Influence and analysis of atmospheric attenuation on the performance of virtual lidar

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Abstract: The complexity of research and development process and the diversity of research methods of intelligent connected vehicles increase the difficulty of establishing, integrating and verifying of virtual simulation experiments. In order to solve the problem of how to quantify the impact of weather environment changes on the virtual lidar in the simulation experiment, this paper first uses the derivation of the lidar range model and the analysis of the influence of atmospheric attenuation on the lidar range. Then, with the help of the empirical model of the attenuation coefficient of rain, snow, and haze, the curve fitting method is used to simplify the influence relationship so that it can be applied to the virtual simulation software of autonomous driving. Finally, the scene verification and evaluation of the quantification method of the lidar in the virtual environment affected by weather changes are carried out. The results show that this method effectively improves the restoration degree of the virtual simulation sensor while ensuring the calculation efficiency.

1. Introduction
Autonomous driving simulation experiment [1] has been the important way for the development of autonomous driving technology. It is to digitally restore the real world through computer modeling and virtual engine technology, and then use the reproducibility and execution of the simulation environment, and combine Vehicle dynamics simulation, sensor fusion simulation [2], parallel accelerated computing and other technologies can achieve objective testing, verification [3] and evaluation of automatic driving related algorithms. The self-driving car in the simulation experiment usually drives in a complex virtual traffic environment. As one of the virtual sensors [4], Lidar [5] needs to interact with the surrounding environment in real time to realize dynamic perception. Weather changes are one of the surrounding environments, such as abnormal weather conditions such as rain, snow and hail, and severe weather conditions with low visibility such as haze, sandstorm.

When the lidar works, it receives the laser beam reflected by the target surface after traveling through the atmosphere, and then calculates the shape, distance and other information of the target object through modules such as photoelectric conversion and data acquisition. When the laser travels through the atmosphere, part of the energy is lost due to absorption, and part of the energy is deviate from the original transmission direction due to scattering, so the actual received laser is only part of the transmitted laser. When the laser beam is transmitted in a complex, abnormal or severe weather conditions will seriously affect the detection performance of the lidar, which is mainly reflected in the impact on the detection range. The current calculation method of the impact is too complicated, which leads to the occupation of more computing resources.
2. Detection range model of lidar

The following will introduce the range model in the detection performance of lidar \(^6\). Assuming that the transmitting power of lidar is \(P\), the target distance is \(R\), the beam cross-sectional area of the laser irradiating the target is \(S_L\), and the angle between the illuminated surface of the target and the beam section is \(\alpha\), the illuminance of the surface is:

\[
E = \frac{P \cos \alpha}{S_L}
\]  

(1)

Assuming that the reflectivity of the target surface is \(\rho\), the light power reflected by the unit area illuminated by it is:

\[
P_e = \rho \frac{P \cos \alpha}{S_L}
\]  

(2)

The solid angle of the entrance pupil area \(S_e\) of the lidar receiving objective to the center of the illuminated area of the target is \(S_e/R^2\), assuming that the target can be diffusely reflected uniformly, the reflected power per unit area to the unit solid angle is \(P_e/\pi\), considering the transmittance \(\tau_o\) of the transmitting and receiving optical system and the atmospheric transmittance \(\tau_a\), the received laser power is:

\[
P_e = \frac{\rho}{\pi} \tau_o \tau_a \frac{S_e}{R^2} S
\]  

(3)

In the formula, \(S\) is the target area that is illuminated and in the field of view.

If the laser beam is completely irradiated on the target, there are:

\[
P_e = \frac{\rho}{\pi} \tau_o \tau_a \frac{S_e}{R^2} S
\]  

(4)

At this time, \(S \cos \alpha = S_L\), then we know:

\[
P_e = \frac{\rho}{\pi} \tau_o \tau_a \frac{S_e}{R^2}
\]  

(5)

Because the maximum detection range \(R_{max}\) corresponds to the minimum power \(P_{min}\) that the system can detect, therefore:

\[
R_{max} = \left(\frac{\tau_o \tau_a \rho P S_e}{\pi P_{min}}\right)^{1/2}
\]  

(6)

If a part of the laser beam irradiates outside the target, \(S_L > S \cos \alpha\), at this time \(S_L\) can be represented by the divergence angle of the laser beam. If the solid angle corresponding to the plane divergence angle \(\theta\) is \(\phi\), then:

\[
\phi = 0.25 \pi \theta^2
\]  

\[
S_L = 0.25 \pi \theta^2 R^2
\]  

(7)

At this time, the expression of the maximum detection range \(R_{max}\) is:

\[
R_{max} = \left(\frac{\tau_o \tau_a \rho P S_e}{0.25 \pi \theta^2 P_{min}}\right)^{1/4}
\]  

(8)

In summary, when the laser beam is all projected onto the target surface, the maximum detection range depends on the reflectivity of the target, the lidar transmit power, the pupil area of the receiving objective, the transmittance of the optical system and the atmosphere, and the minimum detectable power of the system. When the laser beam is not completely projected to the target surface, the maximum detection range of the system is not only related to the above factors, but also closely related to the area of the target illuminated by the beam, the beam projection angle, and the divergence of the laser beam.

