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Mitigation of Mutual Interference among Laser Radarsfor Intelligent Driving

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ABSTRACT: *With the rapid progress of intelligent driving technologies, there are potential trends that more and more vehicles driving on the roads will implement laser radars. A brief review of mutual interference among pulsed laser radars will be presented, following with the typical frequency modulated continuous wave modulating technique. Then, the interference of pulse sequence modulation technique will be investigated, which shows an obvious drop of interference ratio compared with traditional methods. In addition to the range measurement, pulse sequence modulation is also demonstrated to have potential of measuring target speed by Doppler.*

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I. INTRODUCTION

Intelligent driving technologies are classified into two types: self-driving and network connected, among which self-driving vehicles are required to understand their driving environments by using sensors. There are many types of sensors that consists of intelligent vehicles sensing system, including radars, cameras, sonar, etc, each has their own advantages and drawbacks. Even the same type of sensor, there are more than one entity that are implemented on the vehicle body. Take laser radar as an example, typically, intelligent vehicles are implemented with a long range top laser radar, together with two side short-range laser radar and a short range back laser radar. Figure 1 shows an example of sensing system of the intelligent vehicle. From the figure, we see that there are not only many types of sensors, but also large quantities of the same type. According to the operating principle, sensors are divided into two groups: active sensing and passive sensing, among which passive sensing does not need to transmit energy toward targets (e.g. camera, infrared), while active sensing measures target information by transmitting energy (e.g. radar, including laser radar and millimeter wave radar).

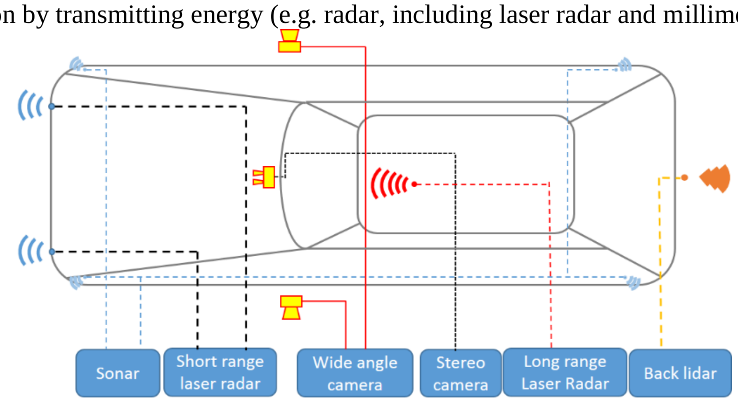

Fig. 1 An example of sensor network implemented on the intelligent vehicle

As passive sensing are easily affected by outside environments, active sensing is indispensable. Currently, radars use frequency modulated continuous wave (FMCW) signal, and has the ability of measuring range and speed simultaneously with single shot[1-2]. However, beam width of millimeter wave is wide so that spatial resolution is poor. Laser radar will inevitably replace part of millimeter wave radars to perform road environment 3D image sensing. Whether millimeter wave radar or laser radar, with the increasing demanding on environment sensing, more and more of them will be configured on the vehicle body. Thus, the interference among these sensors who transmit same wavelength energy will become a serious problem for further development of intelligent driving industry.

As millimeter wave radars transmit continuous wave with large beam width, the probability of their interference in road environments is large. There are many literatures investigating the mutual interference of millimeter wave radar[3-4] and the methods of mitigating such interferences[5-7]. Comparing to millimeter wave radar, laser radar has narrow beam width, so the probability of interference is much lower. For this reason, till present, laser radar interference has not gained enough attention. However, with the further development of artificial intelligence, the driving environments of intelligent vehicles gradually extend from structured roads to unstructured roads, which leads to the problem to be dealt more and more complex. Correspondingly, the quantity of laser radar implemented on the vehicle body becomes larger and larger, and the vehicles that are configured with laser radars become more and more. With this trend, interference of laser radar will become an important topic in the near future.

