TOF Lidar Development in Autonomous Vehicle

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***Abstract*—Lidar has been widely used in military and civilian applications. This passage mainly introduces a type of lidar used in autonomous vehicle: TOF lidar. The working principle of TOF lidar was introduced in detail. Then based on the TOF lidar, there are two types of lidar to be introduced: scanning lidar and non-scanning lidar. Scanning lidar includes single-line scanning lidar and multi-line scanning lidar. 3D-flash lidar was taken as example to introduce non-scanning lidar. The contents of each type of lidar are system structure, working principle, the development around the world and some problems existing currently. Introduction of lidar development direction is made, including MEMS technology and ZOL technology.**

Keywords-autonomous vehicle; TOF lidar; scanning lidar; non-scanning lidar; single-line scanning lidar;multi-line scaninng lidar; 3D flash lidar; MEMS technology; ZOL technology

I. INTRODUCTION

In order to ease the transportation pressure of the city road and to improve the people's life efficiency, companies around the world pay efforts to the research of the autonomous vehicle. What's autonomous vehicle is without the drivers' intervention, it can rely on its own complex sensors system to sense the external environment and to make correct decisions by its own judgments [1]. The current program of the sensor system is combining camera , millimeter wave radar with lidar [2]. The advantage of the camera is that the target can be detected intuitively and clearly under normal weather conditions, while it can't see the road condition under the bad weather. Millimeter wave radar is small and can see the distant target clearly, but like myopia, it can't see the near things. Lidar can offer high resolution and distant 3-D data in the absence of light and bad weather. When making fusion of camera, millimeter and lidar data, the redundancy can cover all the driving conditions reliably and completely. The newest lidar can distinguish a man's status, whether riding, walking, movement speed or direction [3]. It can operating normally under the extremely weather. It's a necessary sensor of a L3 or higher level driverless vehicle.

Dating back to sonar and radar, lidar is a advanced sensor transmitting information via laser. With the birth of the laser, lidar appeared firstly in 1971 used to Lunar surface mapping during Apollo 15's mission, later used in archeology and agriculture mapping. In 2005, lidar appeared in vehicle filed during the DARPA challenge. It is just like the eye of the autonomous vehicle, serving location and avoidance for the vehicle. As to the location, the SLAM algorithm of the lidar is applied to make high resolution mapping and location with the merits which are of low CPU consumption, good robustness and stability [4]. The accuracy of the depth information of the scanned point cloud is high, and the position, orientation can be directly optimized when back loop is optimized. Since laser has smaller diffraction and beam divergence angles, it can better identify the adjacent objects than other radar. Higher angular resolution is provided especially at high speed. Consequently it can give the vehicle enough time to deal with the potential dangers such as head-on collisions.

Lidar can be divided into scanning lidar and non-scanning lidar according to whether there is moving units or not [5]. There is another method to divide lidar by implementation method into time of flight(TOF), triangular ranging lidar and phase ranging lidar. While the mainstream lidar used in autonomous vehicle is TOF lidar. There are many companies committing to the study of lidar such as Velodyne, Quanergy, Innovusion, Ibeo, SICK etc. in foreign countries, domestic companies such as SureStar, HeSai Technology, Benewake, and Leishen Intelligent Technology are also making research on it. Depending on the current mainstream TOF lidar, this paper makes introduction of the TOF ranging schematic, the working principle, development around the world of scanning and non-scanning lidar, system construction, existing problems and developing directions of lidar.

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II. WORKING PRINCIPLE OF TOF RANGING

Lidar applied in autonomous vehicle is mostly based on TOF. What's TOF is pulsed laser emits pulse singly or continuously to the target. When emitting laser pulse, internal timing circuit is triggered instantly. The calculator measures the time between the laser pulse arriving at the target and return to the receiver from the target Δt, so the distance of the target is obtained, the TOF ranging schematic is shown as Figure 1:

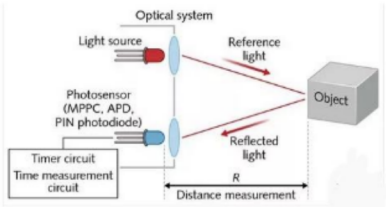

Figure 1. TOF ranging schematic.