3. Influence and analysis of atmospheric attenuation

Atmospheric attenuation is one of the factors that have a greater impact on the detection range of lidar. When the laser beam passes through the atmospheric medium, atmospheric molecules and aerosol particles will absorb and scatter the laser beam, resulting in weakening of the beam energy and the degree of weakening. Except for the wavelength, it is mainly related to the weather conditions at that time.

Scientists have conducted a large number of experimental determinations and summarized the attenuation effect of the laser and the atmosphere as: when the beam propagates in the atmospheric
medium, part of the photon energy is absorbed by atmospheric molecules and aerosol particles and converted into other forms of energy, and the other part deviates from the original propagation direction due to scattering, resulting in attenuation of the total energy. It can be expressed by Lambert-Beer law as:

$$\tau_\lambda = \frac{l_i}{l_0} = \exp(-\beta_\lambda L)$$ (10)

Among them, $l_0$ is the incident laser intensity, $l_i$ is the light intensity after the propagation distance $L$, $\tau_\lambda$ is the atmospheric transmittance after the propagation distance $L$, and $\beta_\lambda$ is the attenuation coefficient of the laser with the wavelength $\lambda$ in the atmospheric medium.

$$\beta_\lambda = K_a + K_s + \sigma_a + \sigma_s$$ (11)

Among them, $K_a$ and $K_s$ are the absorption coefficient and scattering coefficient of atmospheric molecules, respectively. Then $\sigma_a$ and $\sigma_s$ are the absorption coefficient and scattering coefficient of aerosol particles, respectively.

For lidar, the main molecules such as water vapor, carbon dioxide, ozone, and nitrogen in the atmosphere basically have no absorption effect, so it is in the micro-window area of atmospheric transmission. The absorption coefficient of atmospheric molecules calculated according to the standard atmospheric model is less than $10^{-6} \text{km}^{-1}$, the attenuation of the laser light due to the absorption of gas molecules is negligible relative to the scattering effect [7].

In addition, the lidar has selected the wavelength range that has less influence on the beam absorption during the design and manufacture. The most widely used wavelength is 0.8 $\mu m$~1.6 $\mu m$, of which 905nm is more common. Therefore, the effect of absorption on the attenuation of the beam is not considered for the time being. Scattering will be the main reason for the attenuation of laser transmission in the atmosphere.

3.1. Attenuation of rain and snow

For lidar, spherical rainfall particles can be regarded as large particles ($x = 2\pi a/\lambda \gg 1$), and the attenuation coefficient is independent of the wavelength and is only determined by the geometric cross section of the particle determined by the water content. On the basis of considering factors such as rainfall rate, temperature and humidity, related scholars have established a rainfall attenuation model, in which the formula for calculating the rainfall attenuation coefficient is:

$$\beta_{rain} = \sum_a \pi a^2 N_a Q_s \left(\frac{a}{\lambda}\right)$$ (12)

The use of this formula to calculate the attenuation coefficient of rainfall requires abundant experimental data, and there will be greater difficulties in actual use. Therefore, in the actual calculation, we use the following simpler empirical formula to calculate the approximate value of the raindrop scattering coefficient:

$$\sigma_{rain} = 0.21 r^{0.74}$$ (13)

In the formula, $\sigma_{rain}$ is the scattering coefficient caused by rainfall, $r$ is the rainfall rate.

The attenuation coefficient in snow is similar to that in rain. For the same water content, the attenuation of snow is between fog and rain. In snowy weather, the lower the temperature, the greater the attenuation coefficient; the smaller the visibility, the greater the attenuation coefficient.

3.2. Attenuation of fog and haze

For the attenuation of laser light caused by haze, it is usually estimated based on the atmospheric visibility that can reflect the aerosol concentration. Atmospheric visibility refers to the maximum horizontal distance that a person with normal vision can see and recognize a target from the sky background under the prevailing weather conditions. Usually the empirical model formula of the attenuation coefficient of haze is:

$$\beta_\lambda = \frac{3.912}{V_h} \left(\frac{0.55}{\lambda}\right)^q$$ (14)

In the formula, $V_h$ is the atmospheric visibility, $\lambda$ is the laser wavelength, $q$ is the wavelength correction factor, which is related to the visibility. Under different visibility conditions, the value of $q$ is:
The average visibility is generally 10~12km, and the visibility is particularly good, generally 23km. When the visibility is less than 6km, some scholars have revised the value formula of $q$:

$$
q = \begin{cases} 
1.6 & \text{Good visibility situation} \\
1.3 & \text{Average visibility situation} \\
0.585\sqrt[1/3]{V_b} & V_b \leq 6\text{ km}
\end{cases}
$$

