Computational Simulation of Millimetre Wave Radar with a Modified Ray Tracing Renderer

Trevor G. Anderson & David G. Johnson
Australian Centre for Field Robotics,
The University of Sydney,
Sydney, NSW, Australia 2006.
Email: t.anderson@acfr.usyd.edu.au, d.johnson@acfr.usyd.edu.au

***Abstract*—In this paper a high fidelity simulator for millimetre wave (MMW) radar systems is obtained through the implementation of geometric diffraction methods within a physically-based ray tracing renderer. Our method is formulated on an implementation of Kouyoumjian and Pathak's compact dyadic diffraction coefficient within Pharr and Humphrey's physically based ray tracing renderer, "pbrt". A recursive path tracing algorithm is used to simulate light transfer between surfaces and a randomly-sampled Monte Carlo surface integrator is used to approximate the incident radiation at each surface intersection. The surface path throughput is determined by a micro-facet-based surface model augmented by Kouyoumjian and Pathak's diffraction coefficient evaluated with reference to proximity to and relative orientation of nearby edges. The presented method is validated by comparison to experimental radar measurements, whilst remaining able to simulate the complex light transport problem significantly faster than a full wave simulator on a consumer level PC.**

I. Introduction

MMW radar sensors are favoured in autonomous systems due to their robust operation in adverse atmospheric conditions [1]. However, target signatures at these frequencies remain poorly understood as simulation models cannot exploit the simplifying assumptions used in high-frequency (visible light) simulations [2]. Without these simplifications the alternative, to use one of various full-wave simulation methods, is impractical as they require substantial computational resources even for electrically small scenes [3]. The development of an accurate computationally-fast simulator for MMW frequencies is therefore of substantial interest to the further development of MMW radar for application to autonomous systems.

In this paper a method is proposed whereby geometric diffraction is implemented within an existing ray tracing environment. The benefit of this is two fold: Extending an existing renderer allows the common aspects of visible light and radar simulation to be assumed, such that the scope of development of this paper can be restricted to modelling the light transfer characteristics of millimetre wavelengths not inherent to pure geometric optics. Second, the existing ray tracing environment makes clever use of recently developed optimisations to accelerate the rendering process, particularly in scene intersection and sampling optimisation.

II. Theory

The basis for the simulator outlined in this paper is a geometric (ray tracing) renderer called "pbrt". Developed as a pedagogical tool for use in university level courses, rendering related courses and by anyone wanting to learn the fundamentals of ray tracing, the pbrt textbook provides a very well structured introduction to the topic [4].

Ray tracing, also called geometric optics is the oldest and most widely used light simulation method. As such, it is well reported in existing literature and therefore this paper will focus only on the area's unique to the simulation of MMW radar.

A. Spectral Representation

Light is not merely one dimensional, rather it is defined by a spectral density of wavelengths over the continuous electromagnetic spectrum. Internally pbrt represents this using a piecewise linear curve for each ray.

We require the piecewise linear function to encompass the emitted light of all simulated light sources. Since MMW wavelengths are orders of magnitude different from that of visible light (400 nm to 700 nm) the range of simulation requires modification. We also note that the full range of wavelengths that are referred to as MMW (10 cm to 1 mm) is much wider than the visible range; requiring more data points for accurate representation. However, MMW radar systems generally operate within a narrow band of the full spectrum and so a narrow region with fewer spectral samples can be used, resulting in much faster computation.

B. Polarisation

Sources of visible light, such as the sun or incandescent globes, emit light of randomly varying polarisation making it difficult to extract additional information from the polarisation of reflections. However, at MMW frequencies reduced natural light and the ability to transmit polarised light mean a radar system is able to gather additional information about the scene. It follows then that to achieve accurate simulation of MMW radar systems it is important that polarised light be traced through the scene with each ray.

Since the path throughput given by the Fresnel coefficients is dependant on the polarisation of the incident radiation in the frame of the surface interface, we require that each path throughput be found in terms of two orthogonal polarisation components; one in the plane of the surface normal, and the other orthogonal to the normal plane. This alignment will change with each intersection, as such the polarisation of simulated rays is rotated at each intersection point.

C. Phase Effects

MMW radar systems often use a coherent pulse to excite the scene for observation, we require phase interference and interaction to be accounted for in the simulation. This is particularly important in the inclusion of diffraction effects and in the accurate rotation of polarisation components.

Light is internally represented using complex-sinusoidal waveforms, so the addition of two rays of the same wavelength is a simple complex addition operation.

