in wavenumber-frequency domain along the z-axis in steps z and using the obtained EM field of each step as input to the next iteration, the EM field in the inhomogeneous medium can be reconstructed with updating the parameters μ and ε in the extrapolation factor. This kind of RADAR imaging algorithms are such as phase migration, entropy phase shift migration algorithm. The homogeneous wave equation based RADAR imaging algorithm is suitable to image the inhomogeneous medium structure or detect the interfaces in the inhomogeneous medium. However, it is not accurate for imaging the buried scattering objects, because the scattering sources term is not taken into account by the solution of the homogeneous wave equation. The more detailed information about HSRI is in our reference [3][2]

2.3 General solution imaging algorithm

The general solution of the inhomogeneous wave equation is consist by the particular solution and the solution of the homogeneous wave equation as:

$$U_g(x,y,z,\omega)=U_p(x,y,z,\omega)+U_h(x,y,z,\omega) \quad (9)$$

As the general solution is the plus result of the particular solution and homogeneous equation solution, the general so-

Table 1: Frequency of Special Characters

	PSRI	HSRI	GSRI
Azimuth resolution(3dB width)	0.08	0.018	0.01
Range resolution(3dB width)	0.07	0.012	0.011

lution based RADAR imaging algorithm is the combination of the particular solution based RADAR imaging algorithm and the homogeneous equation solution based RADAR imaging. The particular solution based RADAR imaging is suit to image the scattering objects in homogeneous medium, but is unavailable for inhomogeneous medium RADAR imaging. However, the homogeneous equation solution based RADAR imaging is suit to image the inhomogeneous medium structure, but is unsuitable to image the scattering objects. The detailed processing steps of the GSRI are as follows. Firstly the HSRI technique is applied. By HSRI the first interface location is detected in light speed layer mode, in which the EM propagation velocity in medium is always seen as light speed. After the location of the first interface in light speed layer mode is obtained, we could estimate the width of the first layer in the case of different medium. We do the RADAR imaging again for the first layer. This time the PSRI is applied. With given different medium parameter μ and ε, different images are obtained. The entropy value of these images are calculated. Because the less entropy corresponds to the better focused image, the medium parameter μ and ε for the first layer medium are specified by the minimum entropy of the images. Meanwhile the best focused image for the first layer is obtained. With the estimated medium parameter, HSRI is applied to extrapolate the EM field on the first interface. Then the first interface plane is seen as the RADAR plane and the extrapolated EM field is seen as the received field. The calculation of the interface location and medium property for the equivalent first layer is done again, which is described above. The focused image for the practical second layer is then obtained. By this recursive way, the whole inhomogeneous medium RADAR imaging is finally achieved.

2.4 Algorithm comparison

For inhomogeneous medium RADAR imaging , the comparison between the PSRI, HSRI and the GSRI is done. Firstly, we compare the image resolution of these RADAR imaging techniques. The condition for the comparison is as: frequency range is 3GHz to 10GHz, RADAR azimuth scan is from -0.45m to 0.45m. The inhomogeneous medium is consist by two medium with $\varepsilon = 1$ and $\varepsilon = 9$. The width of the two material are 0.5m and 0.5m. The range resolution curves of PSRI, HSRI and GSRI,for the point in the second layer with total depth=0.6, are shown as table (2.4). It can be found that the GSRI can obtain image with best resolution. In order to analyse the detection rate and false rate of the different RADAR imaging algorithms, the receive operation curve (ROC) of the different RADAR imaging algorithms are calculated as figure (2.4)[]salass:babel1. According to the figure(2.4), it can be found that the false alarm rate of the PSRI, HSRI and GSRI are about 0.59,0.23 and 0.05 respectively when the detection rate is 0.7 for each algorithm. It means objects can be best detected (imaged) by GSRI. For comparing the focusing rate of the different RADAR imaging algorithms, a simulation of GRP system detecting the

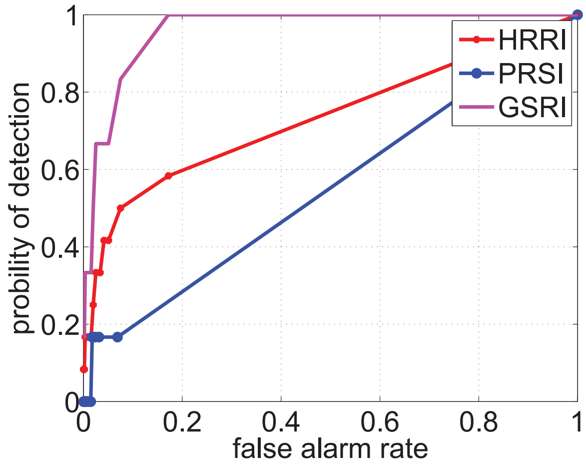

Figure 2: ROC comparison between PSRI(PC), HSRI(PS) and GSRI

reflection signal from an inhomogeneous medium consisting by two layer and four buried object is done. The different RADAR imaging algorithms are applied on the simulation data. The inhomogeneous medium mode and reconstructed images are as the figure (2.4). In order to evaluate the focusing rate of the RADAR imaging algorithms, the image entropy of the reconstructed RADAR images are calculated. Comparing the reconstructed images and the image entropy values, it can easy find that the reconstructed image can be best focused by the GSRI algorithm.

