Special Feature: Active Safety

Research Report

Development of Next Generation LIDAR

Hiroyuki Matsubara, Mineki Soga, Cristiano Niclass, Kota Ito, Isao Aoyagi and Manabu Kagami

Report received on Feb. 21, 2012

ABSTRACT We are developing automotive light detection and ranging (LIDAR) sensing technologies based on both CMOS single-photon avalanche diodes (SPADs) and optical scanning systems. CMOS SPADs are highly sensitive detectors that can detect single photons and can form dense pixel arrays. These characteristics offer significant benefits for high-resolution detection. However, SPADs have the disadvantage of being oversensitive to background light due to their digital binary output. An attempt was made to overcome the adverse effect of beam thinning when the reflected beam is scanned, as well as to reduce background light by detecting only for a limited time and area. By combining a coaxial optical scanning system with a one-dimensional SPAD array, pedestrians can be easily detected at a range of up to 50 m. To the best of our knowledge, this is the first real-time CMOS SPAD-based long-range LIDAR in existence. We are also developing a MEMS mirror-scanned LIDAR using a two-dimensional SPAD array. Although this device is inferior to the coaxial type in terms of distance range, it has the advantage of being smaller in size.

KEYWORDS LIDAR, Laser Rangefinder, Depth Imager, SPAD, GM-APD, MEMS

1. Introduction

We are currently developing automotive light detection and ranging (LIDAR) sensing technologies for scanning and detecting obstacles around cars. At present, there are various sensing technologies on the market that can achieve this, such as millimeter wave radars and stereo cameras. Radar has the advantage of long-range scanning capabilities coupled with a high resistance to unfavorable weather conditions such as rain and fog, and is therefore the existing technology of choice. However, the demand for higher spatial resolution has been gradually increasing, allowing more rapid detection of hazardous situations and improved safety. Stereo cameras satisfy the high-resolution requirement; however, in comparison to radar, their distance range is comparatively short. Furthermore, stereo cameras are more susceptible to adverse weather conditions, most notably at night. In response to this, the LIDAR is designed to simultaneously meet the requirements for both long range and high spatial resolution. As noted in recent literature, the LIDAR system manufactured by Velodyne(1) has been adopted as the primary sensor in research for autonomous driving. Although performance in unfavorable weather conditions continues to be a weak point of conventional LIDAR, it is hoped that its performance in rain can be improved by installing it inside the windshield or by improving its sensitivity.

Our research aims at developing compact LIDAR technology with both high-resolution and long-range capabilities. To date, long-range LIDARs using an optical scanning system as well as a small number of photo detectors have been reported;(2) however, in both cases, the measured vertical resolution is not high. High-resolution LIDARs known as depth imagers have also been reported, although their distance range is considered too short for our applications. Although the above-mentioned Velodyne LIDAR system satisfies the resolution and range requirements, the unit is too large due to the numerous light sources and photo detectors utilized in the device.

One possible method for realizing a compact, high-resolution sensor is to increase the resolution using a detector array. However, since the received signal light would be divided in such an array, higher sensitivity detectors are required. In line with this, single-photon avalanche diodes (SPADs) based on complementary metal-oxide semiconductor (CMOS) technology are expected to be capable of fulfilling the dual demands for an array-type detector and high sensitivity.[3] CMOS SPADs have a very high sensitivity, with the ability to detect single photons, and they can easily be incorporated into an array since their operating voltage is low. Globally, a number of depth sensor designs using CMOS SPAD technology have been reported.[4,5] However, the distance ranges of these sensors are too short for our applications, and performance results in outdoor conditions have not been reported. In addition, the sensors are based on diffuse light sources in combination with two-dimensional (2-D) SPAD array for receiving optical signals in the same manner as a depth imager. In contrast, we have developed a compact LIDAR that has both high resolution and a long distance range by combining a SPAD array with an optical scanning system. By scanning a narrow beam and receiving the reflected light only from the area that is irradiated at that time, the total receiving time can be reduced, and the problem of a SPAD's vulnerability to background light can be mitigated.