According to the source, laser radar interference are majorly categorized into two types: direct incident and reflection. The reflection interference is induced by the unwanted reflections from objects which enters the optical lens of victim laser radar detection terminal. The reflection may come from the transmitting signal of victim laser radar itself reflected by the multi-targets in a beam, or come from a target that reflectstransmitting signal of neighboring laser radar. The direct incident interference comes from the light beam of forward laser radars that directly enters the optical receiving lens of victim laser radar. For a pulsed laser radar, reflection interference would induce ghost target in measurements, which means that laser radar will give a location of an object that does not exist in reality. As the counterpart, the power of direct incident interference signal that achieve the surface of the photo diode of victim laser radar receiving terminal may be several tens Watts, as the transmitting power of pulsed laser radar is generally near 100W. The saturation power of normally used PIN photodiode is decided by the applied reverse voltage. In the receiver circuit, generally several tens of milli-watts incident power may cause the saturation of the photodiode. The saturation current may cover the reflection signal from the target, and cause laser radar blind.

For reflection interference,there exists algorithms such as spatial-temporal filtering[8]for improvingthe measurement quality that are reduced by the interference. Before the problem of mutual interference are totally solved, spatial-temporal filtering algorithm can be used as an effective method for dealing with reflection interference. However, for pulsed laser radar that transmits high peak laser pulses, direct incident interference is particularly difficult to deal with. On the whole, although the problem of laser radar mutual interference has been proposed, theoretical research on the interference is absent. The method for reducing interference is only a way for remedy when the interference happens.

Driving safety requires no interference between neighboring laser radars. For the purpose, we briefly investigate the basics of interference between pulsed laser radars, and discuss the possibility of using FMCW for vehicle laser radar. FMCW is now an on-the-way technology in optical field, because a triangularly chirped optical frequency signal is still not feasible. But we conclude that FMCW is not an efficient method for reducing the influence of interference, and thus it is not suggested as the signal waveform for vehicle laser radar. Finally, we proposethe pseudo-random noise (PN) code modulation as the transmitting waveform of vehicle laser radar, and show an obvious reduction of interference. We also show that PN modulated waveform can measure target speed by Doppler, which is not realized on current vehicle laser radars.

II. MUTUAL INTERFERENCE OF PULSED LASER RADAR

For a pulsed laser radar, any unwanted optical pulses of the same order of width may cause interference. So the probability of interference is studied by spatial overlapping probability during the scanning of the victim laser radar and the interfering laser radar. The interference is classified into direct incident and reflection, which will be studied, respectively.

2.1 Direct Incident Interference

The model for studying direct incident interference can be simplified as is shown in Figure 2. The victim laser radar scans from $180^{\circ} - \theta$to $180^{\circ} + \theta$, counter-clockwisely, then clockwisely. The interfering laser has the same scanning mode as the victim laser radar. To take the initial phase of the scanning angle into account, only the initial scanning angle of the interfering laser radar is randomly set.

