Advances in Two-Dimensional and Three-Dimensional Laser Imagery Modeling

Gerard Berginc[1]

[1]THALES, 2 avenue Gay-Lussac, 78995 Elancourt Cedex, France, gerard.berginc@fr.thalesgroup.com

Abstract

Laser radar (Ladar) technology has enjoyed significant advances over the past decade. Novel focal plane areas, compact laser illuminators and advanced signal processing have enabled the construction of low power 2-D and 3-D laser imagery systems. The applications of such systems range from surveillance, targeting and weapons guidance to target identification. This paper deals with modeling of new optical non-conventional imaging with laser systems. In this paper, we present the simulation of the 3D ladar sensor including physics based modeling of laser backscattering from complex rough targets, reflectance modeling of porous occluders, development of 3D scenes and reconstruction algorithms for identification. This paper addresses the utility of physics based scene simulation in support of tomography algorithms for reconstructing optical three-dimensional scenes. This includes a review of the physics and phenomenology that can be modeled and examples of scene.

1. Introduction

This paper addresses modeling of new optical non-conventional imaging with laser system or ladar (Laser detection and ranging). Optical remote sensing can be divided into passive and active categories based upon the source of the light. Passive systems detect natural sources, such as the sun or blackbody radiation due to the temperature of an object. Laser systems use a laser source (burst illumination laser technique for example), that can be controlled by the user and tailored for specific applications. In addition, the availability of near infrared lasers and near infrared focal plane array can make the system practical and cost efficient. The eye-safe property of wavelengths around 1.5 µm is perfectly suited to active laser imagery applications. Laser active systems provide high-resolution day and night imaging. These systems have several distinct technological and practical advantages over passive imaging systems making them attractive alternatives, or at the very least, complementary components to existing infrared imaging technology. An interesting feature of active imagery is the capability to provide depth position of the target with respect to the background. Optical non-conventional imaging explores the advantages of active laser imaging to form a three-dimensional image of the scene. 3D ladars can be used for three-dimensional topography, surveillance, robotic vision, enhancing operations in public safety and combat identification because of ability to detect and recognize objects hidden behind porous occluders, such as foliage and camouflage. In this paper, we present the simulation of the 3D ladar sensor including physics based modeling of laser backscattering of complex rough targets, reflectance modeling of porous occluders, development of 3D scenes and reconstruction algorithms for identification. This paper provides a more detailed look at scene modeling and suggests directions for the future evolution of modeling and simulation. Our goal is to show how physics based modeling of the imaging chain can be used to relate scene characteristics or phenomenology.

This paper is organized as follows. A description of the physics based model is given in Section 2. In order to see how these physics based tools can be used, emphasis is placed on 2D imagery modeling. Section 3 covers 3D reconstruction algorithms, which are needed to post-process the raw ladar data. Finally, this paper serves to assemble some recent significant examples of 3D reconstruction simulation in the context of emergent tactical applications.

2. Description of the physics based model

The 1.54 µm band is especially attractive for 3D laser imagery applications where eye-safety is of concern. This band pose little chance for damage to retinal tissue at nominal power levels. Detector technology is critical to enabling 2D or 3D laser imagery. Competing focal plane area in the 1.5 µm band are constructed from III-V materials such as InGaAs. Silicon is used for shorter wavelength laser systems that operate in the 1.06 µm band.

The modeling (Fig. 1) includes the physical structure of the environment, the transfer of radiation through the environment, and the interaction of the laser wave with the structure of the different elements of the scene. The results of our models are well validated against real data for a range of sensor systems [1-2]. These models incorporate a detailed understanding of the interaction of the electromagnetic wave [1]. The simulation results are highly accurate

