LIDAR sensor simulation in adverse weather condition for driving assistance development

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Abstract

We present a new LIDAR modelling for automotive applications. Many simulators already exist for this problem, but most of these simulators represent only a punctual modelling of the LASER impacts or cannot simulate the real-time LIDAR operation. The model considers the LASER beam propagation as well as the attenuation of LASER energy not only in clear weather, but also under harsh weather conditions such as fog and rain. The main objective from a LIDAR sensor point of view is to detect all the targets within the observation zone and simultaneously estimate the distance and relative reflectivity of the target in real time. The use of this sensor simulation can easily and effectively replace real LIDAR test campaigns to measure their performance. By comparing real sensors with our model, we demonstrate that this virtual sensor accurately reproduces real LIDAR sensors' behaviour.

1. Introduction

The concept Light Detection and Ranging (LiDAR) technique with high vertical accuracy has been developed across the last decades [1]. LIDAR is used such as range finder [2], detecting [3] and recognizing objects [4, 5, 6, 7] and has been emerged as a vital sensor in robotic-vehicle prototypes in addition to embedded cameras [8, 9 ,10], RADAR [11, 12] and ultra-sonic on vehicles. The LIDAR can monitor 360° around the vehicle and continuously captures high definition data from the environment as point clouds. Such a sensor makes use of multiple scanning layers in order to be able to detect obstacles at different heights even when the pitch of the vehicle changes.

This renders it a premium choice for a perception system on a vehicle. However, as advanced as the LIDAR may be, no current single sensor system guarantees a perfect accuracy of the measurement. Ensuring the reliability of an intelligent vehicle's perception systems is recognized as one of the challenges for the transition to the higher levels of autonomous driving. Safety is enforced using sensors exploiting different optical systems such as camera, laser and radiofrequency – with their very specific detection processing and sensitivity to the environment characteristics. Due to the complexity of testing such systems, considering the multiplicity of sensors and the variety of conditions to test, new testing processes are being evaluated. Physics-based simulation of sensors is

gathering traction to support testing such multi-sensor systems in the variety of real-world situations. Reliable simulation must take account physical complexity to obtain correct prediction of the causes of compromised detection [13]. In the case of Lidar sensor simulation, the only point modeling of the LASER beams is not enough, it is necessary to define more realistic models able to provide synthesis data much richer. Indeed, the LIDAR images quality depends mainly on the exploitation of scanning beams with configurable geometry in horizontal and vertical field of view. An energetic modeling of the received signals considering on the one hand a non-punctual character, and on the other hand, the geometry of the illuminated objects with LASER as well as their powers of reflection, diffraction, absorption in different climatic environments [14, 15]. Finally, the parameters of lasers like the wavelength and the transmitted power density must comply with eye-safety standards [16]. All these parameters affect the received signal by the detector and therefore the image resolution.
In this study we propose a new model for LIDAR simulation that covers rotational and solid-state technologies for self-localization and obstacle detection. The model covers most of the LIDAR parameters mentioned in a datasheet such as the spatial resolution, the data recording time. The laser pulse propagation in the environment for each emitted laser beam direction and on the target shape and material composition are addressed. With these considerations, the different energy return from any part of objects are correctly estimated [13, 14, 15]. In addition, the effects of sun glare on the detector as well as the laser energy attenuation under the fog [17, 18, 19] and rain [20, 21, 22, 23] effect are also considered. Simulating these effects increase the model realism of the capability of the lidar to detect or not its surroundings. This increase in realism during the test process enables a systematic testing of various conditions, including hazardous / uncommon situations, overall helping the autonomous system’s developer to qualify and gain confidence in the reliability of the system.

After presenting the simulation tool, we will describe a practical test case where the results of our LIDAR model are compared with experimental results published in [5]. A general discussion and our concluding are presented in the last section.

2. LIDAR sensors simulation in automotive area

The design and development process of the LIDAR lift up to majors challenges. On one hand the testing process of a sensor requires traveling thousands of kilometers in many types of urban and traffic environments [3, 4]. These tests must be performed day and night under different weather conditions (mists, rain, snow, ...). Ensuring that all required conditions are statistically met during the test phases is not trivial. On the other hand, the intrinsic parameters of a sensor as well as its location in a vehicle limit the field of view and therefore impact the collected raw data from the environment. The precise simulation of perception systems and the simulation of the global control loop bring real innovation thanks to the possibility of automated or semi-automated simulation of many scenarios, in which all hypothetical conditions and circumstances can be fulfilled. This allows to computerize and reproduce as in reality, including dangerous situations and almost impossible to play and replay in reality.