2. CMOS SPAD Characteristics

SPADs, also known as Geiger-mode avalanche photodiodes, are reverse biased at their characteristic breakdown voltage, thus providing single-photon detection capability. The output signal of a SPAD is a digital voltage whose amplitude does not depend on the number of photons being detected. Since a full digital pulse may be triggered by a single incoming photon, SPAD technology offers unique detection capabilities. On the other hand, due to its digital nature, it is not possible to determine how many photons were actually involved in one particular detection event. As a result, in order to differentiate optical signals from dark count noise or background light, it is necessary to accumulate a high number of detection cycles and perform statistical processing. For detectors without any amplifying function, thermal noise is dominant. Conversely, thermal noise does not occur with a SPAD, and the main subject of concern is the presence of background light.

As mentioned above, SPADs are fabricated using CMOS technology, the key benefit of which is that detector devices and signal processing circuits can be implemented on a single chip, thereby reducing costs. Additional benefits include a low operating voltage and the ability to implement dense pixel arrays. However, a low operating voltage leads to a narrow depletion region thickness, which, in turn, reduces the so-called photon detection probability (PDP), especially in the near-infrared (NIR) spectral range. For short optical wavelengths, such as those of visible light, the reduction in PDP is small as many photons are absorbed near the surface due to the high absorption coefficient of silicon. However, at 900 nm, which is the wavelength used in our LIDAR, since the absorption coefficient is small, photons tend to penetrate deep into the silicon beyond the depletion region of the device. The probability of detecting these photons is therefore small in devices featuring narrow depletion regions. Nonetheless, a solution to this limitation has recently been proposed.[6]

3. Coaxial LIDAR Using One-dimensional SPAD Array[7]

By combining SPADs with a coaxial optical scanning system, we hope to achieve a significant increase in the distance range. A coaxial optical scanning system refers to an architecture in which the emitted and received light beams are anti-parallel and are simultaneously scanned. This can improve the signal-to-noise (S/N) ratio by narrowing both the emitted beam and the received field-of-view (FOV). The resolution is increased by the use of a one-dimensional (1-D) detector array, since the longitudinal return beam is divided among the individual detectors in the array.

Figure 1 shows a simplified representation of the LIDAR system configuration. An 870-nm pulsed laser diode (LD) emits an optical beam with vertical and horizontal divergences of 1.5 and 0.05 degrees, respectively. The laser beam is aimed at a 3-facet

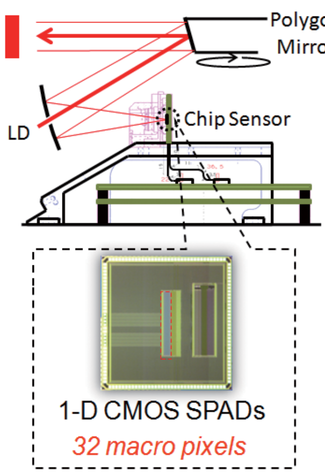

Fig. 1 Overall coaxial sensor architecture.

polygon mirror through an opening in the center of an imaging concave mirror. Each facet of the rotating polygon mirror has a slightly different tilt angle. As a result, during each 100-ms revolution, the laser beam is reflected in three different directions with vertical angles of +1.5, 0, and -1.5 degrees. Since each of these three beams has a vertical divergence of 1.5 degrees, a contiguous vertical FOV of 4.5 degrees is achieved. During 170-degree horizontal scanning with a 0.5-degree pitch, the back-reflected photons from the targets in the scene are collected by the same mirror facet and imaged onto the CMOS sensor chip at the focal plane of the off-axis parabolic mirror. The chip has a vertical line sensor with 32 macro-pixels, each of which consists of 2 × 6 SPADs. These pixels resolve the three different vertical strips that make up the scene at different facet times, thus generating an actual vertical resolution of 96 pixels (32 pixels × 3 facets). The image frame is then repartitioned into 340 × 96 actual pixels at a rate of 10 times per second. A visible light cut-off filter and an interference filter (not shown in Fig. 1) are also placed in front of the sensor for background light rejection.

Since the measurement time available per point during scanning is relatively short, the high number of measurement cycles typically required by SPADs is no longer feasible. To overcome this limitation, our sensor replaces the normal time averaging with a method involving temporal and spatial histogramming of photons. A macro-pixel consisting of 12 SPADs outputs the sum of each individual SPAD output. By taking the output only when two or more SPADs within it react simultaneously, the problem of saturation by background light is resolved.

Figure 2 shows a photograph of the overall coaxial LIDAR sensor mounted on a tripod, in which the 600-rpm rotating polygon mirror can be seen. The remaining electro-optical components are enclosed in a customized case. The dimensions of the sensor are 120 mm (width) × 120 mm (height) × 180 mm (depth). Although the sensor is relatively large, we anticipate that it could be reduced to at least one-quarter of its present size while maintaining the same performance.

