PARAMETRIC RECONSTRUCTION OF INTERNAL BUILDING STRUCTURES VIA CANONICAL SCATTERING MECHANISMS

Nikola Subotic[1], Eric Keydel[2], Joseph Burns[1], Andrew Morgan[2], Kyle Cooper[1], Brian Thelen[1], Brian Wilson[1], Wayne Williams[2], Sean McCarty[2], Bernard Lampe[2], Bryan Mosher[2], Duane Setterdahl[3]

[1]Michigan Tech Research Institute, 3600 Green Court, Suite 100, Ann Arbor, MI 48105
[2] SAIC, 3600 Green Court, Suite 650, Ann Arbor, MI 48105
[3] SAIC, 1901 South 1st Street, Suite D-1, Champaign, IL 61820

ABSTRACT

In this paper, we describe a model-based, non-linear reconstruction method for mapping internal building structures using through-wall radar data. We based the model on canonical geometry constructs that are commonly used in construction practices. These constructs are then formulated as sets of simple scattering mechanisms, which can be estimated from the data. Our non-linear approach employs an iterative, conditional estimation method as a function of the intervening structures between the sensor and the object under consideration. Specific associations of scattering mechanisms are then used to re-create various building structures such as walls, doors, stairs, etc. We discuss some examples of estimating specific scattering mechanisms and a model-based reasoning approach for assembling them to reconstruct the interior structure of a building.

***Index Terms*—**Through wall imaging, EM scattering, conditional parameter estimation

1. INTRODUCTION

Estimation of building interior structures through walls is a highly non-linear inverse problem. The sensed backscatter from interior structures is perturbed by propagation through building walls and multipath interactions with interior objects. This limits the ability to reconstruct the interior structures by inverting the sensed scattered field. A simple example of this is the influence of a wall on the field transmitted through it, which affects the interpretation of scattered field from objects behind it.

Fortunately, construction practices bound the possible variation of building layouts; walls are flat surfaces and typically intersect at 90-degree angles, doorways are constructed to allow for movement of people between rooms etc. Information about construction practices allows for the use of prior knowledge about typical (canonical) interior structures and their expected manifestation in the measured data. Once estimated from the data, these canonical geometries can then be assembled and associated to construct hypothesized interior building layouts.

For example, the scattering from a completely closed room consists of scattering mechanisms due to the flat wall (dielectric plate), orthogonal intersection of two walls (dielectric dihedral), intersection of wall and ceiling floor (dielectric dihedral), intersection of two walls with either a ceiling or floor (dielectric trihedral). The estimation and aggregation of these simple canonical scattering mechanisms enable the establishment of a group of objects that then define a "room." Figure 1 presents an example test building exhibiting these canonical shapes.

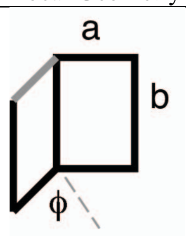
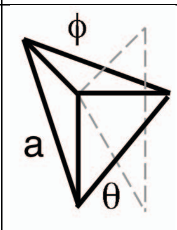
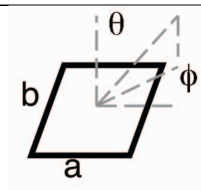
Because of the propagation interactions that perturb the sensed data from interior structures, simple extraction and association of canonical scatterers is not sufficient to reconstruct accurate building interior layouts. Interpretation of the scattering response from a building interior structure must be conditioned on knowledge about the structures that lie between it and the sensor. The algorithms that effect the conditional estimation and association into building structural objects are implemented in the Model-Based Reasoning Engine (MBRE) flow shown in Figure 2. This engine hypothesizes building interior layouts and then iteratively refines them using forward prediction and matching to converge on the interior building floor-plan.

2. PROBLEM FORMULATION

2.1. Signal Models for Scattering from Building Features

Our reconstruction approach recognizes that a building is a sparsely-filled object with a regular interior geometry governed by construction practices. Consequently, we can exploit a large amount of a priori information when we hypothesize signal models that describe the backscattering from building features. Further, we assume that the backscattering from the building can be modeled as the sum of the scattering from a collection of local scattering geometries due to the sparse, regular nature of the structure.

