Simulation Framework for a 3-D High-Resolution Imaging Radar at 300 GHz with a Scattering Model Based on Rendering Techniques

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Abstract—We present a simulation framework for a 3-D high-resolution imaging radar at 300 GHz with mechanical scanning. This tool allows us to reproduce the imaging capabilities of the radar in different setups and with different targets. The simulations are based on a ray-tracing approximation combined with a bidirectional reflectance distribution function (BRDF) model for the scattering of rough surfaces. Moreover, we present a novel approach to estimate the scattering parameters of the BRDF model for different types of targets from the combination of the radar data and information obtained from an infrared structure light sensor. This new framework will serve as a baseline for the design of future radar multistatic configurations and to generate synthetic data to train automatic target recognition algorithms.

Index Terms—Bidirectional reflectance distribution function (BRDF), imaging radar, millimeter-wave measurements, ray tracing, scattering modeling, THz simulation framework.

I. INTRODUCTION

IMAGING radar systems working in the millimeter- and submillimeter-wave bands are now the current trend for concealed object detection [1]–[6]. The specific properties of electromagnetic waves in these bands allow the detection of concealed objects under clothes or inside luggage without rais-

ing safety concerns [7]–[9]. However, in order to develop new and more complex THz systems for security applications, it is necessary to devise reliable simulation tools to help in the design of novel radar architectures. Moreover, these simulators will become crucial to obtain large datasets of realistic example measurements to train automatic target recognition algorithms.

In this sense, electromagnetic scattering modeling plays a crucial role in the development of new simulation frameworks. As wavelengths in the THz band are comparable with microcurvatures in the surface of targets [10], simulators should address the phenomenon of electromagnetic scattering from rough surfaces [11]. Ray-tracing techniques combined with proper scattering models have been shown to adequately characterize these effects [12].

The characteristics of some state-of-the-art ray-tracing THz scattering simulators are detailed in Table I. Most of these systems have targeted the simulation of the propagation properties in the THz band for wireless communications and modeled either specular [13] or nonspecular [14], [15] components of scattering via a Kirchhoff approximation [11]. Other authors have used bidirectional reflectance distribution function (BRDF) models [16] to simulate scattering effects from terrain imaged by an imaging radar in flight simulators [17].

Nevertheless, to our knowledge, THz imaging system simulation for concealed object detection is still a relatively unstudied field. Previous research has targeted passive systems [18]–[21] or active systems at lower frequencies. In the latter, either the scattering from rough surfaces was neglected [22] or a Kirchhoff approximation with no verifiable results was used [23]. More recently, a hybrid approach was taken to simulate a combined active and passive imager [24]. This simulator modeled the scattering produced by the passive system at 100–600 GHz using rendering techniques. Nonetheless, the scattering from the 340-GHz active sensor was simulated using commercial ray-tracing software.

Furthermore, increasing attention is being drawn toward the characterization and measurement of bistatic scattering properties of different materials (especially those present in concealed object detection applications) in the submillimeter band [25]–[27]. These studies have targeted the description of such properties in a way particularly suited for later application in BRDF-based simulators [28].

TABLE I
OVERVIEW OF THZ SCATTERING SIMULATORS

Reference	Illumination	Application	Frequency	Scattering model	Modeled components	Hardware platform
Piesiewicz <i>et al.</i> [13]	Active	Wireless communications	300 GHz	Kirchoff	Specular	Conventional CPU
Priebe <i>et al.</i> [14]	Active	Wireless communications	300 GHz	Kirchoff	Specular + Nonspecular	Conventional CPU
Moldovan <i>et al.</i> [15]	Active	Wireless communications	0.1–10 THz	Kirchoff	Specular + Nonspecular	Conventional CPU
Peinecke <i>et al.</i> [17]	Active	Flight simulation	35 GHz	BRDF	Specular + Nonspecular	GPGPU
Fetterman <i>et al.</i> [18]	Passive	Concealed object detection	95 GHz	Lambert	Nonspecular	Conventional CPU
Grafulla <i>et al.</i> [19]	Passive	Concealed object detection	35 GHz	Fresnel	Specular	Conventional CPU
Murakowski <i>et al.</i> [20]	Passive	Concealed object detection	95 GHz	BRDF	Specular + Non specular	Conventional CPU
Appleby <i>et al.</i> [21], [24]	Passive	Concealed object detection	100–600 GHz	BRDF	Specular + Non specular	GPGPU
Williams <i>et al.</i> [22]	Active	Concealed object detection	56.5–63 GHz	Snell law	Specular	GPGPU
Pätzold <i>et al.</i> [23]	Active	Concealed object detection	80–110 GHz	Kirchoff	Specular	GPGPU
Appleby <i>et al.</i> [24]	Active	Concealed object detection	340 GHz	Ray-Tracing	Specular	Conventional CPU
Present system	Active	Concealed object detection	300 GHz	BRDF	Specular + Nonspecular	GPGPU

