Sensing Technologies to Support Safe Automated Driving Systems

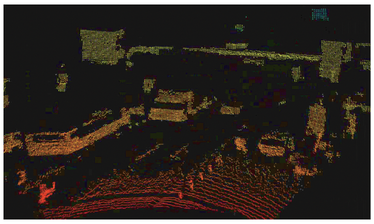
Innovations in automotive sensing technologies to support safe driving have been advancing in terms of both performance and cost as a result of the practical realization of advanced driver assistance systems (ADAS). In order to realize a high-level automated driving system, light detection and ranging (LiDAR), which can provide information on the peripheral conditions of a vehicle as three-dimensional (3D) point clouds obtained by laser beam irradiation, is essential in addition to conventional sensors, including cameras and millimeter-wave radars. An advanced image recognition processor is also necessary to detect and analyze a wide variety of objects using the obtained sensor data.

Toshiba Electronic Devices & Storage Corporation has been developing a photodetector with high sensitivity as well as an analog front-end (AFE) circuit and a distance measurement algorithm to detect small objects at long distances as sensing technologies to realize long-range, high-resolution LiDAR. We have also been improving the performance of conventional image recognition technologies for our Visconti image recognition processor products. Furthermore, in cooperation with Denso Corporation, we are working on the development of an artificial intelligence technology called deep neural network-intellectual property (DNN-IP) to recognize a wide variety of objects with higher accuracy than is attainable with conventional methods.

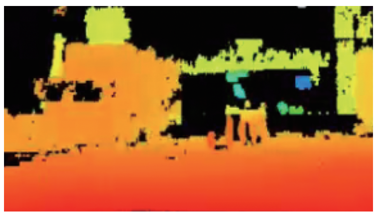
1. Introduction

Driving a car consists of a repetitive cycle of three actions: a) "recognition" to understand the surrounding situation, b) "judgment" to decide the next action from information obtained by recognition, and c) "operation" to execute the determined actions. In particular, the ability to recognize moving objects such as pedestrians, other vehicles and stationary objects such as guardrails and buildings greatly influences driving safety.

Using ADAS, automotive sensors are used as aids for human recognition, but for automated driving systems, it is necessary to perform all recognition by means of automotive sensors. As a new sensor for automated driving systems, LiDAR (Light Detection and Ranging) is attracting attention in addition to existing automotive sensors such as cameras and millimeter-wave radars. LiDAR can acquire information on the environment surrounding automobiles in the form of 3D point clouds (See **Fig. 1**), and are considered indispensable automotive sensors for the realization of future automated driving systems. Also, recognition using camera imaging is carried out by the image recognition processor



(a) 3D point cloud



(b) Distance Image

Figure 1: 3D point cloud and distance information obtained by LiDAR

By emitting a laser beam, a LiDAR obtains the distance between itself and the object as high-resolution 3D point clouds.

“Visconti” developed by Toshiba Electronic Devices & Storage Corporation.
Here, we first explain the features of automotive sensors required for automated driving systems. Next, we describe the semiconductor products for LiDAR and aspects of the technical development of Visconti.

2. Automotive sensors necessary for automated driving systems

2.1 Automated driving levels and necessary technologies

Currently, the development of automated driving technology is being pursued throughout the world, but it is the United States that is in the lead. The National Highway Traffic Safety Administration (NHTSA) in the US has announced guidelines to accelerate the promotion of traffic safety through the development and spread of automatic driving systems. The classification of automated driving levels is shown in **Table 1** (1).
Compared with Level 2, which is currently being deployed using cameras and millimeter-wave radar, Level 3 and above are very different in terms of technology and regulations. Up to Level 2, the driver has the final responsibility for recognizing the driving environment, but from Level 3 onward, the responsibility rests with the system. In order to realize automated driving systems for Level 3 and beyond, new sensing and control technologies apart from the current ADAS are required to improve recognition performance. What are considered particularly important are the self-localization technology and the object recognition technology for determining the moving position of vehicles with high accuracy.
With the self-localization technology, LiDAR can capture the environment surrounding vehicles in the form of high-precision 3D point cloud data, matching them easily with various other forms of high-definition 3D map information such as center-lines of roads, connections between roads, crosswalks, stop lines, traffic signs and signboards. In the area of object recognition, estimating the distance between the host vehicle and the object using LiDAR is improved, and the performance of the image recognition processor for detecting the lanes around vehicles, pedestrians, road signs and other vehicles from the image captured by the in-vehicle camera is very important.

