

A Novel Method of Radar Modeling for Vehicle Intelligence

Jiao Guo, Weiwen Deng, Sumin Zhang, and Shiqian Qi
Jilin University

Xin Li
Jilin University; Aviation University of Air Force

ABSTRACT

The conventional radar modeling methods for automotive applications were either function-based or physics-based. The former approach was mainly abstracted as a solution of the intersection between geometric representations of radar beam and targets, while the latter one took radar detection mechanism into consideration by means of "ray tracing". Although they each has its unique advantages, they were often unrealistic or time-consuming to meet actual simulation requirements. This paper presents a combined geometric and physical modeling method on millimeter-wave radar systems for Frequency Modulated Continuous Wave (FMCW) modulation format under a 3D simulation environment. With the geometric approach, a link between the virtual radar and 3D environment is established. With the physical approach, on the other hand, the ideal target detection and measurement are contaminated with noise and clutters aimed to produce the signals as close to the real ones as possible. The proposed modeling method not only makes it feasible, safe and convenient to develop and test radar-based Advanced Driver Assistance Systems (ADAS) under various simulated scenarios and environment efficiently at lower cost, it also achieves good balance between model fidelity and computational efficiency. The proposed method further enables real-time simulation under a Hardware-In-the-Loop (HIL) platform. Extensive simulation such as Adaptive Cruise Control (ACC) has been conducted under Matlab/Simulink platform with a Simulink model automatically generated by PanoSim, and the results demonstrate that the proposed radar modeling method is valid and effective.

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I. INTRODUCTION

As one of the ultimate solutions to traffic safety and vehicle performance, intelligent vehicle is gaining momentum. Radar detection system plays a key role on environmental perception for intelligent vehicles. Although field experiment has been traditionally dominating in vehicle development, it is not an efficient or even safe way in developing and testing radar-based ADAS for ACC, collision avoidance, and etc. It is hard or sometimes even impossible to set up such field environment that could cover large variations, great uncertainties and complexity of real driving scenarios. Besides high cost, long duration, lack of flexibility, and worse yet, lack of guaranteed safety, limited field experiment can hardly ensure system robustness and reliability. The steadier detection performance, that is, affected slightly by environment like atmosphere, and low cost compared with Light Detection And Ranging (LiDAR), the longer detection range up to 300 meters compared to ultrasonic radar, and the ability to detect the relevant velocity makes millimeter wave radar widely used in ADAS applications by now. So this paper intends to propose a millimeter wave radar modeling method of high fidelity with the abundant driving environment provided by PanoSim [1] aimed to maximum the meaning of virtual simulation experiment before field experiment in the minimum cost.

There are indeed lots of radar simulation solutions resulted in mature commercial products in different domains like ENDOCOM in medical domain, MultiPASS and OP2H in telecommunication, WinPROP, FERMAT and so on in environment perception [2]. The first two solutions are based on statistical modeling and hardly meet the requirements of complex dynamic situations. This paper focuses on automotive radar simulation solutions to be discussed in detail next.

The technologies in prior research on radar modeling for automotive applications are mainly through function-based approaches, physics-based approaches or both [3].

The function-based modeling approach mainly focuses on the functions of radar detection and measurement with little detail on its physical components and working mechanism. In this approach, the radio wave that radar fires is treated as a confined geometrical shape, such as a cone; the targets to be detected are modeled as a collection of polygons, bounding box or just scattering center for the sake of computational efficiency. Radar detection is abstracted as a solution of the intersection between the geometrical representation of radar beam and the targets. However the simulation result is ideal and often unrealistic.

There have been mainly two ways to model radar in a physics-based approach. One approach is to model radar components with electromagnetic and electronic circuits software and concurrently to simulate the propagation channels usually by means of “ray tracing”. This approach can be very time-consuming and often real-time prohibitive [4]. The other approach is signal-based that synthesizes radar signal echoed from the targets and other objects in the driving environment with clutter and noise that affect radar detection with various physical factors [5][6].

Then this paper presents a novel radar modeling approach, of which the architecture is depicted in Section II. This novel approach primarily consists of two modules. The first one, geometric model is discussed in Section III and the second one, physical model is described in detail in Section IV. Section V shows the independent validation of physical model in Matlab/Simulink and the integrated validation of the whole model in Matlab/Simulink and PanoSim. Finally the paper concludes in Section VI.