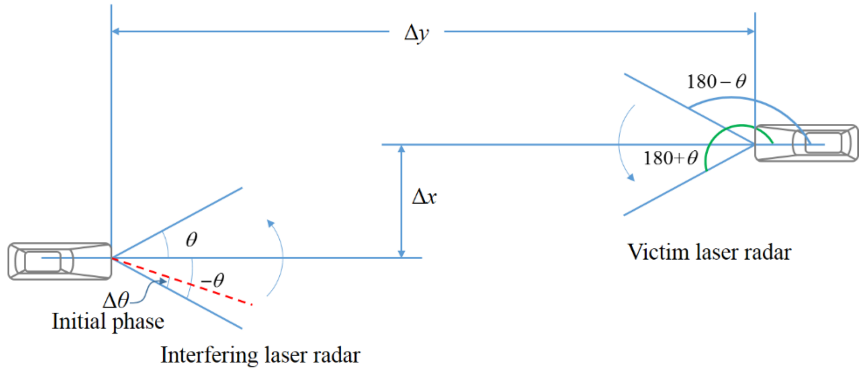

Fig. 2 Research model for direct incident interference

The influence of longitudinal and lateral displacement Δy and Δx on the spatial overlapping probability is calculated, by assuming that scanning field angles of both interfering laser radar and victim laser radar are $2\pi/3$. Figure 3 shows the obtained results when the lateral displacement Δx= 3m, which nearly equals to a lane width. The x coordinate stands for the longitudinal distance between two laser radars. The obtained interference probabilities are the same when the initial phase difference of scanning angle $\Delta\theta$ is less than 0.0135rad. When $\Delta\theta$is larger than 0.0137 rad, no interference will occur. Supposing $\Delta\theta$is uniformly distributed, and the scanning angle is limited in the range from $-\pi/3$ to $\pi/3$, the spatial interference probability will equal to 0.65%, which shows a high interference ratio in the urban streets.

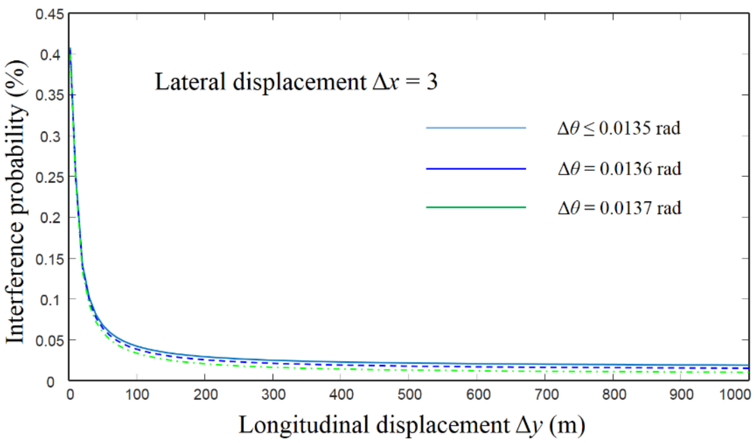

Fig. 3 Spatial overlapping probability of the two reversely placed laser radars

2.2 Reflection Interference

As obstacles in the road scatter the incident laser to all directions equally, and the reflection ratio of is generally not high, reflection interference will not induce photodiode saturation in the way as incident interference. However, it will cause "ghost target" in the victim laser radar.Since the forward vehicle can be at any lateral positions across the road, for simplicity, road targets can be assumed as a lateral bar that traverses the road, as is shown in Figure 4. The transmitting lens and receiving lens are at the same side of the obstacle. Different from the directive property of incident interference, reflection interference is isotropy at the incident point, for the reason, initial scanning angle difference between interfering laser radar and victim laser radar is not need to be considered. Here, we only study the effects of lateral displacement on the interference probability.

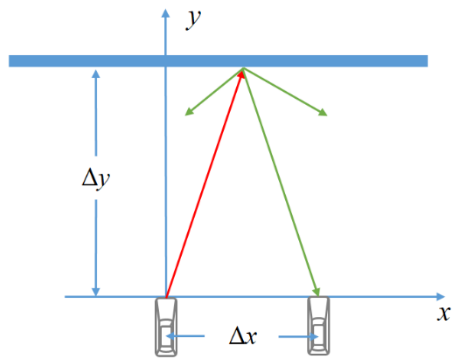

Fig. 4 Research model for reflection interference

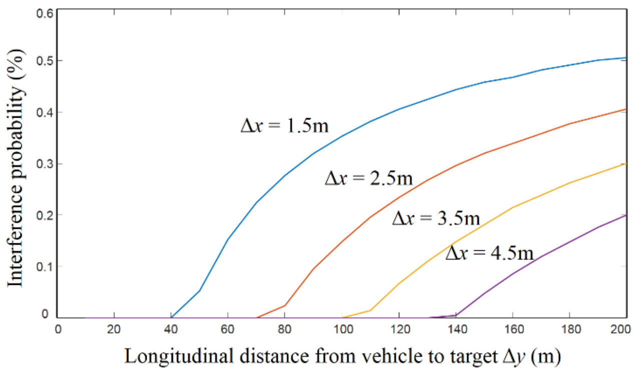

Fig. 5 Influence of Longitudinal range from vehicle to target.