Table 1: Definition of automated driving levels

Level	Summary	Safety execution
Level 1 (Driving Assistance)	Driving mode- specific execution by a driver assistance system	Driver
Level 2 (Partial Automation)	Part-time or driving mode-dependent execution by one or more driver assistant systems	Driver
Level 3 (Conditional Automation)	Driving mode-specific performance by an automated driving system of all aspects-Human driver responds appropriately to a request to intervene.	Driver and System
Level 4 (High Automation)	Driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task	System
Level 5 (Full Automation)	Full-time performance by an automated driving system of all aspects	System

*Based on Strategic Conference for the Advancement of Utilizing Public and Private Sector Data, Strategic Headquarters for the Advanced Information and Telecommunications Network Society: Public-Private ITS Initiative/Roadmap 2017 (1)

2.2 Comparison of automotive sensors required for automated driving systems

Table 2 shows a comparison of automotive sensors typically used in automated driving systems.
In addition to distinguishing vehicles and pedestrians, the camera can recognize road signs and the color of traffic lights. However, at

Table 2: Tradeoff table for automotive sensors

Item	Camera	Millimeter-wave radar	Sonar	LiDAR
Distance measured	★★	★★★	★	★★★
Spatial resolution	★★	★	★	★★★
Weather resistance (Fog, rain, etc.)	★	★★★	★★	★★
Nighttime performance	★★	★★★	★★★	★★★
Object detection/ recognition	★★★	★	★	★★

★: OK ★★: Good ★★★: Optimum

night and in the case of backlighting, or in bad weather conditions such as fog and rain, the detection capabilities decline similar to those of human eyesight.

In contrast, since the millimeter-wave radar detects radio waves, it is hardly affected by environmental lighting or weather. Since spatial resolution is inferior to that of other sensors, however, the capability to recognize objects is reduced.

As a third option, sonar is not greatly affected by ambient lighting but distance measurements are limited to short distances.

Since LiDAR has high spatial resolution, it is possible to detect not only objects but also free spaces. But because near-infrared laser light is used, detection performance deteriorates compared with millimeter-wave radar in bad weather such as fog and rain.

Single sensors can satisfy requirements up to Level 2 of automated driving, but for Level 3 and above, it is difficult to detect complex environments using sensors alone. Therefore, a sensor fusion technology has been developed that improves the recognition performance in the case of using a multitude of sensor types.

3. Semiconductor products for LiDAR

3.1 Principle and configuration of LiDAR

LiDAR measures the reflected light from an object using a pulsed laser beam and calculates the distance d to the object using the reflection time t (the time from light emission to detection of reflected light) (See **Figure 2**).

LiDAR systems capable of acquiring 3D images can be roughly divided into: a) a scanning-type LiDAR using a pulsed laser that repeatedly emits light together with a scanning mechanism and, b) a flash-type LiDAR using a high-power single pulsed laser with a two-dimensional photodetector array. Scanning LiDAR systems are suited for long-range outdoor distance measurements, and **Figure 3** shows a typical example.

Scanning methods used for scanning-type LiDAR include mechanical rotation, MEMS (Micro Electro Mechanical Systems), and phased arrays. The pulsed laser serving as the light source often operates in the vicinity of the 900 nm band.

3.2 Technology development trend of semiconductor products for LiDAR

Traditionally, LiDAR was used for research and development of automated driving systems, and is now finally being implemented on mass-production vehicles. However, there are still issues concerning full-scale adoption in terms of the high-precision, long-distance measurement performance and resolution needed. Therefore, in order for adoption to expand to mass-market cars, more efforts are needed in terms of miniaturization and cost reduction.

To meet these demands, we are developing technologies for highly sensitive photodetectors, AFE for processing signals from these photodetectors, and distance ranging algorithms.

3.2.1 High-sensitivity photodector SiPM

To measure long distances, it is necessary to detect the faint light reflected from a distant object in the presence of strong sunlight.