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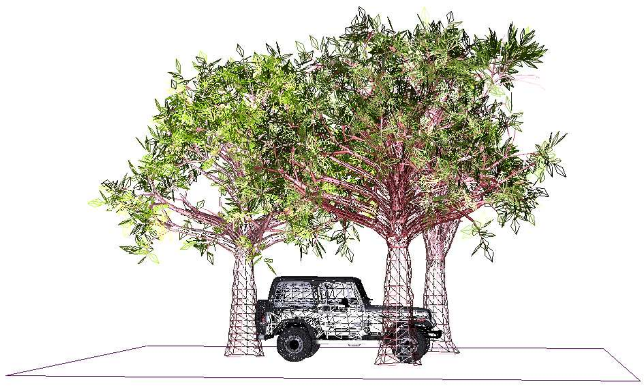
(Fig. 1). The first step of the 3D ladar simulation process is the generation of a scene of interest which consists of many types of objects: buildings, trees, vehicles. The vehicles are often obscured by other objects. A CAD model of the scene is generated (Fig. 1). We must notice that one of the most critical parts of the simulation is the generation of high fidelity scene models. The scene is described by a geometric database which is a representation of the world in the form of facetized surfaces making up terrain, trees and all 3D objects on the surface. Facets are flat triangles. The motion of the platform is simulated by different view points of the CAD model. The second step contains the simulation of the receiver, the transmitter and the optics system. For the transmitter, we define the wavelength, the laser pulse and the temporal convolution of the laser signature of the scene with the laser pulse. For the receiver, we simulate the response of the different types of detectors we can use: detection and false alarm probabilities, detector response function, noise sources. The blurring caused by the optics of the system is simulated. The simulation of the system can also contain scanning schemes.

The third step is the modeling of the electromagnetic scattering from the different objects of the scene [1]. The physics based modeling approach attempts to model the imaging process based on computer simulations of the fundamental electromagnetic interactions. In practice, it usually consists of a mixture of mathematical expressions of physical process, approximations of scattering theory and statistical functions. Our physics based model is designed to provide accurate results but to also include all of the electromagnetic interaction mechanisms. The surface of the different vehicles or hard targets is considered as randomly rough surfaces and we compute the laser signature (laser cross-section) of the vehicles. To model the laser interaction with the randomly rough surface, we use the second order Small-Slope Approximation method. Because the problem, we consider in this paper, is three-dimensional, all the scattering coefficients (coherent and incoherent component of the electromagnetic field) are functions of the azimuth angles, and the cross-polarized terms do not vanish. We define, in this case, the Mueller matrix, which gives all the combinations of the polarization states of the scattered electromagnetic waves. The randomly rough surfaces of the complex object are characterized by electromagnetic parameters (permittivity...) and roughness parameters (standard deviation of rough surface height and autocorrelation function). Our model addresses also transparent structures. With this model, we can obtain high temporal resolved laser backscattering from complex objects. For example, we may need a physics based description of the laser scattering by trees, buildings. The value of the scattering coefficients due to the structures of trees, buildings used in the scattering equation is derived from empirical measurements rather than SSA model. Our intent is to capture the link to the underlying physics while maintaining a tractable model. Thus, buildings and trees are modeled by polarized reflectance applied to the different facets generated by the CAD model.

The fourth step contains the absorption and scattering of the laser wave by the components of the atmosphere, the simulation of the atmospheric turbulence effect: speckles, scintillation, beam spreading, beam wandering.

The last step of the simulation contains the development of three-dimensional reconstruction algorithm to obtain a high-resolved three-dimensional image. This computer model can help predict 3D ladar performance and it is used to develop 3D reconstruction algorithm [2-3]. With this scattering model, we can calculate the total intensity scattered by the scene (Fig. 1).



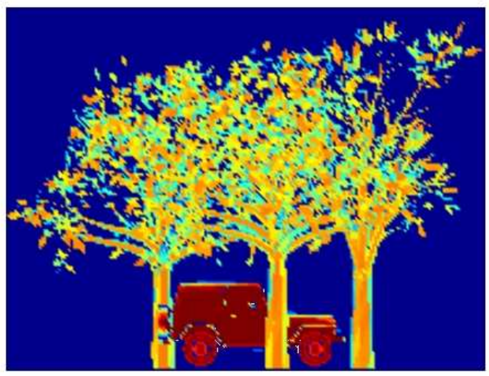


Figure 1. CAD model of the scene and scattered intensity

3. Examples of 3D reconstruction

In this section, we shall focus on tomography algorithms for reconstructing optical three-dimensional scenes. Fig. 2 describes the scenario used for the 3D reconstruction of concealed vehicles and represents the CAD model of the air-to-ground scenario. The occultation rate depends on the zenithal angle. The rate varies from 30% to 55%. Most of the incident laser energy is reflected, scattered or absorbed by the foliage, a small amount can reach the target, this energy is back-scattered by the target towards the focal plane area of the sensor. The sensor collects two-dimensional intensity images from which target recognition can be improved. We propose an alternative approach to the 3D reconstruction problem by taking advantage of the properties of scattered intensity, instead of using the scattering profile of the object. We use a cone-beam algorithm, the Feldkamp algorithm which is a convolution-backprojection algorithm deduced from the Radon transform [3]. It uses a set of two-dimensional projections. In our case, these sets contains the data collected by the pixels of the planar detectors. These data are related to the intensity scattered by the scene illuminated by a laser pulse. This 3D reconstruction requires a laser system of lower complexity than in the case of a 3D range-profiling concept.