In this paper, we present a new simulation framework for a 3-D high-resolution imaging radar at 300 GHz with mechanical scanning [1]. Our main contributions are as follows:

- 1) a ray-tracing framework that simulates the elliptical mechanical scanning of the system;
- 2) a simulation model for the scattering from rough surfaces based on a BRDF;
- 3) a novel approach to estimate the scattering parameters of the BRDF models for different types of targets based on the combination of radar information with 3-D measurements obtained with a structured-light camera in the infrared spectrum;
- 4) an optimized implementation of the simulator on a general-purpose graphics processing unit (GPGPU).

This paper is organized as follows. In Section II, an overview of the imaging radar system is presented. In Section III, the simulator design is described. The underlying scattering models are explained in Section IV. The details of the measurement procedure and experimental results for the estimation of the scattering parameters are presented in Section V. Finally, in Section VI, some brief conclusions are provided.

II. OVERVIEW OF THE RADAR SYSTEM

The present simulator is based on the imaging radar developed at the Universidad Politécnica de Madrid [1]. In this section, its key performance parameters, as well as an overview of its functioning, are summarized.

A. Imaging Operating Principle

The imaging system is based on a pixel-by-pixel elliptical scanning antenna subsystem and a continuous-wave linear-frequency modulated radar sensor with a homodyne architecture at 300 GHz for standoff detection at 8 m, which is measured from the primary focus of the scanning antenna subsystem.

After stretch processing [29] in each chirp period, a peak detection algorithm measures range R of the detection from the fast Fourier transform of the mixed signal. Afterwards, a fifth-order polynomial approximation $\varphi_5(\gamma, \phi, R)$ maps the rotation and tilting angles of the mirror (γ, ϕ) to the (x_t, y_t) coordinates in the target plane using information of range [30]. This is

$$(x_t, y_t) = \varphi_5(\gamma, \phi, R) \quad (1)$$

Fig. 1. (a) Scanning pattern projected in target plane. (b) 3-D image of a female mannequin holding hidden explosives captured by the radar. The color in the image represents range information.

Finally, (x_t, y_t, R) are plotted as a point cloud to visualize the recovered surface. Fig. 1(b) shows an example of this visualization.

B. Antenna Subsystem and Mechanical Scanning

Fig. 2 shows the multireflector antenna subsystem [30]. This is formed by a main reflector (a), a subreflector (b), a scanning mirror (c), a feeding reflector and a dual-mode horn (f).

The mechanical scanning is carried out by means of the rotation and tilting of the flat mirror (c), which redirects the plane wave produced at the feeding reflector (d), while it is fed from a transmitting and receiving conical dual-mode horn (f) connected to a compact radar front-end [31].

To achieve a field of view (FoV) of 50 cm $\times$ 90 cm, a two-axis movement of the mirror is used, as shown in Fig. 3. The first movement consists of a fast rotation of the mirror (coordinate ϕ) that makes the spot beam describe an ellipse with a horizontal major axis of 50 cm and a vertical minor axis of 40 cm.

Fig. 2. Photograph of the imaging radar showing the key components and the transmitting and receiving signal paths.

Fig. 3. Flat mirror and its corresponding tilting and rotating angles and axes.

The second movement is a slow tilting up and down of the whole mirror structure (coordinate γ) that allows the ellipse to vertically scan the FoV, as shown in Fig. 1(a). This system generates an effective spot beam of 1.6 cm in diameter at the center of the FoV. As the scanning beam moves away from the center of the FoV, the spot size increases [1].

III. SIMULATOR DESCRIPTION

In this section, the design of the simulation framework is presented based on the description of each of the modules that compose it. In Fig. 4, the interaction between these modules is depicted.