II. DESCRIPTION OF MODEL ARCHITECTURE

The architecture of the proposed radar model is shown in [figure 1](#) below. At first, it is necessary to clear the differences between the two conceptions, “Radar Model” and “Radar System Model”. Radar, an acronym for radio detection and ranging, is an object detection system which fires electromagnetic wave into the surrounding environment, then receives and processes its echo signal reflected, so as to determine the range, range rate and angle of objects.

To abstract the function of radar, if treat the actual radar as a black box, then the input of this black box should be the surrounding environment information and the output should be the detected result. Thus the black box and its input and output composes the radar system. Accordingly in the virtual world depicted in [figure 1](#), the red frame named radar model is equivalent to the actual radar or the black box. Note that the block of environment model refers in particular to infrastructure like buildings, ground, trees, bush and transport facilities, excluding the active transport participants like all kinds of vehicles and pedestrians, what the block of target model exactly means. The block of RCS estimation serves as the response of objects to the radar EM-wave which will be discussed more detailed later. These three blocks provide a complete input information to the radar model and the detection output which is not expressed in a block flows into the ACC controller as input. Hence all the blocks except ACC controller composes the radar system model as blue frame shows.

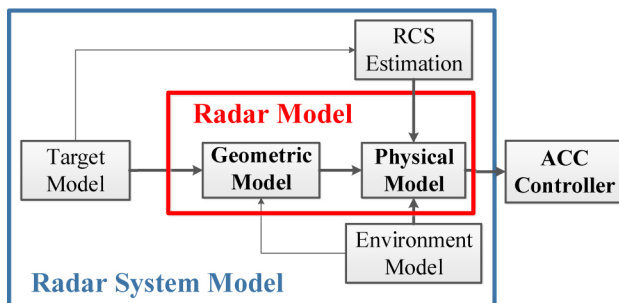


Figure 1. The Architecture of the Novel Modeling Method.

III. GEOMETRIC MODELING APPROACH

This paper firstly adopts a geometric modeling approach to establish the link between the object information and the radar without concerning about any details of physics factor. In this approach, the object to be detected is abstracted as a set of pre-defined Points of Shape Characteristics (PSC) illustrated in [figure 2](#), the EM-wave radar fires is represented as a closed geometry created by an elliptic cone and a plane, and then the radar detection process is transformed into a problem to find out the PSC illuminated by the EM-wave, or radar beam. These illuminated PSC should meet the following two conditions: a) located inside of the radar beam geometry; b) not blocked by other objects, that is, there exists no objects, not PSC, on the line from the radar beam firing point to the illuminated PSC. Then among these PSC, find out the closest point to the radar of each object and transmit them to the physical model.

Geometric Representation of Objects

The object in general refers to any moving or stationary things that may fall into radar RVV and generate echo signals physically. To discretize a complex object in terms of its shape, a set of points are pre-defined that capture the major characteristics of the object shape (PSC), such as vertices, center, edge, etc, as illustrated in [Figure 2](#).

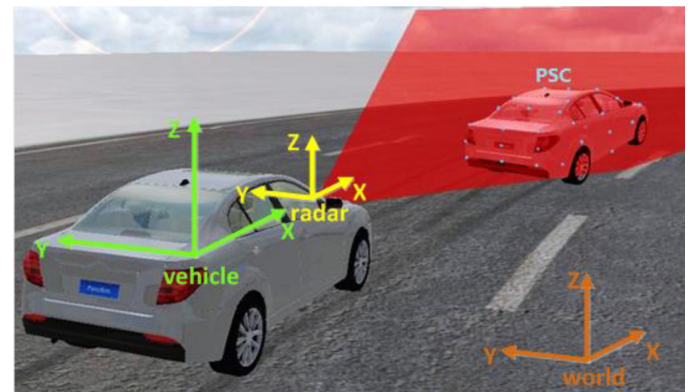


Figure 2. Points of Shape Characteristics and Coordinate systems

Geometric Representation of Radar Beam

As [figure 3](#) shows, the radar beam is assumed to be a close geometry named Radar View Volume(RVV) created by an elliptic cone and a plane and have the three property parameters: range R , azimuth angle α , elevation angle β . The RVV geometric representation is defined in the [equation \(1\)](#) where $[x, y, z]$ denotes the coordinates of a 3D point.

$$\begin{cases} \frac{x^2}{\left(y \tan \frac{\alpha}{2}\right)^2} + \frac{z^2}{\left(y \tan \frac{\beta}{2}\right)^2} \leq 1 \\ y \leq R \end{cases} \quad (1)$$

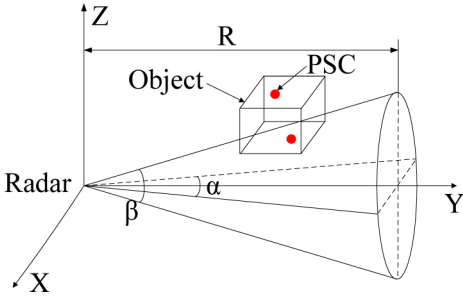


Figure 3. Radar View Volume(RVV).

