THROUGH WALL IMAGING: HISTORICAL PERSPECTIVE AND FUTURE DIRECTIONS

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ABSTRACT

Through wall imaging is highly desirable for police, fire and rescue, first responder, and military applications. The ultimate desire of such system is to provide detailed information in areas that cannot be seen using conventional measures. Borrowing from successes in geological and medical imaging environments, researchers are applying radio frequency (RF) and other sensing modes to penetrate wall materials and make intelligent decisions about the contents of rooms and buildings. For this application, they are many propagation differences that provide unique challenges that must be addressed to make through wall penetration sensors operationally viable. This paper outlines the historical context of early research as well as providing new directions for future research in this exciting interplay between electromagnetic propagation, signal processing, and knowledge-based reasoning algorithms.

Index Terms— Microwave imaging, Electromagnetic propagation, Radar, Electromagnetic tomography

1. INTRODUCTION

Through wall sensing addresses the desire to see inside structure to determine the layout of buildings, where occupants may be, and even identify objects within buildings. Through wall sensing grew from ground penetrating radar systems applied to walls, and specific applications have been increasingly documented in the literature since the late 1990's showing abilities to sense beyond a single wall from near-range [1]-[7].

These approaches have generally borrowed from traditional optical, radar, and sonar image processing techniques, which begin with basic wave physics to form matched filters for every point in the imaging target space. In true free space conditions, this represents a mathematically accurate way to perform imaging. Imaging of structure features and contents of buildings requires 2-D and preferably 3-D systems. It cannot rely on Doppler processing for separation of desired features, so multilateration or SAR approaches have been the most common approaches. The general idea behind multilateration is to correlate range measurements from multiple sensors to specific points in the image. With sufficient spatial diversity from a large set of transmit/receive combinations, specific reflection points will start to integrate above the background interference. However, ambiguities will arise as the number of reflection points increases. This can provide an overdetermined system relative to the transmit/receive signal pairs which can detract from the quality of imaging products.

Synthetic aperture radar (SAR) can be thought of as a coherent extension of the multilateration concept. Instead of incoherent combinations of range returns from multiple transmit/receive pairs, coherent algorithms are used to provide a complex matched filter to specific points in the target space. This technique generally assumes free-space propagation to each point in the target scene, although platform motion compensation and atmospheric effects are often removed with autofocusing algorithms. SAR approaches usually neglect propagation distortions such as those encountered by signals passing through walls and objects. These distortions degrade the performance and can lead to ambiguities in localization and understanding of the sensor data.

Free-space assumptions no longer apply after the electromagnetic waves propagate through the first wall. This provides unique challenges and opportunities for exploiting building dependent features. Rather than using free-space focusing assumptions, propagation effects can be included in the imaging solution. Practical systems will need to unravel several layers of distortion to unscramble the waveforms to correctly interpret the physical scene causing the waveform degradation. Free-space approximations may carry imaging systems through to the first wall, but propagation effects will then affect further imaging results. Shadowing, attenuation, multipath, refraction, diffraction, and dispersion all play a role in how the signals will propagate after the first interface. Without factoring in these effects, imaging of contents with buildings will be severely impacted. Uncompensated refraction through walls can lead to localization or focusing errors, leading to image offsets and blurring [9]. Bragg scattering off repeating structural elements such as rebar in concrete walls or repetitive voids in concrete block walls can cause image ambiguities and modulation of subsequent wavefronts.

These effects may be partially corrected using repeated application of image focusing techniques [8]. These techniques will perform the proper wavefront corrections and adjust the imaging focusing algorithms. Tomographic algorithms are capable of making some of these adjustments for projection data through solid materials. However, tomographic projection approaches are well suited for shadowing and attenuation effects, but do not account for multipath and Bragg scattering.

2. FUTURE THROUGH WALL IMAGING DIRECTIONS

Compensation for multipath, dispersion, and reflection needs more than just projection information. It requires knowledge of the propagation interaction between the physical components of the structure being examined. Model-based reasoning is a potential way that propagation effects can be overcome. Structural details need to be estimated iteratively, component by component. As structural details are hypothesized, their presence (or absence) can be used to determine their potential effects on other components. In this way, the building model can be constructed layer by layer.