First, the coordinate system definition of the spatial scenario is introduced. Then, the ray-tracing algorithm and the power balance model are defined. Finally, the peculiarities of the graphics processing unit (GPU) implementation and its performance improvement are described.

Later, in Section V, the simulator calibration procedure, i.e., the estimation of its underlying parameters, will be discussed.

A. Spatial Scenario Definition

Fig. 5 shows a schematic diagram of all reference systems used in the simulator based on the antenna design in [30]. There are three main systems.

Fig. 4. Overview of the simulation framework modules. The dashed lines represent modules that are executed before the simulation to adjust the scattering parameters to the real measurements.

Fig. 5. Top view of relations among different coordinate systems in spatial scenario definition.

- 1) Antenna's reference system S_a defined by vectors $\hat{x}_a$ and $\hat{y}_a$ contained in the focal plane and $\hat{z}_a$ perpendicular to it. It has origin O_a in the primary focus.
- 2) Target's reference system S_t defined by vectors $\hat{x}_t$ and $\hat{y}_t$ contained in the target plane (rotated an angle τ with respect to the focal plane due to the offset configuration) and $\hat{z}_t$ perpendicular to it. It has origin O_t in the secondary focus.
- 3) Global reference system S_g defined by vectors $\hat{x}_g, \hat{y}_g$, and $\hat{z}_g$ in the directions defined by the radar table and origin O_g in one of the corners of the table.

As seen in Section II-A, radar detections are defined by the triple (x_t, y_t, R) , where (x_t, y_t) are coordinates with respect to S_t and R is the detection range, measured from the center of the main reflector. This non-Cartesian coordinate system does not allow us to define an intuitive spatial scenario, where targets are easily placed at a standoff distance of 8 m from the radar, and therefore, S_g is used to define the geometry of the simulator.

The transformation from (x_t, y_t, R) to coordinates in S_g is done as follows.

- 1) Let $O_c = (x_c, y_c, z_c)^T$ be the coordinates of the center of the main reflector in S_t , and let $\mathbf{r}_t = (x_t, y_t, z_t)^T$ be the coordinates of the detection in S_t . Coordinate z_t is, therefore,

$$z_t = \sqrt{R^2 - (x_t - x_c)^2 - (y_t - y_c)^2} + z_c. \quad (2)$$

2) Then, the coordinates of the detection in S_a are

$$\mathbf{r}_a = \mathbf{O}_t + \begin{bmatrix} \cos(\tau) & 0 & -\sin(\tau) \\ 0 & 1 & 0 \\ \sin(\tau) & 0 & \cos(\tau) \end{bmatrix} \mathbf{r}_t. \quad (3)$$

3) Finally, coordinates $\mathbf{r}_g$ of the detection in S_g are

$$\mathbf{r}_g = \mathbf{O}_a + \begin{bmatrix} -\sin(\alpha) & 0 & -\cos(\alpha) \\ 0 & 1 & 0 \\ \cos(\alpha) & 0 & -\sin(\alpha) \end{bmatrix} \mathbf{r}_a. \quad (4)$$

Simulated targets inside the framework are modeled as triangular faceted surfaces defined in a PLY file (Polygon File Format). This file contains a matrix $\mathbf{P} \in \mathbb{R}^{N_v \times 3}$ that stores the coordinates of N_v vertices and a matrix $\mathbf{T} \in \mathbb{N}^{N_t \times 3}$ that stores the indices of the N_t triangulations.

All coordinates in $\mathbf{P}$ are referred to S_g allowing to easily apply geometrical transformations to the simulated target.

B. Ray Tracing

The simulation framework works under a geometrical optics assumption that simplifies the electromagnetic interaction of the focused-radar-emitted waves and the target, to the intersection of a ray with a faceted surface. This way, for each chirp period, the simulator traces a ray with origin in the center of the main reflector and direction defined by the chosen scanning pattern.

The definition of the scanning pattern is flexible and can be extended to any desired shape. Nonetheless, by default, the simulator uses the configuration parameters of the imaging radar to define an elliptical scanning pattern with the same structure as the one in Fig. 1(a). This pattern is defined by a matrix $\mathbf{S}_{\gamma,\phi} \in \mathbb{R}^{N_r \times 2}$ that stores the rotation angles of the N_r chirp periods that will be scanned in the (γ, ϕ) plane. In order to obtain the directions of the rays, these coordinates must be transformed to 3-D spatial coordinates in S_g . This is done by transforming each point in $\mathbf{S}_{\gamma,\phi}$ first using (1) with $R = 8$ m, and then following the steps in Section III-A to obtain its coordinates in S_g .

