Laser eyes for driverless cars: the road to automotive LIDAR

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Abstract: Automotive LIDAR is one of the primary sensors for fully autonomous vehicles, and the performance requirements of these sensors places challenges on the optical technologies used in the device. We analyze the requirements for automotive LIDAR and then suggest a novel taxonomy of classifying different beamsteering methods.

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1. Introduction

Autonomous vehicles (AV) propose a transformation in mobility and safety, and a fully autonomous vehicle senses the environment with a plurality of sensor types. Light detection and ranging (LIDAR) sensors are one of the primary sensor modalities, requiring exceptionally high performance to satisfy the requirements for self-driving vehicles.

The majority of analysis on automotive LIDAR appears to focus their taxonomy of LIDAR into ranging methods. While ranging techniques are incredibly important and a worthwhile analysis of suitability for use in automotive applications, we propose a discussion that starts in analyzing the high level performance requirements of automotive LIDAR for AVs, and then producing a novel taxonomy of the state-of-the-art LIDAR systems.

2. Requirements for level 4 autonomy

Fully autonomous vehicles are often described as starting with Level 4 autonomy, as defined by the SAE J3616, refers to a vehicle that is able to operate under defined conditions without any human intervention. At the moment, this level of autonomy necessitates the use of high performance LIDAR, with specifications outlined in Table 2.

Table 1. Performance specifications of a LIDAR for level 4 autonomy.

Item (unit)	Spec.	Note
Range (m)	>200	@10% reflectivity
Horizontal FOV (deg)	>120	(HFOV)
Vertical FOV (deg)	>25	(VFOV)
Resolution (deg)	<0.1	in HFOV and VFOV
Refresh rate (Hz)	>15	

2.1. Range

The LIDAR maximum range is usually defined as the maximum distance that a 10% Lambertian target can be detected. The definition of “detected” can vary widely, but one approach is to define “detected” as a probability of detection greater than 90% and a probability of false positive less than 10% [1].

2.2. Field-of-view (FOV)

The original Velodyne LIDAR rotated horizontally around its mounting base, enabling a 360 degree horizontal field of view (HFOV). Next-generation LIDAR, however, aims to be statically mounted (that is, with no visibly moving elements) and designed into the chassis, combining multiple LIDAR sensors into a unified point cloud.

2.3. Resolution

High performance LIDAR aims to provide long range sensing, and this, in turn, necessitates higher resolution. The ability to detect an object at 200 m must be coupled with enough angular resolution to have confidence that any potential hazards can be detected in operation. At an angular resolution of 0.1 degrees, this corresponds to an object that is roughly 35 x 35 cm in dimension.

2.4. Refresh rate

Refresh rate, also known as frame rate, governs how often a LIDAR sensor refreshes the point cloud. It has been suggested that a frame rate of 10 - 20 Hz is required to track moving objects in most road conditions [2].

3. The impact of LIDAR specifications

3.1. Maximum point throughput

Taking the previous requirements into account, we can calculate the amount of data created by the ideal LIDAR system. Let us calculate the ideal point throughput, R, as

$$R = \frac{HFOV}{\Delta\theta} \cdot \frac{VFOV}{\Delta\phi} \cdot Q,$$

where $\Delta\theta$ is the angular horizontal resolution (°), $\Delta\phi$ is the angular vertical resolution (°) and Q is the refresh rate (Hz). For a refresh rate of 10 Hz and meeting the requirements in Table 2, this is point throughput of 3 million points per second.

Another way to look at the problem is to consider only the transit time of light. Let us consider that the maximum range for detection is 300m, assign this to t_{tr}. For a single scanned laser system, the total number of points that it can complete a measurement is

$$N_{pts} = \frac{c}{2t_{tr}} = \frac{299792458 m/s}{2 \cdot 300 m} = 499654 pts/s.$$

This is quite a discrepancy between the required number of points and the physical number of points that we can scan given the transit time of light. The obvious solution is to have parallel lasers scanning different regions, and from this we can calculate that 6 lasers operating in parallel would be able to meet the sensing requirement.

3.2. The impact of resolution and frame rate

The number of fast sweeps required in a frame is the VFOV divided by the angular resolution, or 25°/0.1°= 250 sweeps. If we have 10 frames per second, as per the requirement, then in 24 hours, the fast axis sweep must sweep 120 degrees HFOV 216 million times in one day. While automotive LIDAR technology is still nascent, we can look at similar technology in optical communications, for example 1x2 MEMS optical fiber switches, where they often specify 10 billion cycles or 46 days of continuous use before failure. This limitation suggests that the fast axis scan method is actually the most critical architectural decision in automotive LIDAR, as this can be the bottleneck for a credible technology platform.

4. Fast-axis Scanning Methods

The requirements of automotive LIDAR are to create high resolution point clouds over large field-of-views(FOV) with a refresh rate of at least 10 Hz. The real metric of interest to the customer is the number of points per second delivered by the LIDAR device; as an example, the Velodyne 64 has 1.3 million points per second over a 360°FOV, with 64 vertical points of resolution. High performance LIDAR requires high resolution in both horizontal and vertical axes, which suggests that a continuous scan method is required in both axis.

4.1. Methods of fast scanning

4.1.1. Spatial Tx Rx

Some types of LIDAR use a plurality of sources and receivers in one axis. Since multiple emitters are firing simultaneously, the integration time per point is proportionally longer, which potentially allows the LIDAR to fire multiple shots. Typically, this is combined with 360°rotation to generate a 3D point cloud.