Δt is the time difference of the light pulse from emitting to the target and returning to the receiver from the target, calculating product of the clock pulse number n of the calculator and pulse interval τ, which is

$$R = \frac{1}{2} c n \tau = \frac{c}{2f} n = \ln \tag{1}$$

For which f is the clock pulse frequency, $l = \frac{c}{2f}$, l of each clock pulse representing the distance base; n is by calculating the clock pulse number, thus we get the distance R of the target.

The specific working principle is depicted as following: [6] firstly, aiming the target, starting the laser to emit light to the target by the emitting light system; meanwhile, the emitting signal collected by the sampler is as the gate open signal of the counter and the counter starts counting. The clock oscillator effectively inputs the clock pulse to the counter. The echo signal returning by the target diffusely passes through the atmosphere and enters the receiving optical system, converting into electric pulse by the photoelectric detector, amplified by the amplifier, which serves as the gate closing signal to the counter, and the counter stops counting. The clock pulse number entering the counter during the gate opening and closed is calculated to get the target distance R.

The TOF ranging method is mainly applied into topographic measurement, tactical front-end ranging, guided missile tracking, laser lidar ranging, and artificial satellites, land and moon distance measurements, etc. the factors effecting the ranging accuracy are mainly the rising edge of the laser pulse, receiving channel bandwidth, signal to noise rate of the detector and the time interval accuracy.

III. SCANNING LIDAR

A. A Brief Introduction of Scanning Lidar

Scanning lidar is a traditional rotated mechanical scanning lidar, and it's consisted of laser diode, scanning motor Triangular prism, receiving sensor and microprocessor and can be divided into single-line scanning lidar and multi-line scanning lidar. The single-line scanning lidar only scans plane obstacles, so a 2-D picture can be gotten. Showing as Figure 2 is the Military rotating machinery scanning radar.

Multi-line scanning lidar combines many scanning plane and offers varieties of point cloud data. Domestic companies paying efforts into scanning lidar are HeSai Technology, Sailing Technology, etc. foreign companies like Velodyne、IBEO are also researching scanning lidar.

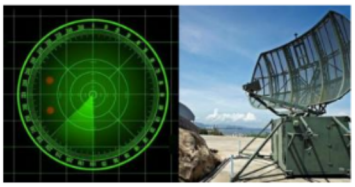

Figure 2. Military rotating machinery scanning radar.

Military radar such as microwave radar or millimeter radar is scanning around 360 degrees, calculating the target distance by time difference of transmitting and receiving wave .

This passage mainly introduces the TOF lidar of scanning technology, such as the conception, working principle, representing product, researching status and some defects of current products.

B. Single-Line Scanning Lidar

Single-line scanning lidar is actually a high-frequency pulse laser range finder plus a one-dimensional rotation scanner. It has only one Transceiver channel and high scanning rate and angle resolution. Small volume, low weight and low consumption are its big advantages. When used in autonomous vehicles, it mainly plays a role as anti-collision in the forward direction.

The first time it used in autonomous is in Stanly, a vehicle participating in 2005 DARPA Automatic Driving Challenge. There are five single-line lidars on it. Currently foreign companies like SICK and HOKUYO, Osight of domestic are studying single-line scanning lidar. When used in autonomous vehicle ,its function is realizing obstacles avoidance of the front. For example, when there is a vehicle in the left, it can realize automatic avoidance by detecting the position and size

C. Single-Line Scanning Lidar Development at Domestic and Abroad

The single-line scanning lidars produced by Osight LSXXX™ whose product series are shown by Figure 3, and foreign companies are shown following and their technical indicators are listed in Table I:

Figure 3. LSXXX™, TiM561,and UTM-30LX.

TABLE I. PARAMETERS OF SINGLE-LINE SCANNING LIDAR

type	LS1XX	LS2XX	LS3XX	LS4XX	UTM-30LX	TiM561
Scanning angle	270°					
Angle resolution	0.25°/0.125°/0.0625°				0.25°	0.33°
Distance range(m)	0.5to50	0.5to100	0.5~8	0.5~20	0.1 ~30	0.05~10
10% reflectance maximum distance	30m	50m	40m	10m	0.1 to 30m	8m
producer	Osight	Osight	Osight	Osight	HOKUYO	SICK

From the table, we can see that Osight, the domestic lidar company has the advantages over the foreign companies, especially in distance range, and angle resolution. With the distance detected nearer and nearer, its angle resolution is higher and higher. But as the same detected distance, 8m for example, the angle resolution of Tim561 is 0.33 degree, while LS3XX is only 0.0625degrees.