The intersection of the ray with the surface of the target is found using the Möller–Trumbore ray-triangle intersection algorithm [32]. For each chirp period, the intersection of the corresponding ray with all the facets of the simulated target is checked. Then, for each ray, the closest intersection in range is selected as the detection. The position of the detection and the angle between the ray and the intersected facet are stored.

Even though this method does not allow us to simulate multiple bounces, simulation results, presented in Section V, have shown to be comparable to real measurements.

C. Power Balance Model

The monostatic radar equation for distributed targets is [33]

$$P_r = \frac{P_t \cdot G_t}{(4\pi R^2)} \cdot \frac{A_{eq}}{(4\pi R^2)} \cdot \int_{A_{spot}} \sigma^o(\mathbf{r}, \theta_i) dA \quad (5)$$

where

P_r received power;
 P_t transmitted power;
 G_t transmission gain;
 R target range;
 A_{eq} equivalent area of the receiving antenna;
 A_{spot} spot area;
 $\mathbf{r}$ position vector;
 θ_i angle of incidence;
 σ^o differential radar cross section.¹

In this setup, with a highly focused radar, we can approximate the power density of the first fractional term in (5) by $\frac{P_t}{A_{spot}}$, leaving the radar equation

$$P_r = \frac{P_t}{A_{spot}} \cdot \frac{A_{eq}}{(4\pi R^2)} \cdot \int_{A_{spot}} \sigma^o(\mathbf{r}, \theta_i) dA. \quad (7)$$

If we assume that the electromagnetic properties and roughness of the target do not change within the spot, (7) simplifies to

$$P_r = \frac{P_t \cdot A_{eq}}{(4\pi R^2)} \cdot \sigma^o(\theta_i). \quad (8)$$

Given (8), the only free parameter to model the scattering response is the differential radar cross section and its dependence with the angle of incidence. Different models for this term will be discussed in Section IV, as well as an experimental method to estimate their parameters in Section V.

The information obtained from the ray-tracing algorithm is used to feed (8) that renders the received power for each detection.

D. GPGPU Acceleration

In an initial stage, the complete simulation was executed on a MATLAB 2015b environment in a conventional PC based on an ASUS P5KSE motherboard with an Intel Core 2 Quad CPU Q6600 @2.40-GHz processor with 8 GB of RAM. The recorded time to simulate a radar scan composed of 18 529 rays and 28 655 triangular facets was 126.85 s. Of that total time, 98.99% was due to the computation of the ray-facet intersections in the scan, with this mechanism being the primary bottleneck of the code.

In an effort to speed up this code, the calculation of the intersections was transferred to C code, compiled so that it could still be invoked from the MATLAB environment without disrupting the rest of the software. This technique produced a speedup factor of 13x, with a new recorded time of 9.7 s for the entire simulation and 9.5 s for intersection computing.

In a final attempt to further optimize the software, a hybrid CPU-GPU architecture was established. In this scheme, we offloaded the processing of the intersections to a GPU, while the rest of the code is still executed in the CPU. Once again, the new code does not disrupt the rest of the software and is

¹The differential radar cross section is a generalization of the radar cross section for distributed targets [33].

$$\sigma = \int \sigma^o(\mathbf{i}, \mathbf{o}) dA. \quad (6)$$

Fig. 6. Diagram defining the BRDF geometry. The coordinate system is referred to the target surface. The incidence and viewing angles, θ_i and θ_r , are measured with respect to the surface normal ($\mathbf{n}$).

callable from the MATLAB environment. Our chosen GPU is a GeForce GTX 970 from NVIDIA, and the code is programmed using NVIDIA's CUDA architecture.

In this new format, the calculation of ray-facet intersections is parallelized. The GPU launches an independent processing thread per ray, and these are executed in parallel on its multiple cores. Each thread is tasked with finding the foremost facet that intersects with its ray, and this processing is completely independent of other rays. The registered time for the GPU code was 0.557 s, which results in a speedup factor of 17x from the C code, and a total simulation time of 0.757 s.

As more powerful GPUs become commercially available, further parallelization can be achieved. For example, each thread could be tasked with a single ray-facet pair, instead of all interactions of one ray.