The empirical formula only involves atmospheric visibility related to the concentration of atmospheric particles, and does not involve the physical properties of the aerosol particles themselves. The corresponding relationship between the comprehensive attenuation coefficient and visibility in typical different relevant weather is as follows:

| Weather conditions | Visibility | Attenuation coefficient |
|--------------------|------------|-------------------------|
| Heavy haze        | 40-70 m    | 392-220 dB/km           |
| Dense haze        | 70-250 m   | 220-58 dB/km            |
| Medium haze       | 250-500 m  | 58-28.2 dB/km           |
| Light haze        | 500-1000 m | 28.2-13.4 dB/km         |
| Misty haze        | 1-2 km     | 13.4-6.3 dB/km          |
| Fog or haze       | 2-4 km     | 6.2-2.9 dB/km           |
| Mist              | 4-10 km    | 2.9-1.03 dB/km          |
| Sunny             | 10-20 km   | 1.03-0.45 dB/km         |

4. Applied in simulation scenarios

The above is theoretical analysis of the impact of weather conditions on the performance of lidar. The following will conduct application experiments on the impact of rain, snow, and haze in simulation scenarios. The schematic screen of adjusting the weather in the simulation scene built by the simulation engine is as follows:

![Figure 1. Schematic screen of adjusting weather in simulation scenario (Upper left is afternoon, upper right is Fog and haze, down left is rain, down right is snow)](image-url)
4.1. Curve fitting of rain and snow attenuation

The precipitation intensity classification standard issued by the National Meteorological Administration is shown in the following table:

| Precipitation status         | Total precipitation in 24 hours | Total precipitation in 12 hours |
|------------------------------|---------------------------------|---------------------------------|
| Light rain                   | 0.1-9.9 mm                      | ≤4.9 mm                         |
| Light rain- Moderate rain    | 5.0-16.9 mm                     | 3.0-9.9 mm                      |
| Moderate rain                | 10.0-24.9 mm                    | 5.0-14.9 mm                     |
| Moderate rain- heavy rain    | 17.0-37.9 mm                    | 10.0-22.9 mm                    |
| heavy rain                   | 25.0-49.9 mm                    | 15.0-29.9 mm                    |
| heavy rain- Torrential rain  | 33.0-74.9 mm                    | 23.0-49.9 mm                    |
| Torrential rain              | 50.0-99.9 mm                    | 30.0-69.9 mm                    |
| Torrential rain- rainstorm   | 75.0-174.9 mm                   | 50.0-104.9 mm                   |
| rainstorm                    | 100.0-249.9 mm                  | 70.0-139.9 mm                   |
| Rainstorm- heavy rainstorm   | ≥250.0 mm                       | ≥140.0 mm                       |

According to this classification standard and the formula for calculating the raindrop scattering coefficient derived above, the relationship between the scattering coefficient and the rainfall rate is drawn as follows:

\[
\sigma_{\text{rain}} = 1.44 r_s \tag{17}
\]

Among them, \(r_s\) is the rainfall set in the simulation software, and the value range is [0, 1].

According to the relationship between the scattering coefficient and the attenuation coefficient, the relationship between the attenuation coefficient and the transmittance, the relationship between the transmittance and the detection range, then the coefficient is corrected by the empirical value, the relationship between the lidar detection range and the rainfall as follows:

\[
R = R_{\text{max}} e^{-3.6 r_s} \tag{18}
\]

We assume \(R_{\text{max}} = 200\) m, at this time, the relationship between detection distance and rainfall is shown below:
4.2. Curve fitting of fog and haze attenuation
Because the raindrop size is many times larger than the laser wavelength (about 3 orders of magnitude), the laser still has a high transmittance in the rain. The impact of haze on laser transmission is different from that of rain and snow. The attenuation of laser light by haze is generally greater, and with the gradual decrease of visibility, the laser attenuation is very fast. The relationship between the comprehensive attenuation coefficient and atmospheric visibility in haze weather is shown below:

![Figure 3. the relationship between detection distance and rainfall](image1)

![Figure 4. the relationship between attenuation coefficient and atmospheric visibility](image2)

Among them, the red circle is the original empirical data, the blue line is the polynomial (5th power) fitting result, and the red line is the exponential (e is the bottom) fitting result.

Similar to the attenuation of rain and snow, the relationship between the detection range of lidar and the amount of haze is:

\[ R = R_{\text{max}} e^{-5.4 f_s} \]  \hspace{1cm} (19)

Where \( f_s \) is the haze amount set in the simulation software and the value range is [0, 1].

We assume \( R_{\text{max}} = 200 \text{m} \). At this time, the relationship between the detection distance and the amount of haze is shown below:
Figure 5. the relationship between the detection distance and the amount of haze

5. Conclusions
In order to increase the degree of simulation reduction of the virtual sensor, in order to quantify the impact of the weather environment on the lidar in the simulation scene, this paper first derives the detection range model of the lidar, and then analyzes the influence of the scattering of gas molecules on the laser transmission in the atmosphere. Then according to the empirical relationship of the attenuation coefficient of rain, snow and haze, the attenuation fitting relationship of the rainfall rate and visibility to the lidar is determined. Finally, in the self-developed intelligent networked vehicle simulation software, the experimental application of the relationship between atmospheric attenuation is carried out, and the results show that the use of this method can improve the accuracy of the relative relationship between the lidar detection range and the atmospheric attenuation, and ensure the calculation efficiency under the premise, the restoration degree of the virtual simulation sensor is effectively improved.

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