When Δx is from 1.5m to 4.5m, the obtained interference probability between the two laser radars when they are from 0 to 200m away from targets are shown in Figure 5. From the figure, it is obvious that the interference probability increases when the lateral range between the two laser radars becomes small. In urban road environments, vehicle following distance is generally lower than 30m, thus two parallel laser radars nearly do not interfere each other. With the increase of longitudinal range between laser radar and obstacles, the interference increases.

Our further study shows that, if interfering laser radar and victim laser radar have a longitudinal displacement, the forward laser radar is more easily affected by the interference. The interference ratio can be high even when the longitudinal distance Δy is smaller than 20m, which will be a serious problem in urban streets.

III. FMCW LASER RADAR INTERFERENCE

FMCW is the most widely used technique in the development of millimetrewave radar, which can realize range and speed measurement at the same time. However, interference is a serious problem in continuous wave radars. There are many literatures discussing the mitigation of interference among millimetre wave radars. FMCW interference problem can be summarized as shown in Figure 6. Here, we assume all laser radars use laser of the same wavelength andthe same chirp ratio as transmitting signal,the maximum range to be measured is 150m,and the maximum light flight time equals to 1μs. If the interference signal arrives at a time less than 1μs relative to the transmission starting point, ghost target will appear.

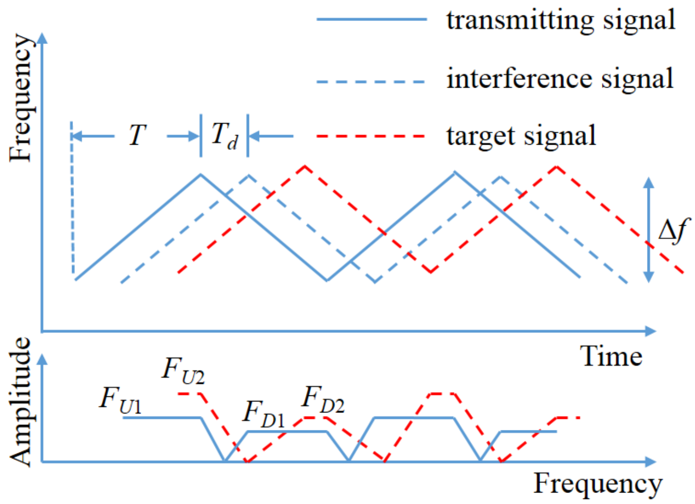

Fig. 6 Interference of FMCW laser radar

High spatial resolution requires laser radar measure more than 200 000 points per second. Such a specification means that the signal length for one point measurement cannot be larger than 5μs. Thus, the interference probability equals to 1μs /5μs = 0.2. This result means that the interference ratio of FMCW can be reduce to 1/5 of the pulsed laser radar. If the target signal and interference overlap at the receiver end, the receiver will output more than one group of beat frequency, as is shown in the lower of Figure 6. For this reason, the target will be indistinguishable from the interference.

By upper discussion, a result that FMCW cannot improve interference significantly can be drawn. Moreover, there is no method for producing short triangularly chirped optical signal at present. Thus, FMCW is not suggested as the transmitting signal of vehicle laser radar.

IV. PSEUDO RANDOM NOISE CODE MODULATION FOR REDUCING INTERFERENCE

PN code has an advantage of anti-multipath interference performance[9-10], which can be used to reduce vehicle laser radar interference. Compared to single pulse, PN code modulation improves anti-interference performance by correlation convolution. The transmitting peak power is much lower than the single pulse format. Even the PN pulse sequence directly enters the receiver of victim laser radar, it would not cause PD saturation. Secondly, in addition to the range measurement, the scheme of PN code modulation can measure relative speed according to Doppler shift.