Table 1 Local Scattering Center Models Representative of Local Building Geometries

Type	Local Geometry	Cross Section
Dihedral		$\sigma_{dih}(k,\theta=\pi/2,\phi)\approx |R|^2\frac{4\pi}{\lambda^2}(2ab)^2\sin^2(\phi+\pi/4)$
Trihedral (near bore-site)		$\sigma_{tri}(k,\theta,\phi)\approx\frac{4\pi}{\lambda^2}|R|^2a^4 \left\{\cos\theta+\sin\theta(\sin\phi+\cos\phi) - \frac{2}{\cos\theta+\sin\theta(\sin\phi+\cos\phi)}\right\}^2$
Plate		$\sigma_{plt}(k,\theta,\phi)\approx\frac{4\pi}{\lambda^2}|R|^2(ab)^2 \cos^2\theta\left(\frac{\sin ka\sin\theta\cos\phi}{ka\sin\theta\cos\phi}\right)^2 \left(\frac{\sin kb\sin\theta\sin\phi}{kb\sin\theta\sin\phi}\right)^2$

A building generally consists of a collection of basic local structural geometries, such as walls, floors, and ceilings. These geometry elements usually intersect at right angles to produce local geometries that give rise to simple scattering mechanisms, such as wall glints, dihedrals and trihedrals. We model the total scattering from a building as a collection of *N* canonical scattering mechanisms that are associated together as

$$s(\Theta)=\sum_{n=1}^{N}s_n(\Theta)$$

where $s_n(\Theta)$ are simple, localized scattering mechanisms and Θ is their parameterization.

The formulae for the frequency and angle dependence of these simple scattering geometries are available in the literature (for example, see [1]) and are summarized in Table 1. The parameters ϕ and θ are angles of incidence to the scattering object, *R* is the reflection coefficient, and *a,b* correspond to the size of the object. Note that the angular beamwidth of the plate backscatter is inversely proportional to plate size. Thus, the scattering from a large plate, e.g. wall, dominates a very small angular extent in the collected data. On the other hand, the scattering from the trihedral and the dihedral (at least when the data collection is transverse to the dihedral axis) varies slowly with angle. Dihedrals and trihedrals exemplify intersections of walls into either creases or corners. An illustration of this is shown in Figure 3, which shows the angular response of an example intersection of two walls. Note that the wall responses (a large flat plate) are highly concentrated in angle whereas the crease response of the intersecting walls (dihedrals) has a much larger angular response.

The general formula for a localized, simple backscattering mechanism, $s_n(k,\theta,\phi)$, originating from a point $\bar{r}_n$ has the form

$$s_n(k,\theta,\phi)=A_nP_n(\mathrm{k},\theta,\varphi)\sigma_n^{1/2}(k,\theta,\phi)\frac{e^{-j2k|\bar{r}_s-\bar{r}_n|}}{|\bar{r}_s-\bar{r}_n|^2}$$

where $k = 2\pi f/c$ is the wavenumber, *f* is frequency, $\bar{r}_s$ is the position vector to the sensor, and $\bar{r}_n$ is the position vector to the scatterer. The angles θ,ϕ reflect the relative orientation of the scatterer with respect to the sensor. $\sigma_n^{1/2}$ is the frequency- and angle-dependent scattering amplitude (examples of which are given in Table 1). A_n is a complex constant, and $P_n(k,\theta,\phi)$ is a function that describes any perturbation due to propagation through nearer range walls. The remaining exponential term describes two-way propagation from the sensor to the scatterer. The specific form of the parametric function depends on the type of local scattering geometry. It is parameterized by the physical characteristics of the local geometry, such as size, material properties and physical orientation with respect to the sensor. These functions can also be modified to parametrically model the effects of propagation through walls between the sensor and scattering geometry, such as delay and attenuation, if desired.

Modeling the total measured backscattering from the building as the sum of the backscattering from a collection of specific building features suggests a decomposition approach to detecting, classifying and estimating the parameters of a set of building features. The parameterized set of functions, selected to span structures of interest, provides a natural set of basis function to use in the decomposition.

2.2. Feature Detection and Characterization

To detect, classify and characterize scattering mechanisms associated with basic local building geometry, we apply a basis decomposition approach to the collected data to estimate the type and location of the various canonical scattering mechanisms as [2]

$$s(k,\theta,\phi)=\sum_n s_n g_n(k,\theta,\phi)$$

$$s_n=\iint s(k,\phi)g_n(k,\phi)dfd\theta d\phi$$

where $s(k,\theta,\phi)$ is the collected data in frequency and angle, and $g_n(k,\theta,\phi)$is an element of the scattering basis set. Our basis is comprised of the canonical scattering mechanisms $g_n(k,\theta,\phi)=s_n(k,\theta,\phi)$. There are numerous decomposition algorithms that can be applied. We have used Matching Pursuits [3], which is an iterative L_2-based formulation along with Basis Pursuits and Reweighted Minimum Norm L_1 methods [4-5]. Matching Pursuits was the most computationally efficient for our purposes. The examples given in the subsequent narrative are based on Matching Pursuits.

