Investigation of LiDAR efficiency for ADAS performance improvement

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Abstract. One of the most fascinating engineering research fields today is ADAS (Advanced Driver Assistance System). This system, integrated into cars, assists drivers in achieving safer and more efficient driving. The paper investigates and examine the operating principles of LiDAR sensors, their types, performances of various technological solutions, operational classes, and their importance in ADAS technology. Additionally, it draws attention on the facts of LiDAR in autonomous driving technology.

1. Introduction

The accuracy of ADAS increases proportionally with the spread of autonomous vehicles, leading to new challenges that, in turn, require new solutions. One of the most used tools in ADAS sensor systems is LiDAR. Operating at a higher frequency and thus a lower wavelength than traditional RADARs, it creates sharper and clearer images of objects. The most common wavelength is selected between 532 nm and 1064 nm. Therefore, this type of sensor can be used as a solution for autonomous driving or various driving assistant functions. While all LiDARs perform very well in clear weather conditions and during the day, certain types can overcome harsher weather conditions and provide accurate data to the system. Dense fog, light rain, or sand on the highway may slightly reduce the accuracy of more advanced LiDAR systems, but even with these conditions, their margin of error remains negligible. [1] [2]

2. Types of LiDAR sensors based on modulation techniques

We can measure distance from the time of flight, AMCW (Amplitude Modulated Continuous Wave) and FMCW (Frequency Modulated Continuous Wave).

Time of Flight is the most common way to measure the distance. An IR emitter diode emits the laser beam pulse that mirrors the objects, and a receiver diode gets the echo, through this time system measures the time and then easily can calculate the distance using (1) equitation. This formula is enough to accurately measure the distance with an accuracy of 1 cm at the range of 200-300 meters in clear weather conditions.

While ToF LiDARs were sending pulses, other types sent continuous signals. AMCW (Amplitude Modulated Continuous Wave) is sending a continuous wave laser whose signal is modulated with a specific frequency or pattern. By analysing modulations of the received echo, the system can determine the distance to the target. This technique is more reliable since much less environmental impact, as snowflakes or fog, can influence the result of the measurement, so the error factor is significantly less. The formula to measure the range is (2) equation.

As for the last one, we should mention FMCW (Frequency Modulated Continuous Wave). With this technique, we do not modulate the amplitude but the frequency. Nowadays, it is said that FMCW could replace Time of Flight LiDARs in the self-driving car space because it can even perform 4D localization without GPS (Global Positioning System). [3]

3. Time of Flight LiDAR

This sensor emits intense, focused pulses of laser energy, detects the reflected beam, and measures the elapsed time. On the electromagnetic spectrum, the emitted laser is between the ultraviolet and IR (infrared) light spectrum. They are classified the operational principle as:

1. Laser emission: The sensor emits intense, focused pulses of laser energy in one or more directions. This laser light emission usually occurs in very short pulses.

2. Light reflection: When the laser light encounters an object in its path, a portion of the light is reflected toward the sensor.

3. Light receiving: The sensor receives the reflected light. The sensor precisely measures the time elapsed between the emission and return of the laser light.

4. Distance calculation: Based on the time measurement, the LiDAR sensor calculates the distance between the object and the sensor. Since the speed of light is known, the sensor can easily convert the time measurement into a distance value.

5. Data processing: The distance data collected by the sensors are subjected to further processing to determine the exact position and movement of objects.

LiDAR differs from other sensors in that the electromagnetic wave speed it uses is the speed of light enabling LiDAR to provide extremely fast and accurate position determination. This characteristic makes it valuable for automotive applications, including detecting and locating various objects.

Used equation for distance measurement with ToF LiDAR:

$$d = \frac{c \cdot t}{2} \qquad (1)$$

Where:
d- distance [m];
c -speed of light (c=299.792.458 [m/s];
t -time [s]

ToF modulation technique has several advantages. It provides millimeter-level in short and satisfactory accuracy with medium and long-range in distance measurement during clear weather conditions. Integration in cars is not a real challenge and can collect environmental data in real-time.

Besides them, we also need to talk about fundamental shortcomings like the sensitivity of weather conditions, interference from external light sources, high energy consumption, data processing demand and wavelength. To make it clear, ToF LiDAR performance is the best in clear and bright (but not too bright) weather conditions, but harsher ones like fog, light rain, snowflakes, etc., can reduce its achievement. It’s because laser beams can reflect off water droplets or particles, leading to inaccurate measurements and poor-quality data. ToF LiDAR is also sensitive to interference from external light sources, such as sunlight. In strong sunlight, the reflected laser beams may weaken, reducing the LiDAR's sensing capabilities and accuracy. About energy consumption, ToF LiDARs operate high energy consumption, because the system consequently emits high-energy pulses. This can be problematic especially in electric vehicles, where low energy consumption is a critical concern.