Geometric Representation of Detection Process

In order to determine which sets of PSC are falling into RVV and not blocked simultaneously, the premise of detection process is to unify the coordinate systems. Then find the special PSC that meet the demands quickly with a series of steps taken.

A. Unify the Coordinate Systems

Considering that RVV has accurate and succinct mathematical expression and the point coordinate is easy to be converted, so transform the coordinates of PSC from world frame to vehicle frame and actually to radar frame, as shown in figure 2.

First, to transform the coordinates of a point $P_w [x_w, y_w, z_w]$ given under world frame to vehicle frame, denote the position of vehicle or the origin of vehicle coordinate system under world frame by $T_v [X_v, Y_v, Z_v]$, and orientation of vehicle (in yaw-pitch-roll sequence) or the Euler angles (Gillespie, 1992) by $[\psi, \theta, \phi]$, then the coordinate of the point under vehicle frame can be expressed as follows

$$[x_v, y_v, z_v] = [x_w, y_w, z_w]R_w^v + [X_v, Y_v, Z_v] \quad (2)$$

Where the rotation matrix is given by $R_w^v = R_{x,\psi}R_{y,\theta}R_{z,\phi}$:

$$R_{x,\psi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & \sin\psi \\ 0 & -\sin\psi & \cos\psi \end{bmatrix}$$

$$R_{y,\theta} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}$$

$$R_{z,\phi} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

To obtain a homogeneous transformation matrix defined as $H_w^v \in R^{4 \times 4}$ considering both rotation and translation for the sake of format conciseness, add a dimensionality to the point coordinate, thus equation 1 is turned as follows:

$$[P_v \ 1] = [P_w \ 1]H_w^v$$

$$H_w^v = \begin{bmatrix} R_w^v & 0_{3 \times 1} \\ T_v & 1 \end{bmatrix}$$

Similarly, the transformation from the vehicle frame to the radar frame can be represented by the homogeneous matrix H_v^s :

$$H_v^s = \begin{bmatrix} R_v^s & 0_{3 \times 1} \\ T_s & 1 \end{bmatrix}$$

Thus the total transformation formula of a point from world frame to sensor frame can be defined as

$$[P_s \ 1] = [P_w \ 1]H_w^s \quad (3)$$

where $H_w^s = H_w^v H_v^s$

B. Detailed Detection Process

The key problem to the radar detection process of the virtual world is how to screen PSC to get those special ones which are “visible” to the radar beams quickly. Consequently this paper adopts the approach of Axis Aligned Bounding Box (AABB) among others to achieve this goal. As illustrated in figure 4, AABB is defined as the minimum hexahedron that encloses object and of which each edge is parallel to the coordinate axis. The coordinate of AABB vertices can be easily calculated through the maximum and minimum values of the mesh point coordinate of objects.



Figure 4. Axis Aligned Bounding Box (AABB)

The figure 5 shows the flowchart of the detailed detection procedure of which the function is accomplished primarily by four steps of judgement highlighted by four yellow diamonds. Firstly, in view of the fact that the 3D scene is far greater than the radar beam and there generally exists plenty of objects which are definitely can not be detected by radar, this paper adopts quadtree to establish and query the 3D scene. A quadtree is a tree data structure in which each internal node has exactly four children. Only those AABB located in the same node as radar beam, namely, the so-called minimum visible zone, go on with the next judgement and other AABB with the sets of PSC enclosed are excluded. Secondly, according to the different position relationship of AABB and RVV (figure 3 shows one situation that AABB lies partly in RVV), choose different measures. Then the following two procedures deal with PSC instead of AABB.

Eventually the detection information (relevant range, range rate, angle) the radar geometric model outputs can be easily calculated based on geometric relationships. Note that among all the visible PSC of one object detected, only the closest PSC to the radar should be converted as detection information.