Future systems will need to carefully understand the dispersive propagation and develop architectures that provide sufficient diversity to correctly model the building and its contents. This approach can be seen in the closed-loop architecture of Figure 1. This architecture attempts to produce the model-based representation that best matches the sensed data using all available propagation and phenomenology information. Inferences can be made to determine why sensed data differ from predicted data, and the model can be updated accordingly. The iterations continue until acceptable convergence is obtained. The final product will be the model that provides the best maximum likelihood match to the sensed data collected. This approach is a major focus of the DARPA VisiBuilding program.

A sufficient architecture will therefore be dependent on three technical areas: phenomenology of signal penetration into buildings, sensor positioning and utilization to maximize information about the building, and model-based 3-D building deconvolution that operates in a multipath-rich, diffractive environment.

2.1. Phenomenology and propagation

Through wall propagation diffraction and multipath through walls have been partially addressed in tomographic approaches [10]-[11]. Ignoring propagation effects limits the degree of understanding of the sensed data, reduces resolution, and reduces the effective depth of penetration results. An imaging architecture must address the physical propagation effects and modeling of the environment so that the system can sense deeper within the buildings. Initial autofocusing approaches have shown promise for identifying some of these parameters by testing various model hypotheses [8]. Sensor architectures must support system design decisions to resolve significant building parameters (such as wall position and densities) but are not overly sensitive to nuisance microstructure (such as cavities in concrete block walls or stud locations) that are less important to operational tasks. This may also require fast propagation solvers to work through 3-D multipath models, and perhaps support fast processing architectures that can handle these tasks in near-real-time.

Frequency choices for the system must strike careful balances between wall attenuation favoring lower frequencies and resolution favoring higher frequencies. Lower frequencies also have the potential benefit that smaller microstructure (wiring, pipes, air gaps in concrete block walls, etc.) may provide less distortion on the RF signal. All of this must be factored into the propagation assessment and physical modeling.

Propagation modeling will also have to be done quickly to test multiple hypotheses. As shown in Figure 1, the model-based reasoning will require analyzing the expected

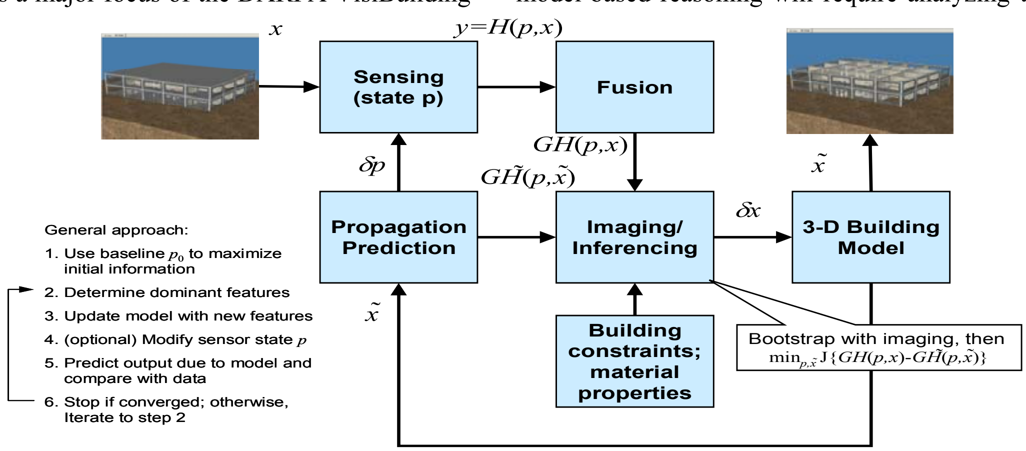

Figure 1 Model-based imaging architecture

propagation results of the candidate model with each iteration. Multiple hypotheses may be carried simultaneously so that uncertainties and ambiguities in the model state can be probed more deeply. This may require varying fidelity in the propagation model to dig deeper into secondary or tertiary effects. Resolving these ambiguities may also require careful sensor diversity in position, frequency, waveform, or temporal characteristics, thus leading us to the second area of technical inquiry.