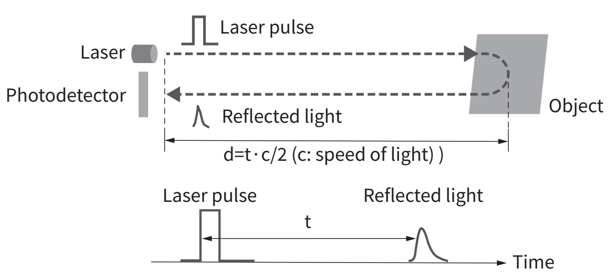


Figure 2: Principle of distance measurement using LiDAR

By emitting a laser beam at an object and measuring the time for the reflection to arrive (using the Time of Flight (TOF) method), the distance is measured.

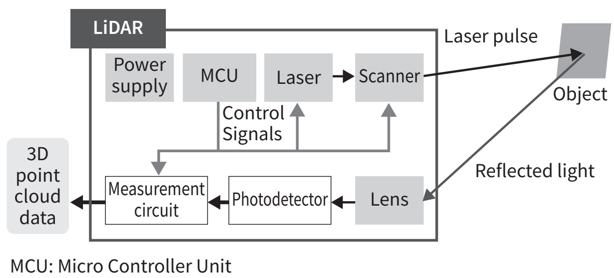


Figure 3: Configuration of scanning LiDAR

The optics block (scanner and lens) and the electronics block (photodetector and measurement circuit)

The amount of reflected light from the measured object is very small, and a silicon photomultiplier (SiPM: Silicon Photo-multiplier) that can count individual photons is effective as a high-sensitivity photodetector (See **Figure 4**).
Compared to avalanche photodiodes (APD) and PIN (positively-intrinsic-negative) photodiodes (PD) widely used for current LiDAR, SiPM has high sensitivity, low operating voltage and low temperature dependency (See **Table 3**). Furthermore, we are optimizing the device structure in order to improve the sensitivity at around 900 nm.

3.2.2 AFE

An averaging process using an ADC (Analog-to-Digital Converter) circuit is effective for extracting the necessary signals from noisy signals that include sunlight, and is mainly applied to long-distance measurements. However, in the averaging process using the ADC, it is difficult to perform high-speed processing for short distances with high accuracy. Therefore, we developed a proprietary hybrid circuit consisting of two components: short-distance TDC (Time-to-Digital Converter) circuit and long-distance ADC circuit. By dedicating the ADC for long distance, it is possible to balance short-distance and long-distance measurements while reducing the processing speed required for the ADC circuit. By adopting this unique structure, the ADC circuit is small in size and low in power consumption, and it is possible to build a LiDAR system that offers higher performance and is more compact than conventional devices.

3.2.3 Measurement algorithm

In a conventional averaging process, when the laser light is reflected from multiple objects, the resolution is lowered and small objects may go undetected and be overlooked. In order to avoid this problem, we developed a high-resolution distance measurement algorithm SAT (Smart Accumulation Technique) that can detect small objects by discriminating whether objects reflecting laser light are identical or not, selecting only the identical objects, and performing averaging processing (See **Figure 5**) [(2)].

In addition, if there is no object at a measurable distance, the LiDAR outputs a result based on noise and causes erroneous detection. When performing averaging processing to eliminate erroneous detection, a phenomenon called "range-value clustering" occurs where correct data detected from a measured

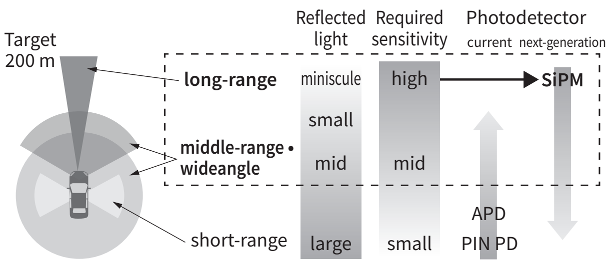


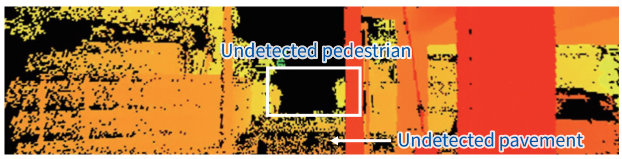
Figure 4: Requirements for photodetectors to achieve long-range distance measurement

For long-range distance measurements, since the reflected light is miniscule, SiPM is considered the solution for the high-sensitivity photodetector.