IV. SCATTERING MODEL

A. Introduction to BRDF

The BRDF [16] is a radiometric concept used in computer graphics to simplify the rendering of rough 3-D models. It is defined as the ratio between the reflected radiance L_r of a surface, or power per unit solid-angle per unit projected area, and the incident irradiance E_i to the same surface, or power per unit area, or more commonly, power density. This is,

$$f(\mathbf{i}, \mathbf{o}) = \frac{dL_r(\mathbf{o})}{dE_i(\mathbf{i})} = \frac{dL_r(\mathbf{o})}{L_i(\mathbf{i}) \cos(\theta_i) d\omega_i} \quad [\text{sr}]^{-1} \quad (9)$$

where $\mathbf{i}$ and $\mathbf{o}$ are unit vectors in the direction of the incident waves and the measurement direction, respectively. Fig. 6 shows the geometry for this definition.

In a monostatic setup, $\mathbf{i} = \mathbf{o}$, and thus, $f(\mathbf{i}, \mathbf{o}) = f(\mathbf{i})$. Furthermore, if we assume that the scattering is isotropic, i.e., does not depend on ϕ_i , $f(\mathbf{i}) = f(\theta_i)$.

The BRDF is related to the differential radar cross section, or differential scattering coefficient, in the isotropic monostatic

case [34] as

$$\sigma^o(\theta_i) = 4\pi f(\theta_i) \cos^2(\theta_i). \quad (10)$$

Substituting (10) into (7), the radar equation becomes

$$P_r = \frac{P_t \cdot A_{\text{eq}}}{R^2} f(\theta_i) \cos^2(\theta_i). \quad (11)$$

B. BRDF Models

Scattering from rough surfaces can be categorized in two terms [33]: a diffuse term and a specular term. In specular or even slightly rough surfaces, the specular term dominates the scattering. However, when the dynamic range of the measurement instrumentation is large enough, and there are measurements taken with incidence directions far from the normal, the diffuse term should also be modeled.

A simple way to model this duality for isotropic surfaces is

$$f(\theta_i) = k \cdot f_d(\theta_i) + (1 - k) \cdot f_s(\theta_i), \quad 0 \leq k \leq 1 \quad (12)$$

where $f_s(\theta_i)$ refers to the specular term, $f_d(\theta_i)$ to the diffuse term, and k is a parameter that measures the relation between both terms.

Depending on the properties of the medium, there are several families of functions that can be used as BRDF [35]–[38]. In general, these functions model either the specular reflection, or the diffuse scattering. Therefore, in order to model the complete backscatter response, at least a specular model and a diffuse one must be used.

The simulation framework allows us to use any BRDF model to render the received power. However, by default, the simulator uses the most common families of BRDF models as prebuilt functions to simulate the power balance.

The Cook–Torrance model [36] is the most used function to model specular reflection from slightly rough surfaces due to its versatility. It decomposes the specular term [38] in the BRDF as

$$f_s(\mathbf{i}, \mathbf{o}) = \frac{F(\mathbf{o}, \mathbf{h}) \cdot D(\mathbf{h}) \cdot G(\mathbf{i}, \mathbf{o}, \mathbf{h})}{4 \cdot |\mathbf{n} \cdot \mathbf{i}| \cdot |\mathbf{n} \cdot \mathbf{o}|} \quad (13)$$

where

$F(\mathbf{o}, \mathbf{h})$ Fresnel term;
 $D(\mathbf{h})$ microfacet distribution term;
 $G(\mathbf{i}, \mathbf{o}, \mathbf{h})$ shadowing mask;
 $\mathbf{n}$ surface normal;
 $\mathbf{h} = \frac{\mathbf{i} + \mathbf{o}}{\|\mathbf{i} + \mathbf{o}\|}$.

The versatility of this model comes from the possibility to use different types of functions for the terms $F(\mathbf{o}, \mathbf{h})$, $D(\mathbf{h})$, and $G(\mathbf{i}, \mathbf{o}, \mathbf{h})$.

By default, the simulator uses Schlick's computationally efficient approximation to the Fresnel term [39]

$$F(\mathbf{o}, \mathbf{h}) = f_\lambda + (1 - f_\lambda) \cdot |\mathbf{o} \cdot \mathbf{h}| \quad (14)$$

where f_λ is the reflectivity of the medium at normal incidence. Greater values of f_λ render higher received powers.