D. Diffraction

Ray tracing renderers adequately describe the majority of light transport and interaction, however near edges a randomly sampled ray has zero probability of striking an infinitely thin edge. As such, ray tracing fails to describe light interaction at model edges. This was noted by Keller who developed the Geometrical Theory of Diffraction (GTD) to deal with edge cases in a ray tracing environment [5]. It was noted by Kouyoumjian and Pathak that Keller's theory includes singularities at the reflection and shadow boundaries, they went on to develop a more robust version of the dyadic diffraction coefficient in their Uniform Geometrical Theory of Diffraction (UTD) [6].

Kouyoumjian and Pathak's dyadic diffraction coefficient includes a Fresnel integral of the form

$$F(X) = 2j\sqrt{X}e^{jX}\int_{\sqrt{X}}^{\infty} e^{-j\tau^2}\mathrm{d}\tau \tag{1}$$

To achieve computational speed at the cost of limited accuracy a pair of asymptotic approximations are used instead of a more exact solution to this integral. For small X we obtain

$$F(X) \approx \left[\sqrt{\pi X} - 2Xe^{-j\frac{\pi}{4}} - \frac{2}{3}X^2e^{-j\frac{\pi}{4}}\right]e^{\left(-j\frac{\pi}{4}+X\right)} \tag{2}$$

Similarly for large X

$$F(X) \approx \left(1 + j\frac{1}{2X} - \frac{3}{4X^2} - j\frac{15}{8X^3} + \frac{75}{16X^4}\right) \tag{3}$$

For $X > 10$ the Fresnel integral may be approximated simply by unity and the UTD solution reduces to Keller's GTD solution.

III. Implementation

We have identified and discussed four aspects where the high-frequency simulation method used in pbrt is inadequate for simulating MMW radar: in spectral response, polarisation, interference and phase dependent interaction and diffraction. Through implementation of suitable simulation methods for each of these features we are able to demonstrate reasonably accurate simulation of MMW radar.

Additionally, the original output of a single three channel image was deemed insufficient. As such, we output four channels, two polarisations in both magnitude and phase, in a csv file that can be easily

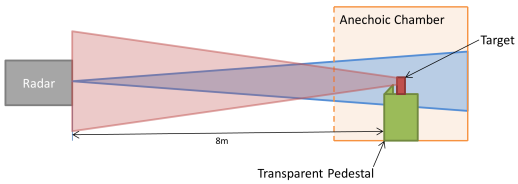

Fig. 1: Experimental set up for simulation verification.

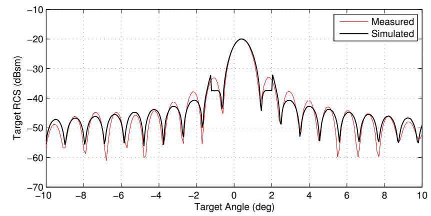

Fig. 2: Comparison of measured and simulated RCS of the 90 mm Power Cube taken about the specular region (from $-10°$ to $10°$ in $0.1°$ increments).

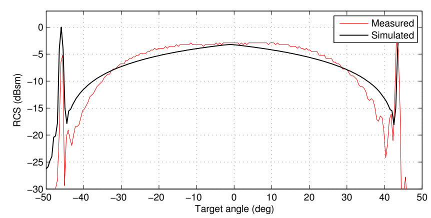

Fig. 3: Comparison of measured and simulated RCS of dihedral corner reflector for the entire range of internal reflection angles.

imported into a processing tool such as MATLAB. This was necessary to enable simple comparison of the measured and simulated Radar Cross Section (RCS) plots as described in the following section.

IV. Results

To verify the simulation we used a custom built 94 GHz radar [7] and an anechoic chamber [8] to measure the RCS of a number of simple targets. Comparison of these measured results to the simulated RCS for the same simple targets leads to positive verification of the accuracy of the simulation under the three primary regions: specular, diffraction and multi-bounce dominated reflection.

Our experimental set up (Fig. 1) consists of the radar on a stable platform aligned with the opening of the anechoic chamber. Inside the anechoic chamber the target, initially a 90 mm Schunk PowerCube, was set up on a translucent (at MMW frequencies) pedestal with Radar Absorbent Material (RAM) shielding the lower half of the PowerCube. The PowerCube was chosen as it is both a simple cube and a precise angular actuator, allowing repeatable control of its angle in the radar's main beam; to within $0.01°$.

A direct comparison of the simulated and measured RCS of the PowerCube is shown in Fig. 2. Here it can be seen that our simulator demonstrates good agreement with the experimental system. In the region of the transition point of the asymptotic approximations to the Fresnel integral, some disagreement is apparent, however it is important to note that the simulated response remains within 6 dBsm of the measured RCS.

Comparison of the measured and simulated RCS of a 150 mm dihedral corner reflector (Fig. 3) demonstrates again good agreement in the specular region, as well as good agreement in the multi-bounce region.