In order to investigate the suitability of this approach, experiments were carried out using this prototype on a car. The sensor system was installed on the roof of a car at a height of 2 m and tilted slightly towards the ground. **Figure 3** shows a sample of the measurement results;

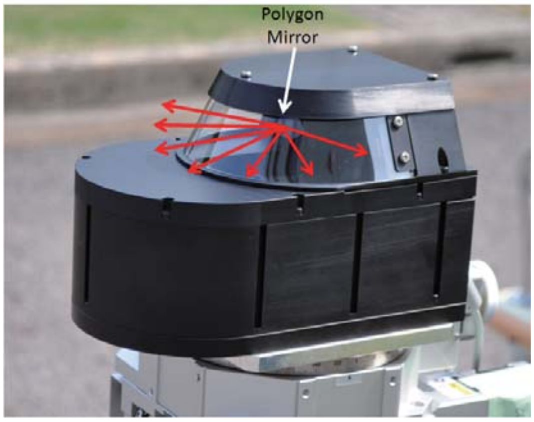

Fig. 2 Photograph of coaxial LIDAR system.

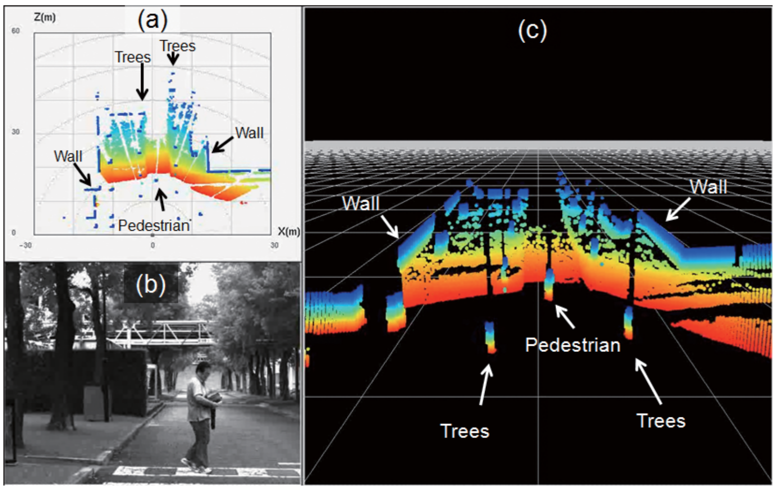

Fig. 3 Measurement results for coaxial LIDAR on a car.
(a) Top view (b) Real-time camera image (c) 3-D view. The vertical scale is color coded from blue (top-most band) to red (bottom-most band) in (a) and (c).

Figs. 3(a) and (c) show measured distances using a top-view projection and a 3-D view, respectively. In addition, Fig. 3(b) shows an image simultaneously acquired using a standard camera. In Figs. 3(a) and (c), the vertical scale is color coded from blue (top-most band) to red (bottom-most band). Pedestrians and road features (trees, building walls, and ground) can be clearly seen, as well as a height difference of approximately 15 cm between the ground and the sidewalk curb. The results were made possible by the suitably high angular and distance resolution of our sensor. In the top view shown in Fig. 3(a), some radial empty lines, i.e., areas without measurement points, may be seen. These occluded areas are caused by nearby trees that block the optical signal.

Additionally, it was experimentally confirmed that this prototype can detect pedestrians at distances of up to 50 m during the day and 80 m at night. For this experiment, a conservative pedestrian model measuring 1.7 m × 0.3 m and coated with a 9% reflectance material was utilized. To the best of our knowledge, this is the first real-time CMOS SPAD-based long-range LIDAR in existence. While an outstanding SPAD-based pixel fill factor of 70% has contributed to this performance, further potential for improvements exists, in particular with respect to NIR PDP.

4. MEMS Mirror-scanned LIDAR Using Two-dimensional SPAD Array

We are also investigating the potential of utilizing a 2-D SPAD array, similar to other reports.[8] Our approach differs the way the targets in the scene are illuminated. Rather than utilizing a diffuse light source, we employ collimated laser beams scanned by a micro-electro-mechanical system (MEMS) mirror. As the laser beams are scanned by the MEMS mirror, only SPADs that image beams with the same direction and FOV are synchronously turned on. This is achieved by applying an electrical scan to the receiver SPAD array. Assuming that the total light source energy is the same, the received signal energy is also the same. However, background light can be sharply reduced by turning on the SPADs for only a limited period of time, such as when they are exposed to the optical signal, and therefore, the signal to noise ratio can be improved.