For the case of the term $D(\mathbf{h})$, the framework allows us to choose between two prebuilt distribution models: the Beckmann's distribution [11] and the GGX distribution [38], both

having a roughness term m as their only free parameter. This parameter governs the width of the specular lobe.

Once a distribution for $D(\mathbf{h})$ is selected, the term $G(\mathbf{i}, \mathbf{o}, \mathbf{h})$ is fixed by the relations shown in [38].

On the other hand, the diffuse term is modeled by default using Blinn–Phong’s model [35], since this model allows us to control the falling curvature of the diffuse term via its parameter α . This is,

$$f_d(\mathbf{i}, \mathbf{o}) = r_s \frac{\alpha + 2}{2\pi} |\mathbf{h} \cdot \mathbf{n}|^\alpha. \quad (15)$$

The parameter r_s is the equivalent to f_λ in (14). It allows us to control the amount of diffusely scattered radiation.

This way, any scattering characteristic can be modeled by fitting five parameters, i.e., k , f_λ , m , α , and r_s , as it will be shown in Section V. In the Appendix, the effect that the modification of each of these parameters value has in the overall BRDF model is described.

V. PARAMETER ESTIMATION

In this section, a novel approach to estimate the parameters of the BRDF that models the scattering phenomenon from a given target is studied.

A. Experimental Setup

The radar measurements produce an unstructured 3-D point cloud consisting of points that store position, power, and phase, but lack information on the angle of incidence of the emitted radiation for each detection. Even though the acquired point clouds include phase information, this was not used in the present work.

The basic idea behind these experiments lies in the estimation of the angles of incidence from the combination of the information retrieved by the millimeter-wave radar with a 3-D model of the target, captured by an infrared structured-light 3-D scanner. This way, since the 3-D model, captured by the infrared sensor, can be considered as an ideal reconstruction of the surface of the target, the angle of incidence can be estimated using this virtual surface as reference.

The target of these experiments was a female mannequin placed at a standoff distance of 8 m from the radar. In order to obtain the maximum angle diversity, the radar system was set to sweep the complete FoV with the elliptical scanning pattern that has the highest spot spatial density allowed by the radar.

Previously, the 3-D model of the mannequin in Fig. 7(b) was obtained. This model was captured using the technique by Newcombe *et al.* [40], where a consumer infrared structured light depth sensor is moved around the surface, which needs to be retrieved. This system filters each depth frame provided by the sensor, creates a 3-D point cloud associated with that particular frame, and estimates its orientation and reconstructs a 3-D surface. This way, every new point cloud retrieved at every new frame is registered² through an iterative closest point (ICP) algorithm [41], which gives us an estimation of the new pose of

Fig. 7. (a) Female mannequin. (b) Measured 3-D model.

the sensor. Furthermore, with every new point cloud, the estimated 3-D surface is updated both reducing the remaining noise from the depth map and also expanding it with a new set of triangles using a volumetric truncated signed distance function [42]. This system is also optimized to avoid loop closure issues.

The polygonal resolution of the resulting 3-D models comes from a tradeoff defined by the “voxels per meter” variable: the system is able to handle up to a 640^3 voxels volume, but it is not possible to obtain both very large volumes with a very high resolution. With our particular reconstruction constraints, we are able to get a polygonal resolution of about 2–5 mm per voxel.

B. Estimation of Angle of Incidence

The steps that were taken to estimate the angles of incidence are shown in Fig. 8(a) and define the procedures that are followed inside the parameter estimation module in Fig. 4. First, the obtained 3-D model was located, where the mannequin was standing during the measurements. And then, the 3-D surface was used as reference to compute the angles.

During these experiments, the ICP algorithm was used to register the 3-D model and the radar point cloud. This algorithm minimizes the distance between two point clouds, measured as the root-mean-squared value of the minimum distance of each point of one cloud to the closest point of the other.

The ICP algorithm is prone to get trapped in local minima, and thus, a good initialization of the algorithm is necessary in order to avoid bad results. Furthermore, ICP is shown to work better when both point clouds have been acquired using the same acquisition pattern and have the same size.