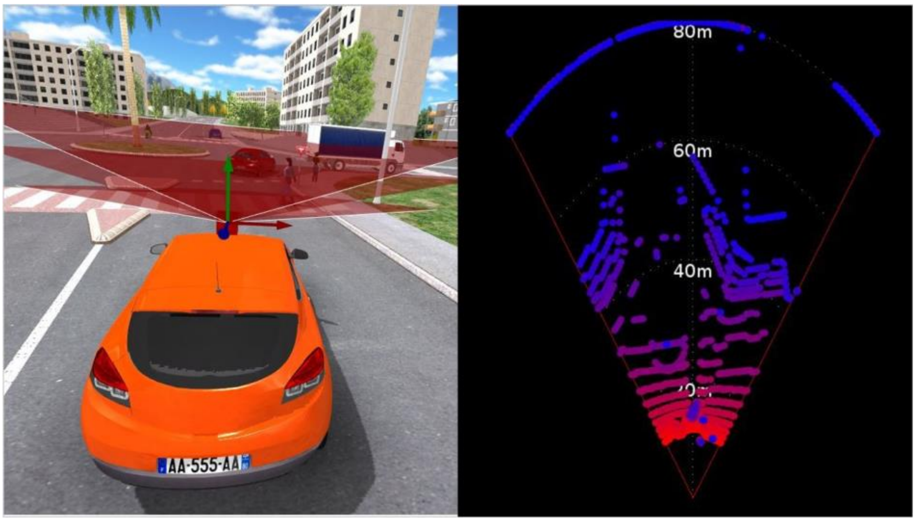


Figure 1: Automotive LIDAR illustration and 2D viewer.

The simulation of a LIDAR sensor is complex due to the physics involved. A LIDAR sensor usually performs the detection of targets, and measures some characteristics of those targets, such as the distance, speed, angular position. The LIDAR system uses lasers pulses with a selected wavelength from ultraviolet to infrared range. The emitter composed by a LASER sends the light pulses and triggers a timer. As shown in Fig 1, the objects which are in the LIDAR Field Of View (FOV) reflecting LASER light to the detector which is composed by an electro-optical system that transforms the light signal into an electrical signal. The electrical signal is then processed by an electronic chain to obtain the targets information (distance, speed and reflectivity). The detected object then appears as a point cloud in the LIDAR display. Then, the LIDAR images quality depends mainly on its resolution. Indeed, the image resolution can vary from one LIDAR to another depending on its horizontal and vertical aperture angles, the number of LIDAR layers and the number of LASER impacts per degree. In addition, the frequency at which images can be developed is affected by the speed at which it can be scanned into the system and create a high-resolution picture. Finally, the modeling of the LASER beams with a point model is not enough. The LIDAR image quality depends mainly on LASER beam propagation, energetic modeling of the received signals, geometry of the illuminated objects with LASER as well as their powers of reflection, diffraction, absorption, different weather condition (fog, rain, snow, sun intensity, ….).

3. Target reflectivity

From the LIDAR’s perspective, the real-world traffic can be seen as a mixture of different objects which have their own geometry, a given incident angle and a specific surface material composition. An object of the scene – for example a car – is composed by different materials: metal for body, plastic for bumper, glass for windows. The different materials of the car will reflect the LASER light with different intensities. It is then necessary to consider the laser-matter interaction in order to estimates the energy returned to the detector. We have used Pro-SiVIC tool, to simulate the variation of the signal to noise as a function of the distance between LIDAR and target for different material. The simulation test is illustrated in Fig 2, where the LIDAR is focused at first on the car windshield, then on the car body, and finally on the bumper.