Additionally, the amount of data generated by ToF LiDAR is enormous, chiefly when creating high-resolution 3D maps. Processing such data requires powerful computing capabilities, which increases not only complexity but also energy consumption. Last, but not at least, ToF LiDAR usually use a wavelength around 800-900nm, which is close to human vision and for this reason can therefore go through the retina and damage eyes.

4. Amplitude Modulated Continuous Wave LiDAR

AMCW LiDAR operates by emitting a continuous wave laser signal that is modulated with a specific frequency or pattern. By analysing the modulation of the reflected laser signal, the system can calculate the distance to the target. This distance measurement is derived from the phase or frequency shift in the modulation pattern of the returned signal.

Used equation for distance measurement with AMCW LiDAR:

$$d = \frac{c}{2} \cdot \frac{\Delta\phi}{2\pi} \cdot \frac{1}{f_{AM}} \qquad (2)$$

Where:
d -distance [m];
c -speed of light   (c=299.792.458 [m/s]);
$\frac{\Delta\phi}{2\pi}$ -shift in waves;
f_{AM} -constant frequency [Hz]

AMCW LiDAR systems can achieve high levels of precision by analysing the phase shift of the returned signal and generally perform better at short distances due to their continuous scanning capability. However, the maximum range is limited by the modulation frequency, and achieving high range resolution at long distances can be challenging. That’s why AMCW is not suitable for long-range. Plus, because of this type of LiDAR detecting with continuous signal, more susceptible to interference from light and another kind of noise sources, which reduces its range.

5. Frequency Modulated Continuous Wave LiDAR

5.1. FMCW LiDAR in general

FMCW LiDAR is a LiDAR, can directly measure the speed of objects. It uses Doppler Effect calculation in its chip, so they are also called 4D-, Doppler-, or chirped LiDARs. FMCW is the technology used in not only LiDARs, but also RADARs (Radio Detection And Ranging) to measure velocity instantly. To give a short example, a conventional ToF LiDAR is usually with an extension of type .pcd, .ply or .xyz and is a set of lines with point coordinates [X, Y, Z]. On the other hand, an FMCW LiDAR also uses these 3 coordinates, but each line also has the velocity measurement. Hence FMCW coordinates become [X, Y, Z, VX, VY, VZ]. See details in figure 1.

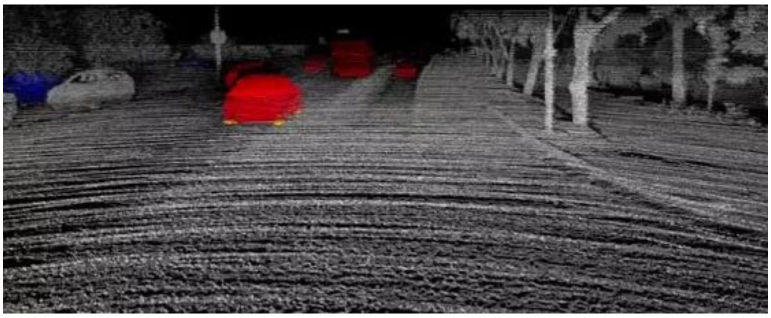

Figure 1: Aeva®'s FMCW LiDAR that can estimate velocities and predict trajectories (red: receding, blue: approaching)

Besides, FMCW LiDAR system not only measures and object's position, but also estimates the exact trajectory of every single point, which means now we can talk about Built-In Optical Flow. This is due to something called Doppler Effect.

5.2. How is FMCW operating?

1. Laser beam emitting: Emitter sends continuous light waves at specific frequency.

2. Laser beam reflecting: When the laser beam hits an object, its echo will be received by a receiver diode.

3. Distance calculation: The local oscillator is mixed with the return signal, by a coherent detector and frequency difference is measured. This frequency difference shows how much the value of frequency has changed while reflected light made its complete round trip. If we multiply that interval by chirp speed, it will result in distance calculation.

4. Determination of speed: Velocity calculation is obtained by further processing which extracts the Doppler shift resulting in the object's velocity with respect to LiDAR. There are 2 ways to change the frequency. If the reflection is higher frequency than the emitted one, the measured object is approaching. On the other hand, if the reflection is lower frequency, the measured object is receding. See details in Fig. 2.