This LIDAR has the following advantages over the coaxial type:

1. The scanning optics can be miniaturized while maintaining the receiving aperture, which directly influences sensitivity. This is accomplished by the use of a movable mirror only for emission, which leads to the miniaturization of the whole sensor.
2. A second advantage is that a high-resolution depth map can be obtained without any distortion, independent of the angular resolution of the scanner, since the resolution is determined by the 2-D detector array. However, the drawback to this approach is that the fill factor cannot be enlarged for 2-D array wiring.

Figure 4 shows a photograph of our prototype sensor as well as an illustration of the scanning mechanism.

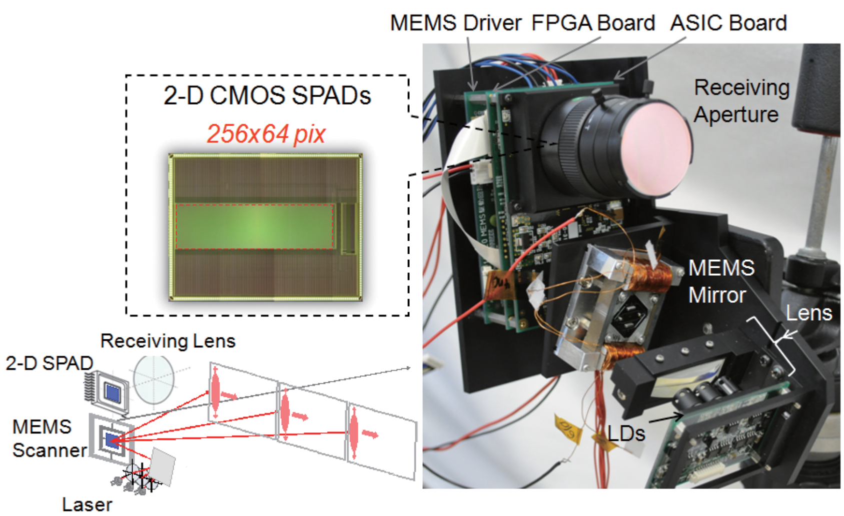

Fig. 4 Photograph of sensor prototype and illustration of scanning mechanism. Three LDs, one MEMS mirror scanner, and one 2-D array of CMOS SPADs are utilized. The MEMS mirror scans the beam in 2-D.

The light beams emitted from three LDs are collimated by the optical system and brought together at a single point. A MEMS mirror placed at this point scans one beam in two dimensions within a horizontal and vertical range of 15 and 11 degrees, respectively. The MEMS mirror is 8 mm × 4 mm, and the three LDs are used to expand the horizontal FOV, thus leading to a total FOV of 45 × 11 degrees. The 2-D SPAD array measures 15 mm × 6 mm and has 256 × 64 pixels. The focal length of the receiving lens placed in front of the detector is set at 8 mm so that the irradiated area and the received FOV are the same.

Figure 5 shows an example of the results acquired with this sensor. Figure 5(a) shows distance data plotted using a top-view projection. As can be seen, the corner between two walls can be recognized. Figure 5(b) shows a color-coded depth map whereby the distance is color coded from red (nearest) to blue (farthest). In addition, the shape of a person's upper body can be clearly recognized, which demonstrates that our sensor can acquire high-resolution distance data.

At the present time, a sufficient distance range for typical automotive applications has not yet been obtained with this sensor. However, we believe that this type of sensor offers significant miniaturization potential for short and mid-range applications.

5. Conclusion

We have developed LIDAR technology based on CMOS SPAD arrays and optical scanning systems. Our experimental data show that the distance range and the robustness against background light are greatly improved by combining a 1-D SPAD array with a coaxial scanning system. Using this sensor, pedestrians can be easily detected in real-time at a range of up to 50 m. To the best of our knowledge, this is the first real-time CMOS SPAD-based long-range LIDAR in existence. Furthermore, a second LIDAR system combining a MEMS scanner and a 2-D SPAD array has also been developed, and its operation was evaluated. Although this device has a shorter distance range than that of the coaxial type, it has the significant advantage of reduced size.