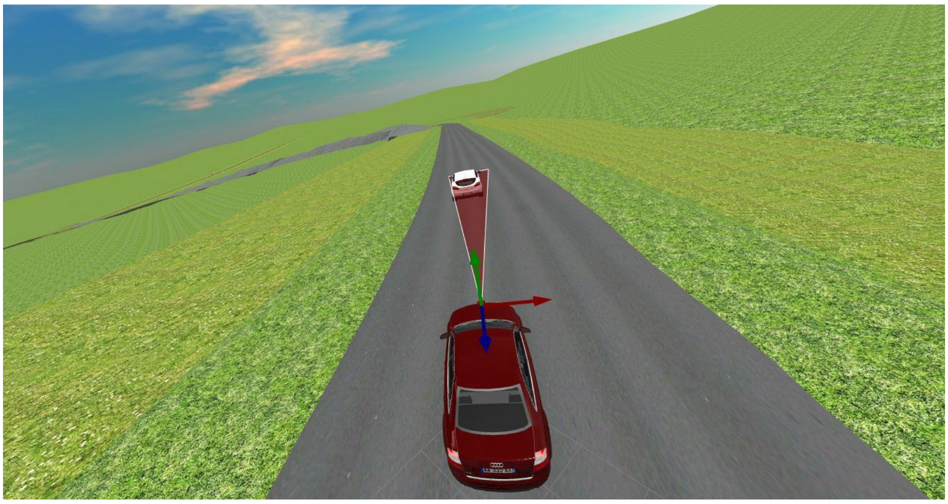


Figure 2: Reflectivity calculation example: The white car is stationary while the red car is in approaching. the LIDAR is placed in the front bumper and is focalized on the car body.

For the first simulation test we consider one LIDAR layer with an opening angle of 10 °. This layer is supposed to be composed by 11 LASER beams in which each beam has the following parameters:

Parameter	Value
Wavelength	905 nm
Pulse energy	1.6 µJ
Pulse duration	16 ns
Divergence	0.07 °

Table 1: LASER beam parameters

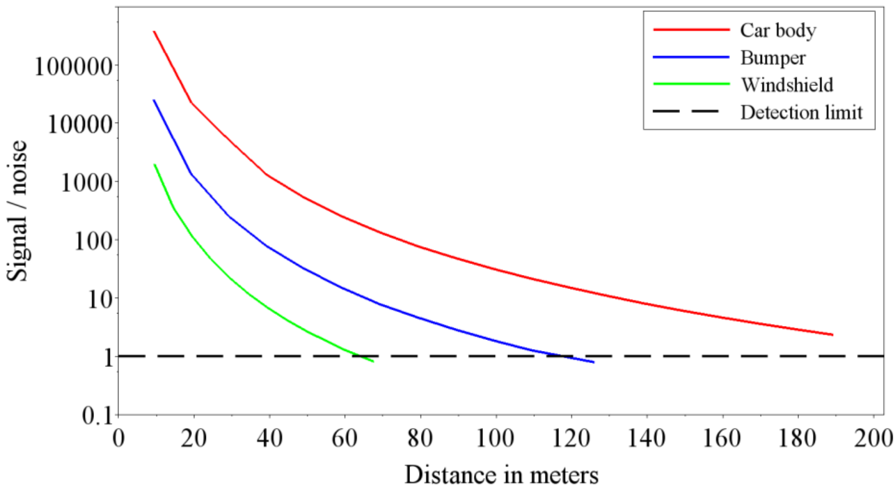


Figure 3: Variation of the signal/noise as a function of the distance between LIDAR and car target. Red curve: body car; Blue curve: bumper; Green curve: windshield; Black dashed line: detection limit

Figure 3 shows the variation of the signal to noise as a function of the distance between the LIDAR and car body in red curve, LIDAR and car bumper in blue curve and finally LIDAR and windshield in green curve. The dashed black curve represents the detection limit meaning the ratio signal to noise is equal to 1. Major remarks can be deduced from the Fig 3:

- For a fixed distance, the signal to noise values are higher for the car body compared to the bumper and windshield. This is explained by the material properties of the metal which is more reflective than plastic or semi-transparent objects like glass.
- The signal to noise decreases with the distance between LIDAR and car objects (body, bumper and windshield) according to the Beer-Lambert law.
- We can notice that the reflective objects like metal can be seen at long distances (190 m) by LIDAR compared to less reflective material (bumper) or semi-transparent objects (windshield). We define that the LIDAR range as the LIDAR ability to detect different objects as distance and material properties function.

Note that the LIDAR range can be increased by increasing the initial LASER power or by reducing the beam divergence. Similarly, the LIDAR is not dazzled by the sun in the night. The threshold detection value can bethen adapted to make more efficient the objects detection.

This experiment can be used to determine the LIDAR's ability to detect a known object based on distance by measuring the signal to noise and the following table gives the maximum range detection according to LIDAR parameters summarized in table 1.