Our mechanism reconstruction is a conditional, iterative procedure. Analysis progressively proceeds from the exterior to the interior of the building. Dominant building features, such as walls and corners, are first detected from the initial scattering mechanism decomposition. Objects that are close to the sensor (e.g. the outside wall) are estimated first. Parameters of features, such as the thickness and material properties of walls, are then estimated from the data. These estimates establish the terms A_n and $P_n(k,\theta,\phi)$ in $s_n(k,\theta,\phi)$. These estimates are then used within the scattering basis set to change the decomposition to detect downrange (further inside) features. In the implemented software, the MBRE keeps track of the location and parameters of the features (the current building model) and the controls the feature decomposition and estimate as it iteratively builds up and refines the building model from the outside through successive layers of the interior.

2.3. Building Reconstruction Using the Model-Based Reasoning Engine

The high-level flow of the MBRE is shown in Figure 2. A description of through-wall phenomenology challenges and the model-based reasoning approach for building interior reconstruction is presented in [6]. Initial layout hypotheses are "seeded" by the canonical feature extraction process described above. The synthetic data example presented in Figure 4 illustrates how elementary scattering types are used to hypothesize candidate layouts in a test building. In this example, the scattering basis set is parameterized to enable the extraction of three-dimensional location and orientation information in a defined building coordinate frame.

Forward prediction and matching compares the expected feature responses from a hypothesized layout with the data and refines the layouts in the multi-dimensional parameter space that defines the interior structures (wall materials, thickness, positions, etc.). Forward prediction must account for the characteristics of the walls, as well as their multiplicative and multipath interactions in producing the features in the data. Figure 5 provides an example of synthetic data from a complex building model and a corresponding forward prediction of direct return (red) and multipath (green) features from a hypothesized layout. The locations and intensities of the predicted features from the interior walls incorporate the effects of propagation (attenuation and delay) through hypothesized intervening building structures. The predicted features are matched against the data, and the errors are used to refine the building parameters that characterize the layout. The hypothesize-and-test loop is repeated until the error metric is reduced to a pre-defined acceptance threshold.

Figure 6 presents the results of a first-floor building reconstruction from synthetic data using the feature extraction and reasoning techniques described above. The building response was simulated using Science Application International Corporation's Xpatch^{TM} and RFScene urban scene simulation tools. The input model is shown at the top of the figure. The collection that was simulated was from a UHF drive-by sensor that has access to all four sides of the building, together with an airborne sensor flying a circular trajectory around the building. The iterative hypothesize-and-test process shown in Figure 2 was used to reconstruct the building interior structure. The reconstructed interior layout is shown at the bottom of Figure 6. Comparison of the reconstructed layout with the input model shows that the reconstruction is quite accurate.

4. CONCLUSION

In this paper, we have presented an iterative, non-linear building reconstruction method based on low-frequency radar measurements. We use a basis reconstruction approach using individual canonical scattering mechanisms. These mechanisms are then associated with construction objects that lead to a floor plan. Our simulations show that this approach has the potential to perform very high-fidelity reconstruction of buildings.

5. ACKNOWLEDGEMENT

This work was supported by Defense Advanced Research Projects Agency (DARPA) under contract HR0011-06-C-0112. The technical point of contact at DARPA is Edward Baranoski, PhD. His support is gratefully acknowledged.

6. REFERENCES

[1] G. T. Ruck (ed.), **Radar Cross-Section Handbook**, Plenum Press, 1970.

[2] J.W. Burns and N.S. Subotic, "Adaptive Decomposition in Electromagnetics," Chapter 10 in Frontiers in

Electromagnetics, D.H.Werner and R. Mittra (eds.), IEEE Press, New York, 1999, pp.437-473.

[3] S. Mallet and Z. Zhang, "Matching Pursuits with Time Frequency Dictionaries," IEEE Transactions on Signal Processing, 41, pp. 3397-3415, Dec. 1993.

[4] S. Chen and D. Donoho, "Basis Pursuits," Tech. Rep. Stanford University, CA, 1995.

[5] I. F. Gorodnitsky and B. D. Rao, "Sparse Signal Reconstruction from Limited Data Using FOCUSS: A Re-weighted Minimum Norm Algorithm," IEEE Trans. Sig. Proc., 45, pp. 600-616, 1997.