2.2. Sensor positioning and utilization

The sensor positioning must analyze how to provide the data diversity necessary for building reconnaissance, with a key requirement that the derived technologies must be operationally useful. This limits the size, weight, power, and logistical tails of sensing architectures. Sensor architectures should permit close-range external reconnaissance of buildings. Stand-off distances may be on the order of street-level access or from neighboring structures to avoid blockage from nearby structures. Airborne systems may also provide useful SAR-based information at significantly longer stand-off distances. Ideally, sensor configurations should allow for examination of the building structure through some combination of any or all of the following: small distributed hand-held or emplaced sensors, vehicle-borne sensors, and/or airborne or perching sensors.

Various collection geometries may be more sensitive to picking up certain features of the building environment. Diversity can be obtained through changes in frequency, sensor position, various bistatic or multistatic collection angles, waveform choice, or even Multi-Input, Multi-Output or MIMO radar approaches. This diversity can be anticipated and included in the original data collection methodology or applied iteratively by providing feedback to the sensors to change their location or operating mode. In the former case, the collection profile will have to anticipate potential areas of ambiguity and provide enough diverse looks through which the model-based reasoning algorithms can resolve ambiguities. Given the near-field ranges for ground-based sensing, collection time periods can easily probe hundreds of thousands of diverse collection intervals per second since pulse repetition intervals can be very high due to the short ranges. Diversity over this period can include waveform (ultrawideband impulse radars, stepped CW, noise radars) and multistatic states as well as mobile vehicle-based or airborne platforms.

Alternatively, the diversity can be handled iteratively using sensor feedback. Due to the inherent highly nonlinear nature of the deconvolution problem, and its known sensitivity to input-output geometric and waveform configurations, real-time feedback during deployment can tailor the diversity to resolve ambiguities not other wise possible with an open loop fixed deployment concept--particularly if asset minimization is key. However, this puts very high requirements on real-time processing to provide ample time for feedback.

2.3. Model-based 3-D building deconvolution

Understanding of phenomenology and sensor architecture configurations will only be useful if the resultant sensor data can be interpreted correctly. Single-pass imaging approaches have been used with limited success to image through walls with image quality quickly degrading through multiple walls or in the presence of challenging multipath. Residual ghosting and shadowing has created problems in image understanding. Successful imaging architectures must concentrate heavily on model-based deconvolution and reasoning to provide 3-D models that best match the sensed data. Such reasoning should be tightly coupled with physical phenomenology. As shown in Figure 1, the model should be continuously updated so that its expected propagation effects represent the sensed data better than any other model hypothesis. This is equivalent to likelihood estimation. Model-based reasoning should allow for any a priori structure information. It should be able to exploit data sources ranging from optical imagery of the building exterior, building construction codes, material properties, as well as derived knowledge from the sensor architecture itself. Conversely, it must also be able to extract information from the sensed data and be able to recognize potential ambiguities in hypotheses and resolve them using sensed data or sensor diversities.

To determine building structure, systems must make conclusions based upon wall signatures. Different wall types will have very different signatures. Sensor returns must be used first to hypothesize the presence and location of a wall, followed by the expected effects on propagation through the wall. Generally, detection can be aided by an object-based viewpoint instead of more traditional pixel or voxel imaging that attempts to make decisions about each volume in space. For example, the presence of strong scatterers at regular intervals consistent with stud spacing may reinforce a wall hypothesis. Other constraints, such as local building practices, building usage, or auxiliary information, can further enforce hypotheses.

This highlights the importance of feature extraction to identify building elements. Buildings have identifiable structures with many dihedrals and trihedrals that have spatially recognizable signatures. These can provide key anchor points in the building model. Facing dihedrals can infer the existence of a wall connecting them that may not be visible itself at unfavorable viewing angles. They also provide focal points for autofocusing after penetrating through one or more walls, which can also help to determine dielectric properties of intervening walls.

An additional goal of building imaging is the detection of objects within the building. Sensor returns may not be able to isolate building structure from the building contents. A model-based approach to determine the structure hopefully recognizes objects that do not fit a building hypothesis. Bandwidth and frequency constraints will not provide sufficient resolution to do full object identification, but crude object models can help include these as part of the building contents.