D. Multi-Line Scanning Lidar

Multi-line scanning lidar refers to the multiple laser that transits the light distributing in vertical direction, and the scanning of the plurality of the wiring harnesses is formed by the rotation of the mirror. Unlike the single-line scanning lidar, it can track the multiple targets. It serves the autonomous vehicle for high accuracy SLAM positioning and 3D modeling to sensing the environment. The working principle of the multi-line scanning lidar imaging is detection, clustering, segmentation, tracking, recognition and reconstruction [7].

The specific working process depicting as follows:

Firstly, multi-line scanning lidar scans the environment around and samples the data, analyzes the data and the pre-selects the obstacle points. Take the four-line lidar for example, if there are two or more data similar, then it can be thought as obstacle points when the four laser scanning vertically. If some obstacle points are lost due to the obstacle points' low reflecting rate, then some comparisons are needed to make with other scanning points around to decide whether it is obstacle or not. As to the possible interference caused by the road or slope, we should obey the rule that the obstacle points selected ignore the same laser scanning plane points. The next step is filtering the non-obstacle points: a threshold should be set. As the distance of any two points inside the coordinate is less than the threshold, they should be clustered. After clustering, we should separate the two, remain the obstacle points and filter the non-obstacle points. Finally, some rules should be obeyed to track the obstacles [8], [9].

The basic idea of 3-D environment mapping is through coordinate transformation. Scanning data is transformed into global coordinate system to obtain the 3-D environment mapping. According to the obstacle points' position in the global coordinate system changed to make judgment and filtering.

E. Multi-Line Scanning Lidar Development at Domestic & Abroad

Multi-line scanning lidar need to emit multiple beams that are split by the raster to scan around the vehicle to create a whole 3-D map. The current companies around the world are Velodyne, SureStar and so no.

In 2007, Velodyne released a 64-line scanning lidar, which was first used in autonomous vehicle of Google; latterly, 16-line and 32-line scanning lidar were released and widely applied in autopilot, terrain imaging, agriculture and geography survey and other fields. In 2018, a 128-line lidar was born. Figure 4 shows the products made by Velodyne in recent years:

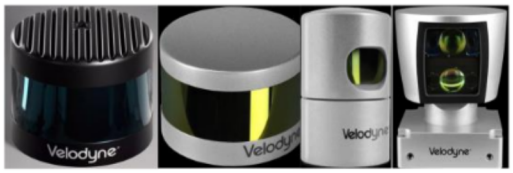

Figure 4. Velodyne series.

TABLE II. PARAMETERS OF VELODYE SERIES

type	distance	Output points(s)	FOV(°)	angle resolution(°)	ranging accuracy(cm)
VLP-16	100m	300,000	360*30	0.1~0.4*2	±3
HDL-32E	70m	300,000	360*41.34	0.16* 1.33	<2
HDL-64E	120m	1,330,000	360*40	0.1*0.4	2
VLS-128	300m	2,200,000	360*40	0.1* 0.1	

As Table II shows the properties of velodyne series products. Seen from the data, that the measurement range rose from 70m to 300m, output points every second rose from 300 thousand 9.6 million points, which means that the scanning accuracy and angle resolution are higher and higher. When applied in autonomous vehicle, it can locate precisely and detect smaller obstacles. While the price of Velodyne lidar series is so high(HDL-64 70 thousand dollars) that it can't be accepted by most people.

As to the domestic company SureStar, in 2016, it released the first 16-line scanning lidar R-Fans-16. In 2017, it released 32-line scanning lidar R-Fans-32 and R-Fans-32G,which is mainly applied to vehicle front loading market 64-line product C-Fans series. Meanwhile, the company is researching 3D flash lidar and plans to release it in 2018, as shown in Figure 5.

Figure 5. SureStar series.