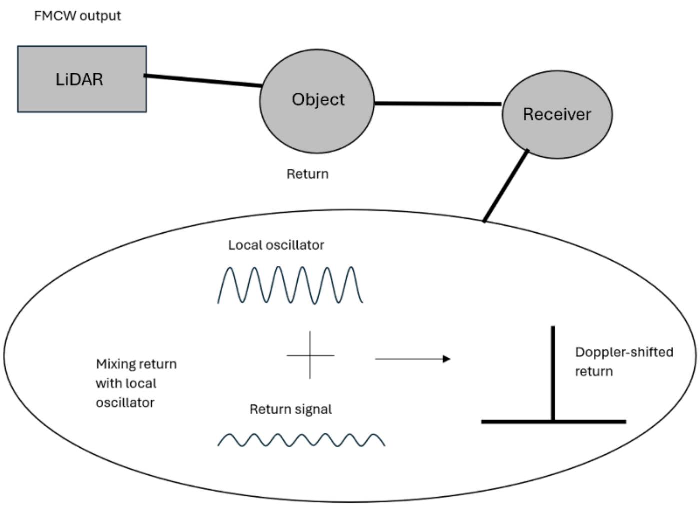

Figure 2: Principle of operation of FMCW LiDAR

5.3. Used equations with FMCW LiDAR:

5.3.1. Distance measurement

$$R = \frac{\tau D \cdot c}{2} \qquad (3)$$

Where:
R-Target range (distance) [m];
τD-Time-delay [s];
c-speed of light (c=299.792.458 [m/s]

5.3.2. Heterodyne beat (difference frequency) between the 2 optical fields

$$f_{beat} = \kappa \tau D \qquad (4)$$

Where:
f_{beat}-heterodyne beat frequency [Hz];
κ-chirp rate;
τD-Time-delay [s];

5.3.3. Combine (3) and (4) to determine the target range through the equation

$$R = \frac{f_{beat} \cdot c}{2\kappa} \qquad (5)$$

5.3.4. Range resolution: Defined as the minimum resolvable separation between 2 targets on the same bearing

$$\Delta R = \frac{c}{2B} \qquad (6)$$

Where:
ΔR-Range resolution;
B-information bandwidth (chirp bandwidth for this case);

However, it is often possible to determine the range of a target much more precisely than the resolution.

5.3.5. Target range

In this case, the range of precision is defined as the standard deviation of a statically meaningful number of range measurements of the same target under the same conditions and is given by the Cramér Rao lower bound.

$$\sigma R \approx \frac{\Delta R}{\sqrt{SNR}} \qquad (7)$$

Where:
SNR-signal-noise-ratio of the measurement

Equations (6) and (7) can be applied at any LiDAR system. To determine the range to a target with the best precision, firstly simplify the large information bandwidth, then the high signal-to-noise ratio.

5.4. Pros and Cons of FMCW LiDAR

The most obvious advantage against ToF and AMCW LiDARs is it can measure velocity and even perform localization without using GPS (Global Positioning System), that is unique in LiDARs.

I think I do not need to mention how important it is for tracking dynamic objects or allowing the car to react more accurately and make the best decision in dangerous situations. FMCW can also manage extreme weather conditions (e.g. fog, rain, bright sunlight, etc.), since continuous waves can penetrate through these particles and because this system is not just about the time of flight, but also measures from frequency modulation. Additionally, FMCW systems have longer functioning range, and it can also detect far object's accurate distance and velocity even around 300-500m, which is crucial in high-speed environments, like highways. Furthermore, FMCW modulation uses 1550nm wavelength, so in this case, we could consider most of them are completely safe for the human eyes (which can see wavelengths 400-700nm). Last, but not at least, since FMCW operates continuously, using less energy than pulse sender LiDARs. This feature reduces the sensor's power requirements and improves vehicle efficiency.

To talk about some challenges, I should mention its costs, integration challenges and laterally movement. FMCW LiDAR's parts are so expensive, so in the future companies should make it for a significant R&D direction to reduce its price. Plus, it is not the easiest sensor to find place for it because of its dimensions. However, there are manufacturers like Aeva® who found several places to integrate it like in the grille or behind the windshield. Of course, it is not the perfect sensor yet, sithence it still cannot measure laterally movement because Doppler effect does not help here, and this is still an indirect computation. So, it's not a 6D, but still a 4D vector (X, Y, Z, V_{long}).

In this case, further investigation is required with real data collection to make FMCW LiDAR modulation technology even better, to create safer and more reliable vehicles for the Future Generations.

6. Conclusion

It was shown that despite that FMCW LiDAR may not be the best decision yet to create a cheap car with such ADAS features, but if this modulation will be a significant R&D direction from now, researchers will make a more wallet-friendly solution soon. Therefore, I think this modulation technology is set to be a defining technology for the future of ADAS and autonomous vehicles, offering more accurate, efficient, and reliable sensing. Its speed measurement capabilities, lower energy consumption, longer range, and better performance in various weather conditions all contribute to its key role in improving road safety.

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