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Through-the-wall radar detection analysis via numerical modeling of Maxwell's equations ☆

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ABSTRACT

The problem of through-the-wall imaging is considered. A numerical method for Maxwell's Equations is developed and implemented with the goal of generating an approximate solution to this problem. The forward problem is solved using the Yee Scheme, and this solver is used in the inverse problem of detecting and analyzing objects inside a room, with no direct vision of the inside. It is shown how different sizes and shapes of objects have different responses to source waves, and these differences can be used to approximate the object. Numerical results show that this reconstruction procedure gives an accurate approximation to the boundary of the object.

1. Introduction

Inverse problems have many applications to physics and engineering problems, and thus have always been a highly researched area in mathematics. In various types of these problems, one can analyze how to reconstruct material properties from the response to a given input, or try to determine under what conditions there is a unique set of material properties that define a given input response. One particular instance of an inverse problem is through-the-wall imaging. In this case, there is a transmitter and receiver set-up outside of a walled room, with no direct vision of the inside. Using electromagnetic waves, one wants to determine if there is an object inside the room, where the object is located, and potentially what it is.

In most applications of through-the-wall imaging, researchers are interested in human detection and analysis. Many sources have looked at using Doppler-type radar effects to study human motion, either using standard Doppler radar [11] or using noise waveforms, which can have the same levels of resolution, with a smaller chance of being noticed by an external party [7]. There has also been work using so-called micro-Doppler, to analyze smaller scale movements with the through-the-wall method, from arm movement (isolated from torso movement) [6] to the small bodily fluctuations associated with breathing and heart beats [2]. Similar analysis has also been used to analyze human gait, and distinguish between human and animal gait patterns [9,10]. More similar to this paper, Wang et al. used a finite difference time domain method to analyze human movement in a room, but used an incident plane wave for analysis, as opposed to the circular source used here [13].

Some of the most recent work in through-the-wall imaging was performed in the master's thesis [4]. The author there performed a series of experiments involving through-the-wall imaging. With the use of a Support Vector Machine, it was

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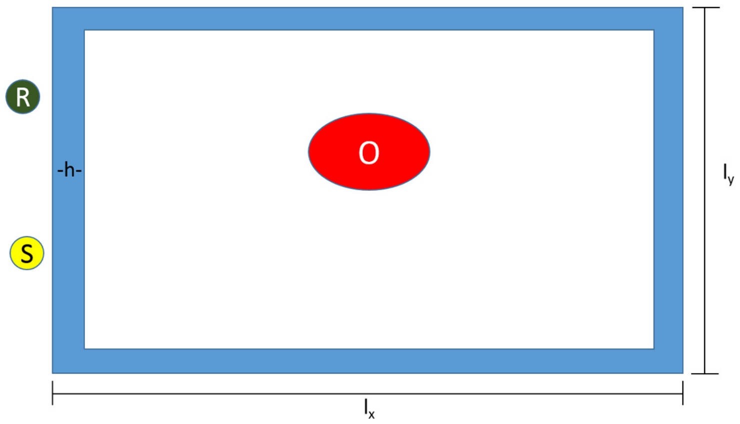

Fig. 1. Model sketch of the problem.

shown that the response data generated from a through-the-wall situation can be used to determine the presence of an object in the room, as well as identify some properties of the object. This last result gives hope that through-the-wall imaging is a well-defined problem, and that numerical and mathematical analysis of this problem could lead to fruitful results.

To that end, in this paper, we develop a numerical method to analyze the through-the-wall imaging problem. We outline the physical system we are trying to analyze in Section 2. In Section 3, we discuss the basic numerical methods involved in approximating Maxwell's Equations in this particular situation. In Section 4, we discuss the adjustments that need to be made to the basic methods in order to accurately approximate the given problem. The facts that material properties are discontinuous and the scattering problem is infinite need to be addressed to ensure that we have the highest order of accuracy possible for our numerical method. In Section 5, we discuss the method for detecting and analyzing the object inside the domain. In Section 6, we show some of the numerical results from these methods, and conclude the paper in Section 7.

2. Model problem

In this paper, we are considering the two-dimensional version of this problem, assuming that all materials are invariant in the z-direction. Our room can be represented by a rectangle of size l_x by l_y. We assume that the walls are of a uniform thickness h, with relative electric permittivity ϵ_w. The object that we are trying to detect is a convex domain $O \subset [0, l_x] \times [0, l_y]$ that has uniform relative electric permittivity ϵ_o. The methods developed here, with a little more work, will function for objects in motion, or objects with varying electric permittivity.

To model the actual physical problem, we will record and use data that could be gathered from a set of antenna transmitters and receivers. Thus, for any given simulation, we will assume that the electromagnetic waves are generated from a source antenna (S) positioned outside of the room and the data is recorded from a (finite) set of receivers (R), also positioned outside the room as shown in Fig. 1.

3. Numerical methods

For this particular version of through-the-wall imaging, we are using electromagnetic radar waves. Therefore, Maxwell's Equations can be used to model this system. Since we are only dealing with electromagnetic waves and have no free charges, the form of Maxwell's Equations we are considering is

$$\begin{cases} \frac{\partial \vec{E}}{\partial t} = \frac{1}{\epsilon} \nabla \times \vec{H} \\ \frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu} \nabla \times \vec{E} \\ \nabla \cdot \vec{E} = 0 \\ \nabla \cdot \vec{H} = 0 \end{cases}$$

For this problem, we are considering a 2-dimensional problem in the transverse magnetic (TM) mode. In general, most physical situations use transverse electro-magnetic (TEM) waves. Since the TM waves arise naturally from considering this problem, we will study those instead. In order to extend the problem to 3 dimensions and implement it in a physical system, the code will need to be rewritten and implemented for TEM waves. Since we are assuming the problem is invariant in the z direction, only the fields E_z, H_x, and H_y are non-zero. Therefore, we are looking at the 3 equations