TABLE III. PARAMETERS OF SURESTAR

type	distance	scanning line spacing(°)	FOV(°)	angle resolution(H°)	ranging accuracy(cm)
R-Fans-16	200m	1/2	360×24	<0.1	<3
R-Fans-32	200m	1°	360*31	<0.1	<3
R-Fans-32-G	200m	0.3/1/2/3	360*40	<0.1	<3
R-Fans-128	200m	0.23&0.46(VAR)	150*30	0.05	<2

From the data listed in the Table III, we can see that as the scanning line grows more and more, the horizontal angle

resolution improves, and the price is also acceptable. But when compared with Velodyne, we can see that there still exists a big gap mainly showing in horizontal and vertical angle resolution. Meanwhile these factors are also the key indexes of lidar. So there is still a lot of room for improvement for the country.

IV. NON-SCANNING LIDAR

A. A Brief Introduction of non-Scanning Lidar

Different from the scanning lidar, the internal of this type has no moving units. And 3-D flash lidar is just a kind of it. Currently domestic companies paying effort to 3-D flash lidar are Benewake, foreign companies like Continental and Guangpo are also paying efforts into researching 3-D flash lidar.

B. 3-D Flash Lidar

The working principle of 3-D flash lidar is similar with camera, which emits a laser to the detecting area, not just a single laser, then receiving the laser returned by the target diffuse reflection through a high sensitive receiver. Finally the surrounding point cloud data are got. The ranging accuracy of 3D flash lidar depends on the detector array [10].

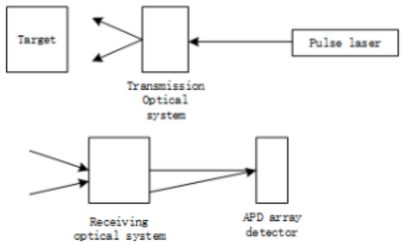

Figure 6. Principle of 3D flash imaging lidar.

Figure 6 shows the principle of 3D flash imaging lidar. The high-frequency pulsed laser beam is collimated, shaped and expanded by the transmission optical system and then irradiated to the target scene. The receiving optical system collects the returning signal and projects it on the APD detector array at the receiving end. Then the readout integrated circuit will process every data in each pixel, which measures the laser pulse round-trip time, target direction, and intensity information individually to obtain a 3-D image of the target.

C. 3-D Flash Lidar Development at Domestic and Abroad

Whether it's IBEO, Velodyne, Leddar Tech abroad Continental, Guangpo or domestic Leishen Intelligent System, Robosense, though they has the traditional mechanical radar products, inward and outward are more or less in the development of 3-D flash lidar.

In 2017, Continental of Germany showed the product of 3D flash lidar, known as HFL, which uses a 1064nm laser source. It can measure the distance range 327m, distance accuracy is 0.04m, field of view angle range 145° （H）× 3.2° (V), Horizontal angle resolution 0.25° , vertical angle resolution 4 layers@0.8° , ranging error <0.1m; distance speeding error 0.25m/s. it has successfully mounted on models such as Audi A8A7A6 and plans to mass production in 2020.

In October 2017, Guangpo released GP003 (Figure 7 shows) using the solid state array technology mainly applied in robotics and autonomous vehicle area. This type of lidar measurement distance is 150m, field of view angle range 360 ° （H）× 31 ° (V)when the distance range in 0.3m~20m, 25° ×16° when the range in 20m~100m. The company plans to apply this type lidar into Security, delivery robots, drones, autopilot and many other areas.

Figure 7. GP003.

In 2018, Canadian company LeddarTech will show the first 3D solid state lidar chip in CES.

In 2018, Leishen Intelligent System denounced the it would cooperate with NEWSIGHT of Israel to research and develop 3D flash V-lidar, whose ranging would be 200m, and of which would meet the regulatory requirements, and would be mass produced in 2018. As far as concerned, there are already five or more companies joining in the V-lidar development.

In 2017, Benewake released 3-D flash lidar CE-30D, which has been tested successfully by Audi vehicles.

Figure 8. CE-30D.