Having verified the three primary components that contribute to target RCS a target with substantially more complex geometry is considered, the scale haul truck (3D model [9]). Fig. 4 shows relatively good agreement produced for this model. We note that the memory requirement for this simulation was only 110 MB, however computation took 8.3 hours on an i7-4770 at stock frequencies.

The measured data is seen to fluctuate significantly more than the simulated data, possibly due to aliasing in sampling. Even so, the general shape of both responses, including the three significant peaks, are quite similar.

There is a notable exception in the peak in the measured data at $35°$ and corresponding peak in the simulated RCS at $\approx 42°$. Visualising the simulated data in MATLAB and isolating the simulated response at the peak (Fig. 5) it is evidently dominated by the response from the front edge of the bucket.

A comparison of the shape of the front edge of the bucket between the scale model, as used in the experiment, and the 3D model, used in simulation, indicate a substantial difference in model geometry

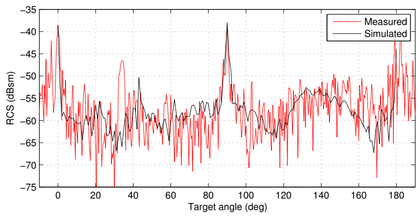

Fig. 4: Comparison of measured and simulated RCS of small scale haul truck. The simulation scan was performed for a 180° scan from front (0°) to rear (180°) around one side, with a step size of 0.5°.

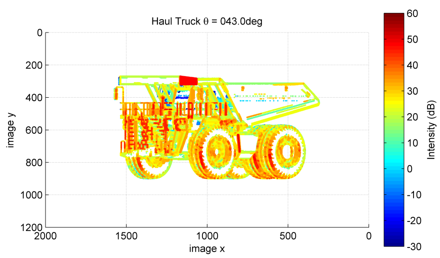

Fig. 5: Simulated response at (43°). Note the significant return from the lip of the bucket.

consistent with the difference in RCS. We conclude therefore, that the simulator as presented demonstrates good agreement when simulating a geometrically complex and electrically large target.

V. Conclusion

In this paper we have presented an implementation of geometric diffraction and phase effects within a ray tracing renderer. The simulation method as presented demonstrates good agreement to experimental results in each of the three primary reflection regions as well as in the example of a complex geometry target. Therefore we present the simulation as capable of simulating novel scenarios for MMW radar application.

VI. Future Work

The simulator as presented may be modified to better suit the requirements for use. Using a more complex model will likely result in more accurate simulation though it remains a trade off with longer simulation times. For example; inclusion of surface diffraction or numerical integration techniques for the Fresnel integrals. Investigation of these changes are deferred to future work.

Additionally we expect that by transferring the bulk of the ray tracing computation to a GPU a speed up of up to 100 times may be achieved.

Acknowledgments

This work was supported by the Australian Centre for Field Robotics.

References

[1] E. Widzyk-Capehart, G. Brooker, S. Scheding, A. Maclean, R. Hennessy, C. Lobsey, and M. Sivadorai, "Millimetre wave radar visualisation system: Practical approach to transforming mining operations," in *Mechatronics and Machine Vision in Practice*. Springer Berlin Heidelberg, 2008.

[2] S. Yumeng, C. Jie, G. CaiHong, S. Bing, and Z. Yinqing, "The advanced simulation system for mmw imaging radar seeker onboard air-to-air missile," in *Signal Processing, 2006 8th International Conference on*, 2006.

[3] K. Sasaki, Y. Suzuki, S. Watanabe, and M. Taki, "A numerical study on milli-meter band electromagnetic dosimetry with complex envelope FDTD method," 2013.

[4] M. Pharr and G. Humphreys, *Physically Based Rendering*. Burlingtong, MA, USA: Morgan Kaufmann, 2010, source code available at: http://www.pbrt.org/index.php.

[5] J. B. KELLER, "Geometrical theory of diffraction," *J. Opt. Soc. Am.*, vol. 52, no. 2, pp. 116–130, Feb 1962. [Online]. Available: http://www.opticsinfobase.org/abstract.cfm?URI=josa-52-2-116

[6] R. G. Kouyoumjian and P. H. Pathak, "A uniform geometrical theory of diffraction for an edge in a perfectly conducting surface," *Proceedings of the IEEE*, vol. 62, no. 11, pp. 1448–1461, 1974.

[7] D. Johnson, M. Calleija, G. Brooker, and E. Nettleton, "Development of a dual-mirror-scan elevation-monopulse antenna system," in *Radar Conference (EuRAD), 2011 European*. IEEE, 2011, pp. 281–284.

[8] D. G. Johnson and G. M. Brooker, "Development of a near-field bistatic synthetic aperture radar for complex target reconstruction," *International Journal of Antennas and Propagation*, vol. 2012, 2012.

[9] Azlyinizam, "Dump truck 3D model," 2013, available at: http://tf3dm.com/3d-model/dump-truck-79822.html.