For this reason, an iterative approach was followed for the registration of the 3-D model as it is shown in Fig. 8(a): First, a rough alignment of the 3-D model to the radar cloud was manually estimated. In this process, we used salient geometrical features of the targets to simplify the alignment. Afterwards, the 3-D model was virtually scanned by the simulator with the scanning parameters used in the real measurements giving a simulated radar cloud. Then, ICP was applied to register the simulated cloud to the original one. The whole process was repeated iteratively, until convergence of the distance between

²The alignment process of two or more 3-D point clouds is known in the literature as registration.

Fig. 8. (a) Process flow and (b) data model to estimate the angles of incidence from the radar measurements and the 3-D model.

Fig. 9. Measured angular backscattering response of a female mannequin.

the two clouds was achieved. Convergence was assumed to be achieved whenever a new iteration of the algorithm did not change the pose of the clouds.

Once the model and the measurements were aligned, the simulation software was used to trace rays with origin in the main reflector and crossing the position of each measured spot. The direction of these rays is an approximation of the direction that the transmitted waves had in each detection. Finally, the angle of incidence for each detection was estimated as the angle between each ray and the normal of the intersecting facet in the intersection point.

C. Results

Fig. 9 shows the scatter plot of the received power of each detection and its estimated angle of incidence. In order to

Fig. 10. Comparison of several simulated images with fitted parameter obtained with different strategies. The color represents the received power in dBm. The red-dashed rectangle in (a) represents the region used for the fitting. (a) Image captured by the radar. (b) Simulated image with TLS fitting and tail adjustment. (c) Simulated image with TLS fitting. (d) Simulated image with piecewise MSE optimization.

maximize the probability of detection subject to a fixed probability of false alarm, measurements below -77 dBm were discarded. For this reason, Fig. 9 only shows power values above this threshold.

The 3-D image of the mannequin obtained by the radar is shown in Fig. 10(a), where the color of the points represents the measured received power. Two different kinds of regions can be distinguished in the image: Small high-power areas and an extended low-power region.

When inspecting Fig. 9, it is clear that the high-power areas correspond to specular highlights, measured when the angle of incidence is very small, and the low-power region corresponds to measurements of diffuse scattering that smoothly decreases with the angle of incidence.

The reason for the noisy nature of these results is unclear. It could be due to subsurface scattering (interaction between radiation and the glass fiber structure under the paint cover of the mannequin) that does not depend on the angle of incidence, since this noisy effect is also visible in the captured image. Other

Fig. 11. Measured angular backscattering response and simulated models of the lower torso of a female mannequin.

possible causes could be unaccounted speckle, nonuniformity of the spot size across the FoV, or errors in the estimation of the angles of incidence that could be contributing to magnify the effect of the noise.

D. Parameter Fitting

As a way to reduce the noisy effect in Fig. 9, only the detections in the lower torso of the mannequin were used to fit the BRDF parameters, since this is the region where the radar shows the highest precision [1].

In compliance with the presented model in Section IV, the specular highlight was adjusted with the Cook–Torrance model. On the other hand, Blinn–Phong’s model was used to fit the diffuse term.

Three different approaches were compared to find the parameters:

- 1) mean-squared-error (MSE) regression;
- 2) total-least-squares (TLS) regression [43];
- 3) TLS regression combined with manual tuning of the diffuse decay.

The resulting models are shown in Fig. 11. Also, Fig. 10 shows the simulated images with parameters obtained from each fitting strategy.

To avoid MSE regression to get trapped in local minima, the specular term and the diffuse term were adjusted consecutively. First, the specular parameters were fitted using measurements under 6° . These parameters were then fixed and the diffuse parameters were found using the rest of the measurements.

MSE regression only minimizes the error in the received power axis, and therefore, it fails to follow the complete dynamic range of the backscatter response. TLS regression, on the other hand, minimizes the error in both directions (received power and angle of incidence), which allows the resulting model to adequately follow the response in the complete dynamic range, even without adjusting the diffuse and specular terms separately. In this sense, TLS regression presents an additional benefit with respect to MSE regression, since it does not need tuning on the angle that separates specular and diffuse components. The whole adjustment is done for all measurements at the same time.

Fig. 12. Line scan at $y = 1.1 \pm 0.01$ m projected over z coordinate of Fig. 10(a) and (b).

However, in the case of the diffuse term, none of these approaches seem to be able to adjust to the visually noticeable power decay in Fig. 11. Due to its sensitivity, the imaging radar is not able to measure detections under -77 dBm, and thus, any automatic regression approach would underestimate the power decay of the diffuse term and overflatten the diffuse component.