Figure 8 shows the CE-30, its measuring distance only reaches 30m, although it's impossible to detect long-distance high-speed automatic driving, it can detect a relatively accurate environment sensing capability within a range of 30m, and realize a relatively simple ADAS function such as automatic start-stop and blind-area detection of a vehicle in a busy road environment.

V. THE PROSPECTS OF LIDAR

Due to the rotate units of scanning mechanical lidar, a new technology is developed called micro electric mechanical system(MEMS) [11]. MEMS is a micro device or system that integrates micro-sensors, micro-actuators, micro-mechanical structures, micro-power micro-energy sources, signal processing and control circuits, high-performance electronic integrated devices, interfaces, and communications. The companies committed to MEMS lidar

around the world are Robosense, Continental of German, Japanese Pioneer, and Cepton, as Figure 9 shows different MEMS lidar made by companies all round the world.

Figure 9. MEMS lidar of Robosense, continental of German, Japanese pioneer, and cepton.

But as the consistency of MEMS solutions and product life can't be always guaranteed, the output energy limitation of 3D flash system can't exceed the single-point ranging system. After synthesizing the merits and defects of the two types of lidar, HeSai technology has proposed a solid-state imaging technology-Zoomable Light Oscillator (ZOL), which can achieve all the functional specifications under the premise of regulations. In April 2014, HeSai Technology released mixed solid lidar Pandar40, in the case of satisfying human eye safety, its ranging performance was updated from the early 100m@%40 reflectance to the 200m@%20 reflectance, and it has been tested on the autonomous vehicles of dozens of autopilot companies in domestic and abroad. The following pictures show the scenes 100m away detected by Camera, Pandar40 and Pandar GT, shown as Figure 10.

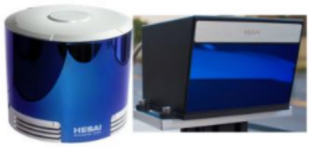

Figure 10. Pandar40 and Pandar GT.

Figure 11. The scens of 100m away detected by camera, Pandar40 and PandraGT.

Figure 11 shows imaging differnces by camera, pandar 40 and pandar GT. Pandar GT mainly solves the system's complexity, the units of the system declining to 100 from 1000 under the condition that doesn't sacrifice the performance, thus lowing the cost and improving the reliability of the system.

The images obtained by Pandar GT are not fixed in the vertical direction, but a dynamically adjustable range, including field of view angle, angle resolution and even the direction of the center area.

In December 2017, HeSai Technology joined Apollo, the Apollo Platform-based Autopilot Developer Suite Pandora is shown as the following Figure 12.

Figure 12. Pandora and Baidu apollo platform.

The properties of this suite realize the mechanical design combing a lidar and five cameras, no need to calibrate repeatly. Pandora starts up with the camera at the same time, and the data of multiple sensors realise the pixels levels alignment. Very low delay transmission of signals and target object tracking recognition are enabled.

VI. CONCLUSION

By analyzing the current development of lidar used in autonomous vehicle, we can see that performance of lidar is better and better, such as Velodyne ,the lidar giants, has improved its detected distance from 100m to 300m, angle resolution and output points are lager and lager, which means the obstacle it can detect is smaller and smaller. But one significant problem is that the price is so high that it's difficult for it to popularize for the masses to accept. So how to low the cost is Velodyne faces the biggest problem [11].

As the products of domestic company SureStar are also improving, but when compared to Velodyne, although the price is quite low, the performance is not so good as Velodyne's. So how to balance the relationship between performance and price is a key problem for multi-line scanning lidar.

According to the MEMS lidar, the problem is how to make the micro mirror, the technology is not so mature that there is still much space to improve.

The relationship of field of view angle, detected distance, and the power of laser source is 3D flash lidar's problem. The development direction of 3D flash lidar in the future is of high-energy, high-repetition-frequency, narrow-pulse microchip laser emission technology to increase the range and distance resolution of the laser radar to meet high image resolution and high frame rate requirements; Increasing the number of APD array bins responding to the visible light band to improve the integration and intelligence of APD/CMOS receiver devices.

In summary, although there are many types of lidar, they are adapted to many kinds of uses. The lidar applied in autonomous vehicle in the future should be of cheapness and high performance(high angle resolution, remote detected distance, low power consumption, etc.) so that it can meet the vehicle level as soon as possible.

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