3. EXPERIMENTS AND APPLICATIONS

As above analysing, the GSRI is a very well inhomogeneous RADAR imaging algorithm. Now the GSRI algorithm is tested by the experiments and applied on practical spine imaging . Some RADAR imaging experiments are done in anechoic champers. The RADAR system for the experiments include two antenna, which work as transmitter and receiver respectively. The operated signal by the transmitter is the step frequency continue wave with the frequency from 3 GHz to 10 GHz. The two antenna are fixed on the scanner. The scanner moves from -0.45 meter to 0.45 m in azimuth direction and from -0.1 meter to 0.1 meter in height direction. The first experiment is metallic rods RADAR imaging. The experiment and processed RADAR imaging is figure (3). In two rods and three rods experiment, the distance between two rods is about 0.02 meter. As figure (3) shown, the rods are good imaged by the GSRI. The RADAR imaging system and the GSRI imaging algorithm are applied on human body vertebral imaging. The imaging measurements are done for breast vertebra and lumbar vertebra. The experiment scenario and the processed RADAR image are as figure(3) and figure(3). From the reconstructed images, the shape of the vertebra the number of the vertebra,spinous process, transverse vortex arc extension-vortex hole vertebra body can be easy seen.

4. CONCLUSIONS

In this paper we introduced the GSRI algorithm applied to RADAR imaging of the human spine. The theory and

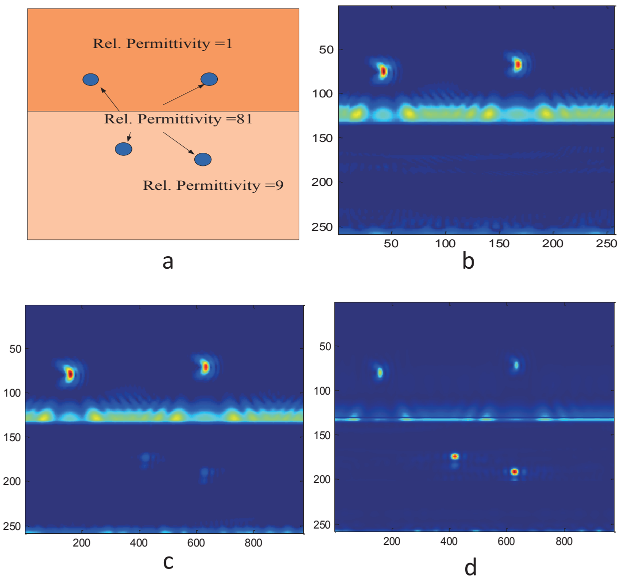

Figure 3: Comparison of algorithms. a) Simulation setup. b) PSRI. c) HSRI. d)GSRI

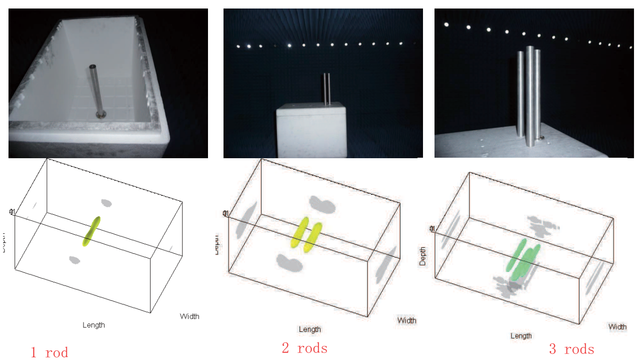

Figure 4: Rods experiment

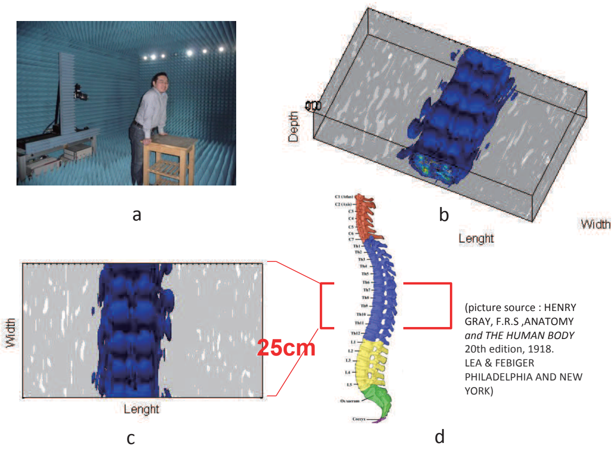

Figure 5: Breast vertebra measurement. a) Measurement step. b) GSRI 3D imaging. c) Frontview. d) Breast vertebra model [1]

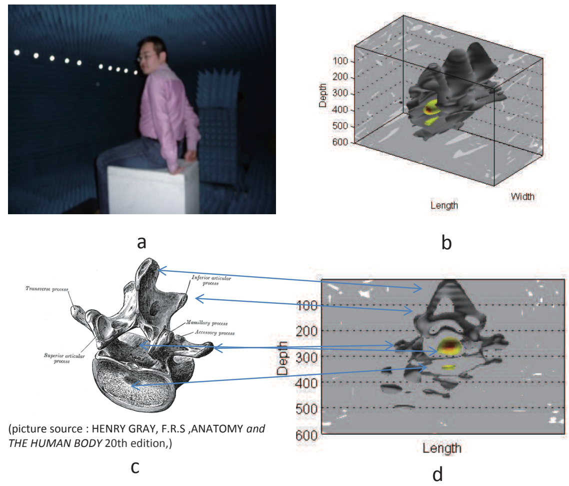

Figure 6: Lumbar vertebra measurement. a) Measurement photo. b) GSRI 3D imaging. c) 2D Lumbar vertebra bone model[1]. d) Topview of 3D imaging

properties of the proposed algorithm are introduced and the viability of the approach has been demonstrated on various simulative and measured examples. Compared to conventional algorithms the GSRI yielded good results in the detection of shape and position of the measured targets. From the measurement of the human spine distinctive features of the vertebra, e.g. the spinous process and vertebra body, can be obtained at high resolution.

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