Object name	Maximal range detection in meter
Container truck	237
Car body	232
Reflective road sign	142
Bicycle: front and back view	22
Bicycle: side view	45
Pedestrian: front and back view	58
Pedestrian: side view	59

Table 2: Maximal range detection of some objects

As expected, reflective objects with flat metal surfaces are detected at distances greater than 100 m. This is valid for container trucks, cars and road signs. For the moto-cycle and pedestrian, both maximal detection range are smaller than those of track, cars and road sign, because there are few or no flat or corner metallic parts. Note that the maximum value for the bicycle and pedestrian are when they are facing sideways the lidar, and this value is weaker when facing front and back. Also, note that the values in the table 2 may vary depending on the incidence and observation angles.

4. Weather effect on the LIDAR detection range

It is not easy to accurately operate and test the performance of a LIDAR under fog and rain conditions because of the non-control of the weather and its randomness. Several studies [13, 14 ,15] show that the moist air acts as a screen for the infrared radiation. Both fog [17, 18,19] and rain [20, 21,22] reduce laser intensity by absorption and diffusion phenomena of the LASER beam by the small water droplets. Fog and rain act then as a screen on LIDAR sensors that limit their capabilities and detection range. It is important to consider than the attenuation factor in order to adapt speed, braking distance and stability control systems accordingly.

4.1 Fog effect on LASER energy attenuation

Figure 4 shows the variation of the signal to noise of the central LASER beam as a function of the fog visibility and distance between LIDAR and car target. The laser beam is focalized on the car body where the different curves represent respectively:

Line color	Weather	Visibility value
Red	Clear	Up to 5 km
Blue	Mist	4 km
Green	Medium fog	400 m
Pink	Dense fog	40 m

Table 3: fog visibility values

We can see that the signal to noise decreases with the decrease of the visibility in exponential manner. A higher visibility value means that the particles density composed the fog (mist) of the atmosphere is light, the signal to noise in this case decreases only with distance. This result is represented by the blue curve which is practically superposed with the red curve in Fig 3.

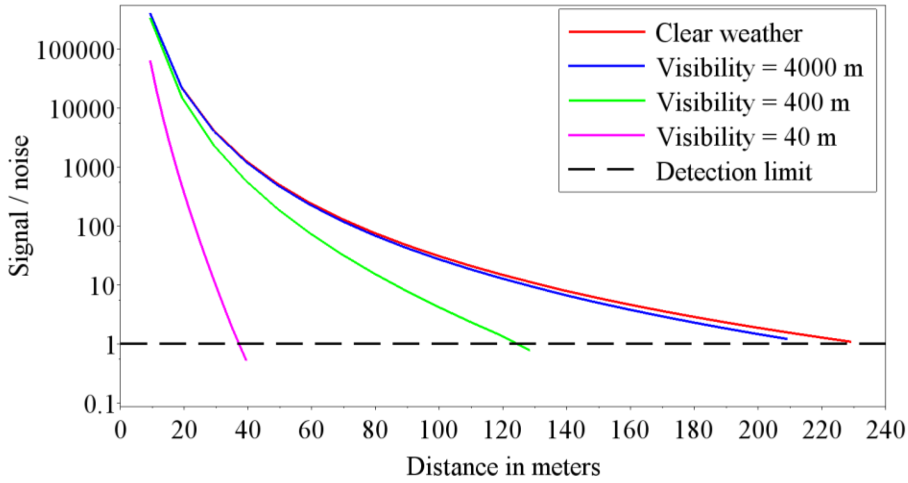


Figure 4: Variation of the signal/noise of the central LASER beam as a function of the fog visibility and distance between LIDAR and car target. The laser beam is focalize on the metal body car.

For medium fog density, the signal amplitude varies slowly with the distance and the LIDAR range decreases. This result is represented by the green curve in Fig 3. Note that the typical visibility values for a medium fog density are around of few hundred meters to 1 kilometer. The pink curve on Fig 3 shows the results for a high fog density (low visibility). In this case the signal amplitude as well as the detection range decreases rapidly with distance.