4.1.2. Reflection methods

The use of reflective element to deflect a collimated beam has been examined in the literature for decades, including use for optical cross-connects [3], scanning interferometry and quantum communications, and LIDAR [4]. Steerable mirrors, also called galvonometers, are readily available, low cost, and can offer highly reflective surfaces, minimizing losses. If the mirror diameter can be sufficiently decreased, optical microelectricalmechanical systems (MEMS) can be used as the steerable element [5]; small mirrors are more robust to the vibration experienced on a vehicle, and MEMS are suitable for volume wafer-based production.

The challenge for reflection methods is a practical one: high performance LIDAR requires long range, which really necessitates a large aperture for receiver collection. Since the mirror has to move to steer the beam, a larger mirror needs to clear more volume to steer over large angles - and this is further complicated by needing to steer in 2D, as the second axis mirror must be large enough to deal with the large deflection angles from the first mirror. This becomes increasingly more difficult for MEMS, which has fabrication limitations on the size of the mirror and deflection angles. Telescopes may be used to increase the beam size after deflection by the mirror, but this reduces the steered angles.

Additionally, there are reliability concerns with galvanometric and mechanical MEMS-based reflection methods. Failure mechanisms such as mechanical fracture, fatigue, creep, stiction, wear, and contamination can occur under normal lifecycle stresses imparted by mechanical loading and environmental conditions in autonomous vehicle applications [6]. Typical cyclical loading, including changes in relative humidity and temperature, can degrade the lifetime of MEMS motor devices by three orders of magnitude. Even the presence of small contaminants has been observed to cause electrical shorts that have adverse effects on the mechanical and electrical performance of MEMS devices [7].

4.1.3. Interference methods

These methods of beam steering use the diffraction of many ‘point’ steering elements to enable the shaping and/or steering of a beam coupled into free space. A prominent approach is the use of optical phased arrays (OPA), which replicates the work from radar phased arrays, translated to work at the wavelength of light. By feeding a multitude of emitters with coherent light, an OPA proposes to use amplitude and/or phase tuning of the emitted fields to create a far field pattern with low divergence and at a desired angle [8]. Additionally, the literature reports that the complexity of 2D arrays, with either thermo-optic or carrier injection methods, makes addressing large arrays challenging.

The research into OPAs has rapidly progressed and increased in recent years, driven by the application space of automotive grade LIDAR. The challenges for OPAs still limit their use in automotive, though. For example, to achieve good collimation over range, a low divergence beam must be created, with no significant energy in beam sidelobes. Low divergence is achieved by maximizing the total emission area and ensuring a flat field on the exiting beam [8].

An alternative to OPAs that leverages interference effects for beam steering is the use of tunable wavelength combined with dispersive optics (called and trademarked Spectrum Scan by the authors). This approach trades complexity at the beamsteering element for complexity at the transmitter - one advantage of this is that dispersive optics, such as prisms or diffraction gratings, can be produced in large sizes, enabling the steering of beams with quite large beam waists, which in turn enable good collimation over hundreds of meters. If we look at diffraction gratings, which are a suitable analog for OPAs, the number of emitting elements is equal to the number of features written into the grating.

4.2. Refraction methods

These are methods that use the refractive index difference between optical materials to deflect a beam; existing concepts have been demonstrated targeting automotive LIDAR with both non-mechanical and mechanical solutions. Liquid crystal prisms have been used as a non-mechanical beam steering solution, and show great promise in being able to steer a beam in one dimension [9]. Mechanical solutions, such as Risley prisms, have been used in LIDAR for decades, as they offer a large beam aperture, continuous sweeps, and relatively robust operation, as the mechanical motion is limited to a constant speed of rotation about the center of the optics [10]. Using refraction of light is advantageous for beam shape and quality, as they generate no extraneous beams other than stray light effects. However, the scan patterns are not typical raster scans, but have an elliptical scan that is rotated around the optical center.

5. Point throughput reduction

A complication of the ideal LIDAR sensor is the sheer amount of data produced. It should be apparent that such high resolution is not necessarily required at close range, nor on large buildings at the edges of the FOV. The next generation of LIDAR sensors offer some alternatives to ensure that high resolution is available where it is needed most.

A proposed method of throughput reduciton is to use complex scan patterns to maximize the valuable information within a point cloud. For example, both OPAs and spectrum-scanning LIDAR can beam steer in non-continuous motion, enabling interleaved scan patterns, where each fast axis scan is shifted slightly to produce superior spatial sampling. This is particularly advantageous for objects with unusual aspect ratios, such as bars or poles that may just slip between scan lines in a traditional LIDAR system.

Similarly, the ability to have arbitrary beamsteering patterns can create nonlinear scan patters, where the resolution is concentrated at the horizon. One complication is that vehicles move through environments that have inclinations that change where the horizon appears relative to the vehicle; however, this is easily addressed by dynamically adjusting the nonlinear concentration to where it is needed. This type of control allows the maximal effective resolution on distant objects without increasing required compute resources or violating eye-safety, refresh rate or FOV requirements.

6. Conclusion

In this abstract, we have considered a generic set of requirements for automotive LIDAR, and then analyzed the impact of those requirements on the laser scanning architecture. Our conclusion is that the method of fast axis scanning is paramount in developing a LIDAR system that will be able to operate reliably on a vehicle, and produce the resolution needed for fully autonomous vehicles.

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