We propose a data integration method for dealing with the laser radar receiver output signal corrupted by noise and interference. The operating principle is shown in Figure 7. From the transmitting instant of the first pulse in each pulse sequence, an array of data are sampled with a fixed length from PD output signal, which should cover the whole backscattered echoes. The data are buried in noise and interference so that they are not visible. We put the data in the first line of Figure 7, in which the time delay corresponds to the light flight time. As we know the distance between neighbouring '01's of the modulating codes, we shift the data toward left by an amount equal to the distance between the first and the second '01's, and put the shifted array on the second line. We repeat this procedure until the last '01' is shifted forward. Finally, all the data arrays are summed. The resulted signal will have a jump from the minimum value to the maximum value, which corresponds to the time delay. An example of the resulted signal by data integration is shown in Figure 8. Although there is another small peak, it does not feature of jumping from negative peak to positive peak, thus it does not correspond to a time delay of road target.

When interference is strong, there is also possibility that data integration is incapable of obtaining the jump even if the receiver is free of noise. If the interference arrives at the same time with the target signal, by our calculation, data integration is unable to obtain the jump when the interference is nearly five times larger than the target signal. The result means that PN modulation has an ability of eliminating most of reflection interference, while still is incapable of dealing with strong interferences, such as direct incident interferences.

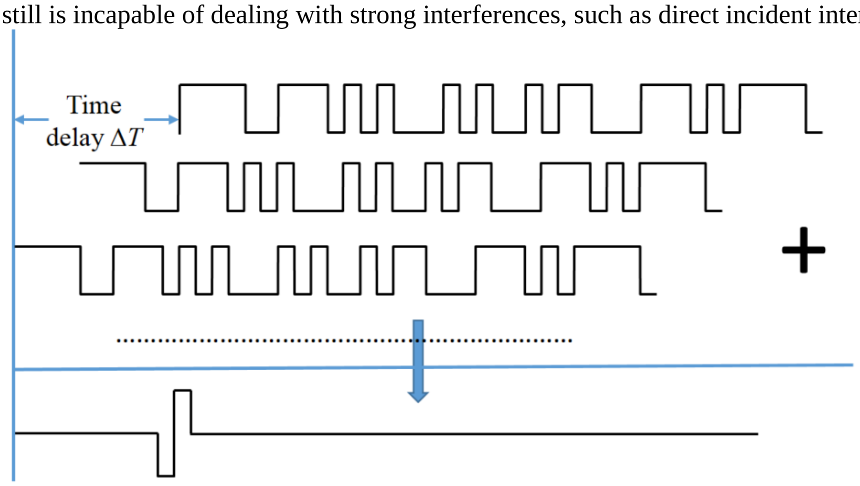

Fig. 7 Operating principle of the proposed data integration.