4.2 Rain effect on LASER energy attenuation

The rain density is related to the rain drop radius and the precipitation. To evaluate the rain precipitation during a rainfall, the amount of water reaching the ground at a specific location and for a given time interval, we measure the thickness of water that covered a horizontal surface. The fallen water had not been infiltrated on the ground or evaporates. The measurement of the thickness of water covering the surface of the ground, carried out by rain gauges, defines the height of precipitation observed during this time interval at the designated place. The rain quantity is expressed in millimeters / hour (mm/h). On the other hand, the size of a raindrop depends on the altitude at which it was formed and its own cohesive force [22]. Six millimeters is the maximum size that can be observed for a falling raindrop. Because, during its fall, the drop is subjected to a frictional force due to friction with the air. The superficial tension force that makes it cohesive becomes comparable to this friction force. When the drops are too large and reach the famous 6 millimeters in diameter, this friction force causes the explosion of the drop into fragments of smaller sizes.

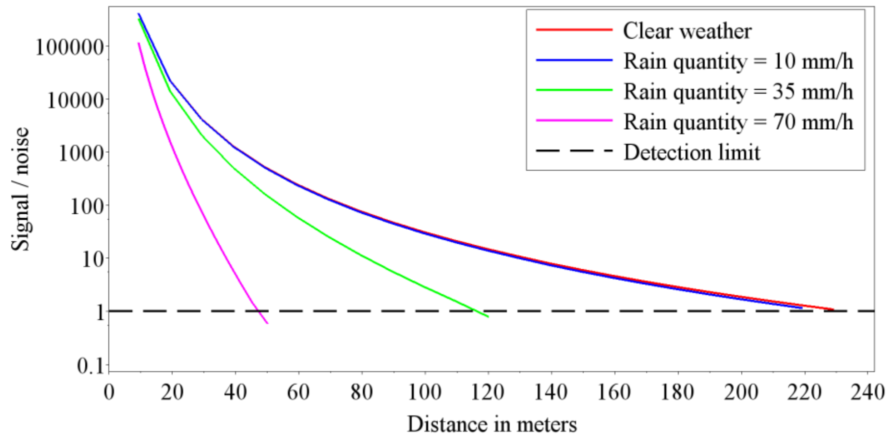


Figure 5: Variation of the signal/noise of the central LASER beam as a function of the rain quantity and distance between LIDAR and car target. The laser beam is focalized on the metal body car and the raindrop radius is equal to 3 mm.

Figure 5 shows the variation of the signal to noise as a function of the distance between car body and LIDAR for different rain quantities. The different curves represent respectively:

Line color	Weather	Rain quantity
Red	Clear	0 mm / h
Blue	Light rain	10 mm / h
Green	Normal Rain	35 mm / h
Pink	Heavy rain	70 mm / h

Table 4: rain precipitation values

red curve: clear weather, Blue curve: precipitation = 10 mm/h, green curve: precipitation = 35 mm/h and pink curve: precipitation = 70 mm/h. As can be seen in this figure, the LIDAR range and the signal to noise amplitude drastically decrease as the rain precipitation increases.

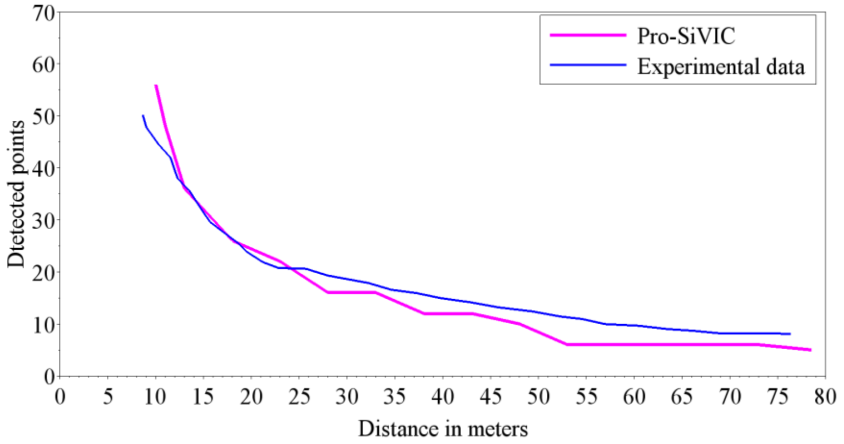
In this section, we presented the behavior of the LIDAR sensor in rainy and foggy conditions. Our conclusions agree with the conclusions published in the literature. A LIDAR provides a measure of distances and reflectivity’s of the targets that are easier to interpret and perfectly adapted to the creation of numerical models of the environment with great precision. However, their efficiencies are degraded in hazy and rainy environments. It is therefore essential to carry out numerical simulations to complete the experimental data and to determine for example the safety distance between cars for vehicle safety warning system. An application of this study is the comparison of the obstacle distance and braking safety distance which are used to determine the moving vehicle's safety distance is enough or not in different environment.