[6] E.R. Keydel, et al, "Model-Based Reconstruction Of Building Interiors From Through-Wall Radar Data," 2006 MSS Tri-Service Radar Symposium, June 2006.

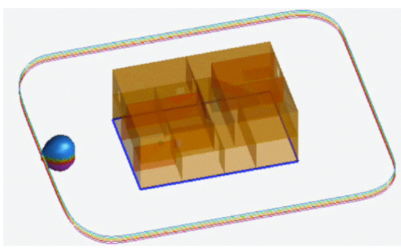


Figure 1: Building structure can be comprised of horizontal and vertical surfaces, horizontal and vertical creases, and three-surface corners.

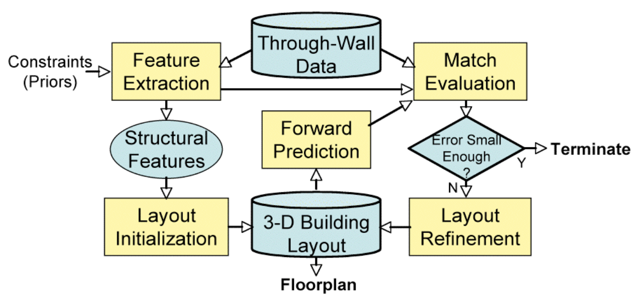


Figure 2: Our reconstruction approach uses both conditional estimation and a hypothesize-and-test approach to develop the building floor plan.

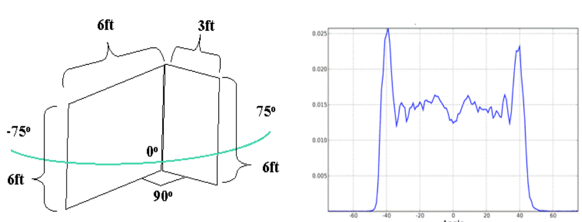


Figure 3: Various canonical scattering mechanisms exhibit different angular scattering characteristics.

TM "Xpatch is a registered trademark of Science Application International Corporation in the United States and/or other countries."

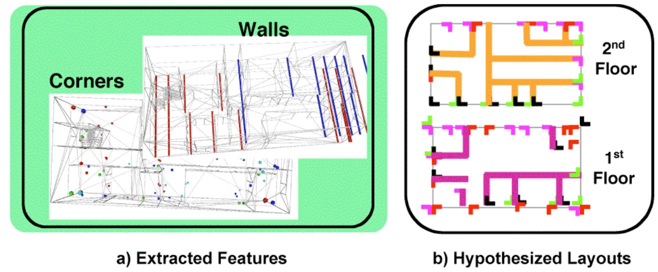


Figure 4: Canonical building structures are used to initialize candidate building layouts.

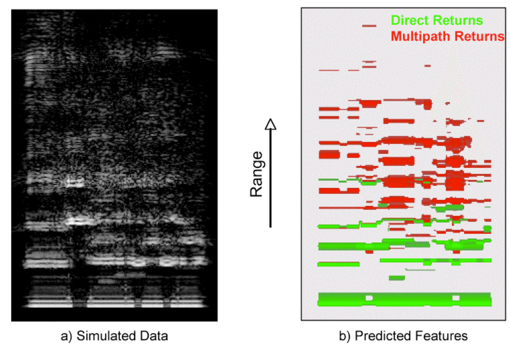


Figure 5: Forward prediction accounts for both direct response and multipath returns.

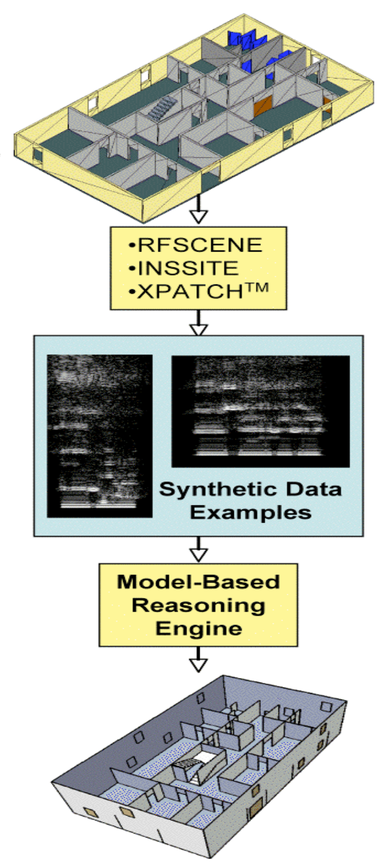


Figure 6: The combination of reasoning and conditional estimation establishes the floor plan of a simulated building.