For this reason, the resulting model from the TLS regression was manually adjusted by tuning the α parameter in its Blinn–Phong model so the diffuse term followed the power decay in Fig. 11. As seen in Fig. 10(b), this approach enhances the appearance of the simulation by extending the diffuse area with the lightest blue tones making it resemble Fig. 10(a) more.

In order to further validate the model, a line scan of Fig. 10(a) and (b) is shown in Fig. 12. From this figure, it is clear that TLS with manual tuning is able to produce a high-quality approximation of the real backscatter response. The reflection peak is adequately located and the power decay of the simulated image follows the one of the real measurement.

It is important to highlight that the fit parameters are purely empirical and not directly related to the topography parameters of the surface such as RMS roughness or autocorrelation length. This approach differs from previous attempts to characterize this type of electromagnetic interaction, where a direct link between the surface geometry parameters and the scattering behavior was sought [44], [45].

E. Human Target

The same set of experiments was run on a naked human target with the aim of modeling backscattering from human skin.

The simulated images for the three fitting approaches on a human target are shown in Fig. 13.

The measured angular backscatter response of the human target is shown in Fig. 14. In this case too, only the measurements in the lower torso of the target were used to estimate the backscatter response, since, due to the overall complexity of the human surface, the estimation of angles of incidence outside this area is extremely noisy.

It is important to highlight that in the human case, the target movement during the radar and infrared measurements is not

Fig. 13. Comparison of several simulated images with fitted parameter obtained with different strategies. The color represents the received power in dBm. The red-dashed rectangle in (a) represents the region used for the fitting. (a) Image captured by the radar. (b) Simulated image with TLS fitting and tail adjustment. (c) Simulated image with TLS fitting. (d) Simulated image with piecewise MSE optimization.

Fig. 14. Measured angular backscattering response and simulated models of a human target.

negligible. Moreover, this could be the reason why the measured backscattering responses for human models are much noisier than those of the mannequin. Besides, in this case, not only the measured backscattering response is noisier, but the original image appears to be more degraded than in the mannequin case, as seen in Fig. 13(a).

Once again, TLS regression combined with a manual adjustment of the Blinn–Phong model yields the most perceptually

Fig. 15. Line scan at $y = 1.25 \pm 0.01$ m projected over z coordinate of Fig. 13(a) and (b).

Fig. 16. Influence of f_λ in BRDF curves.

Fig. 17. Influence of m in BRDF curves.

comparable images, as seen in Fig. 13(b). Furthermore, Fig. 15 validates the model by showing how the simulator is able to correctly characterize the position of the maximum reflections and follows the overall angular backscatter trend.

Fig. 18. Influence of r_s in BRDF curves.

Fig. 19. Influence of α in BRDF curves.

VI. CONCLUSION

A ray-tracing framework for the simulation of THz scattering in concealed object detection setups has been proposed. It has been shown that the system is flexible and lightweight. BRDF rendering can simulate a great range of scattering behaviors with low complexity, allowing the framework to adapt to almost any kind of target.

Besides, the proposed experimental setup has been shown to be an effective method to estimate the BRDF parameters of different materials, such as paint-coated glass fiber and human skin. Understanding these results is crucial to gain insight into the scattering behavior of targets in this band and can serve as a basis to study the best radar configurations.

In the longer term, an extensive experimental campaign will be run in order to produce a comprehensive BRDF database of materials. This database will be used to simulate realistic measurements of the radar system that could be employed to train automatic target recognition classifiers and design new multistatic radar architectures.

APPENDIX

PARAMETERS INFLUENCE IN SCATTERING MODELS

In this appendix, the effect of modifying each of the parameters value in the scattering model is discussed.

Fig. 16 shows the influence of the f_λ parameter in the BRDF curve. As f_λ gets bigger, the height of the specular highlight increases uniformly.

Fig. 17 shows the influence of the m parameter in the BRDF curve. As m gets bigger, the width of the specular highlight increases, while the height of this specular lobe decreases.

Fig. 18 shows the influence of the r_s parameter in the BRDF curve. As r_s gets bigger, the height of the diffuse term increases uniformly.

Fig. 19 shows the influence of the α parameter in the BRDF curve. As α gets bigger, the width of the diffuse term decreases, while the height of the diffuse component increases.

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