Table 3: Comparison of performance of photodetectors

Item	PIN PD	APD	SiPM
Amplification	1	10 to 100	10^5 to 10^6
Operating voltage (V)	to 10	to 300	to 30
Temperature dependency	small	large	small

(a) Camera image

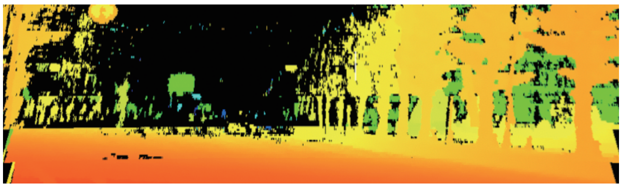


(b) Conventional averaged processing

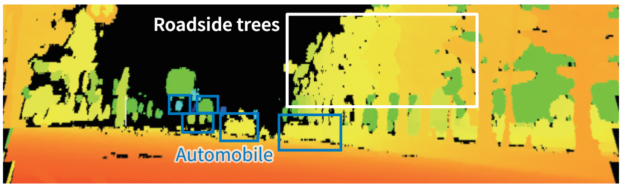
(c) Newly developed SAT processing

Figure 5: Comparison of processing results obtained by conventional method and newly developed smart accumulation technique (SAT)

Pedestrians and pavement not detectable by conventional methods are detected using SAT processing.



(a) Conventional denoising

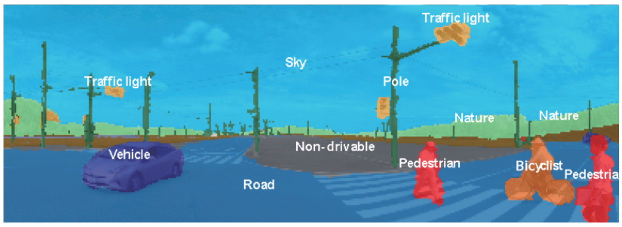


(b) Newly developed denoising

Figure 6: Comparison of de-noising results obtained by conventional and newly developed methods

Compared with conventional de-noising, the newly developed method can detect objects without excessive suppression.

(a) Actual image



(b) Detected targets using DNNIP

Source: Denso Corporation

Figure 7: Example of recognition result obtained by DNN-IP

Using DNN-IP, various objects can be recognized with improved detection accuracy.

object at a long distance are also removed. Therefore, we analyzed this range-value clustering and developed a method of expressing the reliability of the output distance data with a relational expression, from the size of the cluster and the strength of the signal, and adjusting the parameters based on the relational expression. As a result, we succeeded in creating an algorithm to eliminate false detection while suppressing occurrence of range-value clustering (See **Figure 6**) [3].

4. Image recognition processor Visconti

Visconti performs processing on the image from the on-board camera, detects lanes around the vehicle itself as well as other vehicles, pedestrians, signs, etc., and outputs the results. In addition, it has a large number of image processing accelerators that perform various processes necessary for image recognition, and can realize advanced image recognition processing in real time with low power consumption.

For the realization of ADAS and automated driving systems, we are developing technologies for implementation in the next-generation Visconti. In addition to improvements in the baseline image processing technology, we are working in collaboration with Denso Corporation on the development of artificial intelligence technology DNN-IP (Deep Neural Network-Intellectual Property) to achieve a dramatic improvement in the recognition performance for objects and detection accuracy (See **Figure 7**) [4].

5. Conclusion

We described the semiconductor products for LiDAR and the technical development of image recognition processors required for ADAS and automated driving systems.

We will continue to accelerate the R&D in the field of automated driving systems and provide automotive semiconductor products that will contribute to safer traffic.

References

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(3) Tanabe, K. et al. “Data selection and de-noising based on reliability for long-range and high-pixel resolution LiDAR”. Proc. 2018 IEEE Symposium on Low-Power and High-Speed Chips and Systems (COOL CHIPS), Yokohama, 2018-04, IEEE. 2018, p.1–3.

(4) DENSO and Toshiba Agree to Develop Artificial Intelligence Technology, Deep Neural Network-IP, for Next-generation Image Recognition Systems <http://www.toshiba.co.jp/about/press/2016_10/pr1701.htm>,