Another obvious goal is the detection and localization of people. The infinite variety and diversity of people will make exact modeling impossible. However, other characteristics of motion may make this more distinguishable than static objects. Doppler discrimination can readily separate motion from background clutter. Building models can be used to make sure that this Doppler signature can be accurately placed within the building by including multipath and dispersion that could erroneously position detected signals. In addition, tracking of movement through the structure can provide additional data on building layouts. Movement patterns may suggest walkways and openly navigable areas. Also, shadows from moving objects will also have a Doppler detectable signature and may paint the walls behind the moving personnel.

In all these cases, a building model needs to be created and updated with new information. The sensor and waveform diversity can provide extensive knowledge that can be used to develop hypotheses about the building. These hypotheses might then allow for further iteration on the building structure itself, in effect peeling back the building one interface at a time.

Obviously, model accuracy, observability, and resolvability are key technical challenges. Models must be representative of the building structure with sufficient detail that the propagation and phenomenology can be adequately predicted so that the model-based reasoning loop can be closed. The feedback and iterative model development will hopefully permit the system to probe ambiguities and derive knowledge of the building. This is a substantial challenge, but a necessary technical innovation to probe deeper inside the high dispersive and multipath environment of buildings.

3. SUMMARY

Through building imaging is an important area for first responder and military applications. Past sensing approaches have tried to extrapolate free-space sensing algorithms to form images through the dispersive medium of walls. Recent advances in propagation modeling and processing power can greatly extend this capability by exploiting model-based building decomposition. New technology advances will be required in three critical areas: phenomenology of signal penetration into buildings, sensor positioning and utilization to maximize information about the building, and model-based 3-D building deconvolution that operates in a multipath-rich, diffractive environment.

4. REFERENCES

[1] D. D. Ferris, Jr. and N. C. Currie, “A survey of current technologies for through-the-wall surveillance (TWS),” *SPIE Conference on Sensors, C31 Information, and Training Technologies for Law Enforcement*, Boston, MA, November. 1998, Vol. 3577, pp 62-72.

[2] L. M. Frazier, “Surveillance through walls and other opaque materials,” *Proc. IEEE National Radar Conference Electronic Systems*, pp. 27-31 May 1996.

[3] S. Nag, M. A. Barnes, T. Payment., and G. Holladay, “An ultra-wideband through-the-wall radar for detecting the motion of people in real time”, *Proceedings of SPIE: Radar Sensor Technology and Data Visualization*, July 2002, Vol. 4744, pp. 48-57.

[4] E. F. Greneker III, “RADAR flashlight for through-the-wall detection of humans,” *Proceedings of SPIE Targets and Backgrounds: Characterization and Representation IV*, July 1998, Vol. 3375, pp. 280-285.

[5] Lin-Ping Song, Chun Yu, Qing Huo Liu, “Through-wall imaging (TWI) by radar: 2-D tomographic results and analyses,” *IEEE Transactions on Geoscience and Remote Sensing*, Dec. 2005, Vol. 43, No. 12, pp. 2793- 2798

[6] F. Ahmad, Y. Zhang, M. G. Amin, “Three-dimensional wideband beamforming for imaging through a single wall,” *Geoscience and Remote Sensing Letters* (under review).

[7] A. R. Hunt, “Image formation through walls using a distributed radar sensor network,” *Proceedings of the SPIE: Laser Physics and Photonics, Spectroscopy, and Molecular Modeling V*, Volume 5778, 2005, pp. 169-174.

[8] F. Ahmad, M. G. Amin, G. Mandapati, “Autofocusing of Through-the-Wall Radar Imagery under Unknown Wall Characteristics,” *IEEE Trans. on Image Processing*, Vol. 16, No. 7, pp. 1785-1795, July 2007.

[9] F. Aryanfar, K. Sarabandi, “Through wall imaging at microwave frequencies using space-time focusing,” *Antennas and Propagation Society International Symposium*, pp. 3063- 3066 Vol.3, 20-25 June 2004.

[10] A. J. Devaney and G. A. Tsihirintzis, “Maximum Likelihood Estimation of Object Location in Diffraction Tomography,” *IEEE Trans. Signal Processing*, 39:672–682, 1991.

[11] A. Vertiy, S. Gavrilov, “Methods of improving of the subsurface objects images reconstructed by the tomography process,” *International Conference on Mathematical Methods in Electromagnetic Theory*, 2002. MMET '02, 10-13 Sept. 2002, Vol 1, pp. 290-292.