Figure 2. Description of the scenario and the motion of the platform

These theoretical results allow the reconstruction of a 3D scene from a series of images parameterized by an angle of axial rotation. In Fig. 3, we give a full 3D reconstruction of a vehicle for the scene of Fig. 2 without trees. The reconstruction of the object is made of volumic pixels (voxels) whose color is related to the intensity of the scattering process. The laser wavelength is 1.54 µm. The range between a the scene and the sensor is about 500 meters.

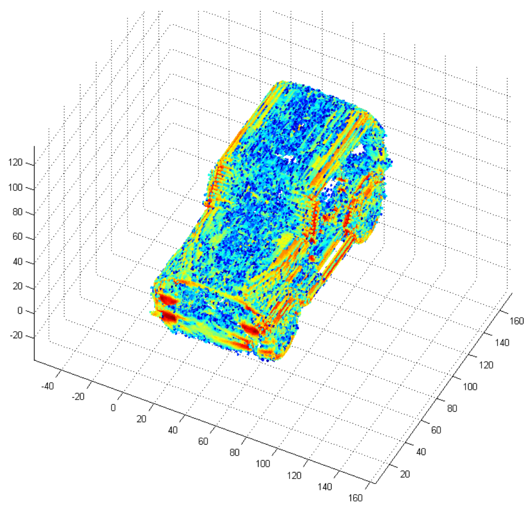


Figure 3. Full reconstruction of the vehicle (scenario of Fig.2 without trees), the color of the voxel is related to the intensity of the scattering, the incident laser wavelength is not polarized, the laser wavelength is 1.54 µm.

In Fig. 4, we show the reconstruction of a vehicle behind canopy. With the three-dimensional reconstruction algorithms, we have developed, we can obtain a high-resolved three-dimensional image of objects behind occluders. The 3D reconstruction process can separate the vehicle from the canopy of the trees. Thus, we can identify the concealed vehicle. In particular, this simulation shows the potentials for identification of concealed vehicle with 2D laser imaging and 3D tomography imaging.

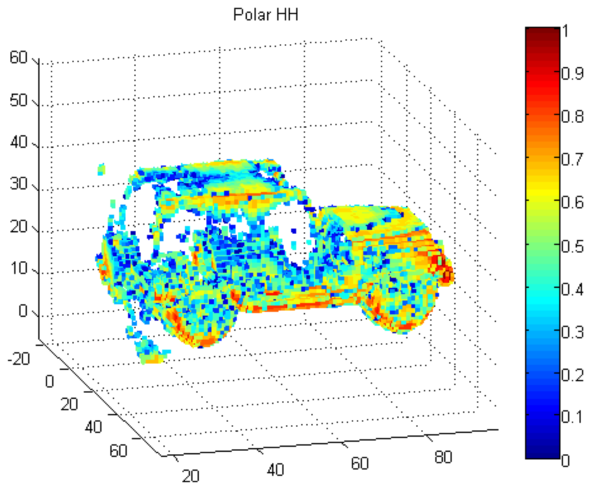


Figure 4. 3D Reconstruction of a vehicle concealed behind a canopy (Air-to-ground scenario), the polarization component is HH.

5. Conclusion

We have presented a general simulation of the laser cross-section of a scene illuminated by a laser pulse. The calculations of the laser cross-section provides data sets with which we can reconstruct a 3D image to identify concealed vehicles. This computer model can help to predict the performance of 3D reconstruction. We have proposed a 3D reconstruction algorithm based upon a Radon-type inversion. This algorithm generates a new original imaging process. With these reconstruction procedures, we can separate objects from forest canopy and reconstruct a three-dimensional image of the considered object. We have illustrated an application with numerically generated data, which simulate laser imagery data. We have demonstrated that it can provide 3D images of camouflaged vehicles. This high fidelity model of 3D laser imagery can support sensor development and algorithm design.

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7. References

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