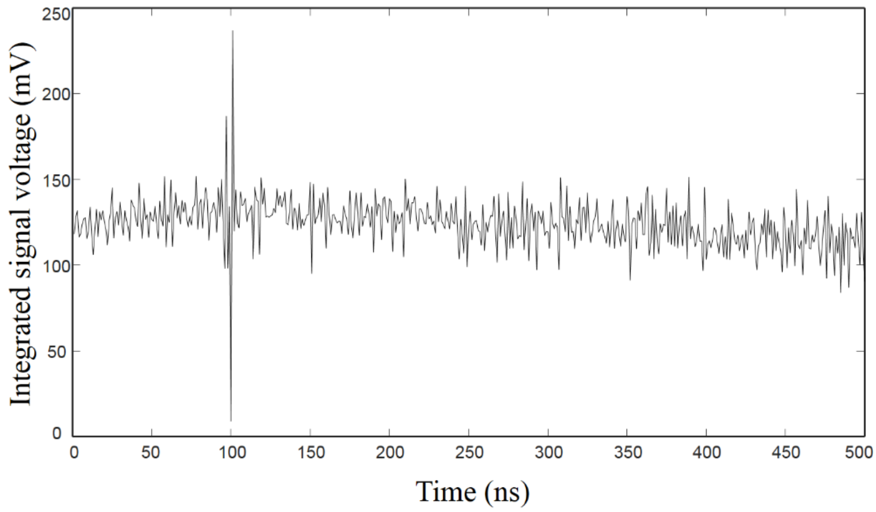

Fig. 8Data integration processed signal corrupted by noise and interference

A special non-uniform Fourier transform is proposed for obtaining the spectrum of Doppler signal. The continuous Fourier transform of equally sampled data is defined as

$$F(\omega)=\sum_{i=0}^{N-1} f(t_i)e^{-j\omega t_i}\Delta T=\frac{1}{F_s}\sum_{i=0}^{N-1} f(t_i)e^{-j\omega t_i} \quad (1)$$

If the sampling intervals are unequal, Eq. (1) can be re-written as

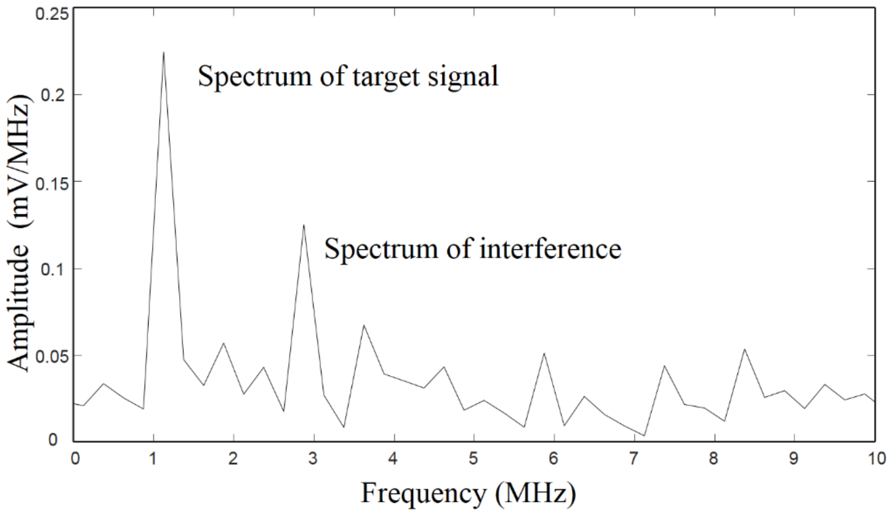

Fig. 9 Doppler spectrum of target signal and interference

$$F(\omega)=\sum_{i=0}^{N-1} f(t_i)e^{-j\omega t_i}\Delta T_i=\sum_{i=0}^{N-1}\left[f(t_i)\Delta T_i\right]e^{-j\omega t_i} \quad (2)$$

According to Eq.(2), we use sampling interval to modify signal amplitude so that FFT is capable of dealing with the non-uniformly sample data. Figure 9 shows an example of the spectrum that includes target signal and interference, in which interference is strong than target signal. Due to the non-uniform property, the obtained spectrum of target signal is larger than the interference spectrum. This feature can be used for classifying target and interference.

V. CONCLUSION

The transmitting waveform of a laser radar has an important effect on its measurement performance. In this paper, we studied the interference of the pulsed waveform and triangularly chirped FMCW, and showed that these transmitting formats are inevitably interfere with each other in road environments. Then, traditional PN modulation scheme is proposed for dealing with the interference in range measurement, and a non-uniform Fourier transform is proposed for obtaining Doppler frequency, which adds a speed measurement function to the current range measurement only laser radar. The result shows that PN modulation can reduce weak interference such as reflection echoes, but it is incapable of dealing with strong interference, such as direct incident interferences. Even so, PN modulation reduces the transmitting peak power, which will not introduce PD saturation of the victim laser radar.

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