5. Model simulation and experimental data

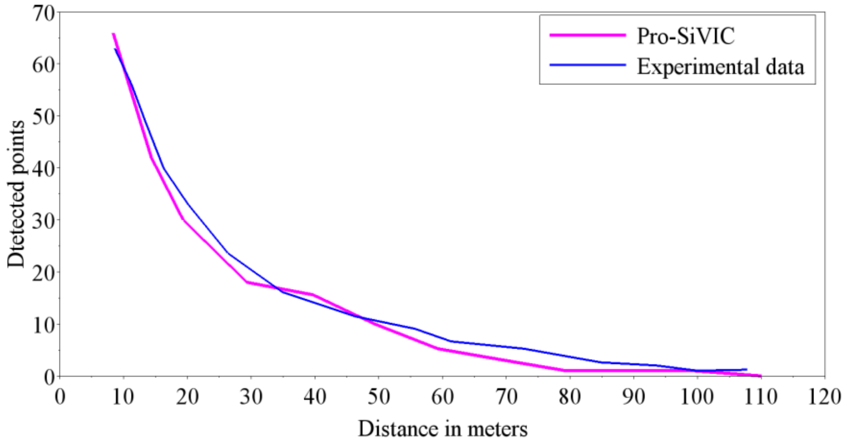
In order to test the reliability of our simulation model, we virtually reproduced an experiment published in [5], and we compare the numerical result with the experimental data. This experiment shows the detection of a car target by 2D LIDAR one long-range and the second is a short-range LIDAR both from SICK [23]. The two LIDARs are mounted in the bumper of a vehicle to perform several test sequences to compare the capabilities of each sensor. Several detection tests are described in the reference [5], and here we represent one of these tests. The chosen test consists in measurement of the detection points returned by a gray car target towards the detector as a function of the distance between the LIDAR and the target. The experimental and numerical results are shown in Figure (6 a) for the short-range LIDAR and Figure (6 b) for the long-range LIDAR.

As we can see in the two figures, the experimental data and numerical simulation are in good agreement with Pro-SiVIC simulation, where the different curves have the same shape and amplitude. The number of detected points decreases as the distance between the LIDAR and the car target increases. This behavior is common for any LIDAR type and can be explained by the decrease of the of the LASER intensity with the increase of the distance between the LIDAR and the car target.

We can note that the slight difference between the simulation and the experimental result is likely due to a lack of information, namely the weather condition of the day where the authors of the article have realized their experience, the exact position of the sensors, the threshold detection value of the two sensors. The simulation results shown here out are based on a clear weather without fog or rain and supposed that the solar intensity is equal to 1370 W/m².



(a)



(b)

Figure 6: Detected point as a function of the distance between LIDAR and car target. a) With short range SICK LIDAR LMS 291; b) With long range SICK LIDAR LRS 1000

Despite the lack of information, we show that an engineer who is user or designer of LIDAR sensor can perform a numerical study performances and validation tests before the machining phase, but also in order to find the optimal parameters for a best detection and objects recognition in different weather situation.

6. Conclusion

We have presented a numerical study of a LIDAR sensor simulation. This study was performed by using an implementation of the model in the simulation tool Pro-SiVIC where the new sensor model aims to simulate the raw data provided by a real LASER scanner. The model takes into account on the LASER pulse propagation as well as the attenuation of the energy under the weather condition. The model considers all objects reflectivity defined by LASER-matter interaction and the obtained simulation results are in good agreement with the experimental data. The level of realism achieved by this model makes it useable for helping decide which technologies are most suitable and improve the realism of virtual testing. Such a simulation tool can be expected to contribute to reduce the cost and time to develop application based on LIDAR sensors. In addition, it enables the replay of any scenario in a vast range of different climatic environment in order to analyze system performance and sensor robustness, which will help increase the confidence in the performance of such systems.

Several additional developments are planned to increase even further the realism of the model: LASER energy attenuation by snow and a sandstorm. Light filters effect; Speed measurement; LIDAR based on correlated photon techniques; Effects of absorption and diffusion of the laser light by the objects color and coatings. Indeed, it is shown in that the same materials with different colors emit a different laser energy which can lead errors in the reflectivity values.

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