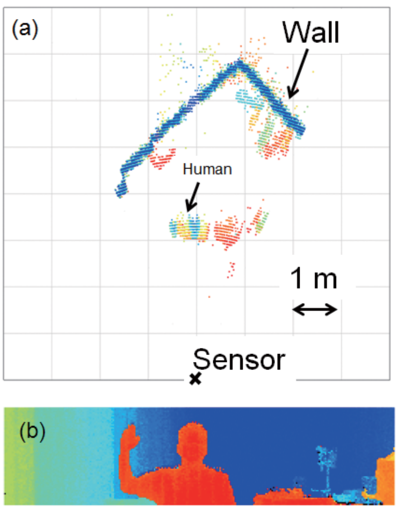

Fig. 5 Measurement result for LIDAR using 2-D SPAD Array. (a) Top view (b) Depth map.

Acknowledgment

The authors received generous support from Mitsutoshi Maeda for the mechanical design, and Yasuhiro Nishimura for the electrical circuit design. We would also like to thank Toyota Motor Corporation and EPFL for their technical support on the design of the SPAD devices.

Reference

(1) "Velodyne Lidar", <http://velodynelidar.com/lidar/lidar.aspx>, (accessed 2011-12-18).

(2) Fuerstenberg, K., et al., "Pedestrian Recognition in Urban Traffic Using a Vehicle Based Multilayer Laserscanner", *Intelligent Vehicle Symposium 2002 IEEE*, Vol.1 (2002), pp.31-35.

(3) Niclass, C., et al., "A 128×128 Single-photon Imager with on-chip Column Level 10b Time to-digital Converter Array", *IEEE Journal of Solid-State Circuits*, Vol.43, No.12 (2008), pp.2977-2989.

(4) Niclass, C., et al., "Single Photon Synchronous Detection", *IEEE Journal of Solid-State Circuits*, Vol.44, No.7 (2009), pp.1977-1989.

(5) Walker, R. J., et al., "A 128×96 Pixel Event-driven Phase-domain ΔΣ-based Fully Digital 3D Camera in 0.13μm CMOS Imaging Technology", *ISSCC Digest of Technical Papers* (2011), pp.410-412.

(6) Webster, E., et al., "An Infra-red Sensitive, Low Noise, Single-photon Avalanche Diode in 90nm CMOS", *IISW2011* (2011).

(7) Niclass, C., et al, "A 100m-range 10-Frame/s 340×96-Pixel Time-of-flight Depth Sensor in 0.18μm CMOS", *ESSCIRC2011* (2011), pp.107-110.

(8) Ito, K., et al., "Imager-type Laser Radar Using MEMS Mirror and Single Photon Avalanche Diode Array", *Proceedings of 47th Meeting on Lightwave Sensing Technology* (in Japanese) (2011).

Hiroyuki Matsubara
Research Fields:
- Development of Laser Rangefinder
- Optics
- Optical Measurement
Academic Society:
- SPIE – The International Society for Optical Engineering

Mineki Soga
Research Fields:
- Laser Rangefinder
- Computer Vision for ADAS

Cristiano Niclass
Research Fields:
- Time-of-flight 3D Image Sensors
- Single-photon Detectors in CMOS Technology
- Picosecond Resolution Time-to-digital Converters
- High-speed and Low-noise Mixed-signal ICs with Emphasis on High-performance Imaging
Academic Degree: Ph.D.
Academic Society:
- IEEE
Award:
- Innovation Grant (innogrant), EPFL, Switzerland, 2006

Kota Ito
Research Field:
- Analog/Digital Circuits
Academic Society:
- The Japan Society of Applied Physics

Isao Aoyagi
Research Field:
- Development of MEMS Devices
Academic Society:
- The Institute of Electrical Engineers of Japan

Manabu Kagami
Research Fields:
- Optical Communication Devices
- Optical Sensor
Academic Degree : Dr. Eng.
Academic Societies:
- The Institute of Electronics, Information and Communication Engineers (IEICE)
- The Japan Society of Applied Physics
- The Optical Society of Japan
- Society of Automotive Engineers of Japan
- The Japan Institute of Electronics Packaging
- IEEE
- The Optical Society of America
Awards:
- Best Paper Award of IEICE, 2008
- Best Paper Award of IEEE CPMT Symposium Japan, 2010

