Direct Time−of−Flight Depth Sensing Reference Designs

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Introduction to Depth Sensing

Depth sensing with precise measurements is a requirement for many applications in today's markets, including industrial, consumer, and automotive. **onsemi** has designed a suite of depth sensing reference designs and evaluation kits to simplify the design process enabling faster development and time−to−market of depth sensing solutions for multiple markets.

There are many different methods for depth sensing. Examples of methods using standard CMOS image sensors are stereo triangulation, phase detection pixels, and structured light.

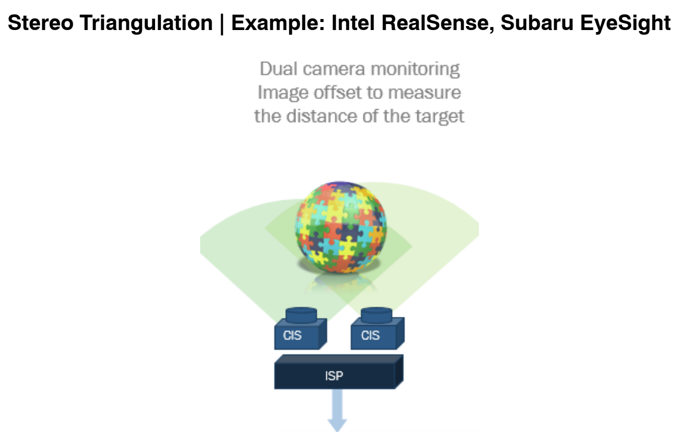


Figure 1. Stereo Triangulation

Distance is obtained from triangulation of received light from two different cameras. By comparing the disparity in position of an object between the images captured by the cameras, the distance to the object can be calculated.

- **Pros**
  - Passive method
  - Standard image sensors
- **Cons**
  - Requires 2x cameras
  - Max distance dependent on distance between cameras
  - Highly dependent on light conditions
  - Computational cost

- **Suitable Applications**
  - Low−cost depth camera
  - Indoors – short distance app

Phase Detection Pixels | Example: iPhone Camera AutoFocus

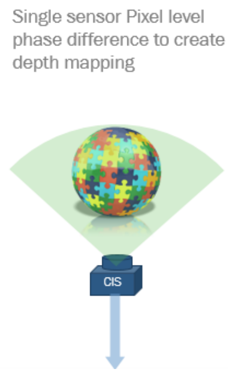


Figure 2. Phase Detection

Distance is obtained for points in the scene with a single camera. The image sensor at the pixel level calculates depth by using the phase difference of light received by pairs of pixels with light shields at difference positions, or by using multiple photodiodes under the same microlens.

- **Pros**
  - Passive method
  - Standard image sensors
- **Cons**
  - Poor depth resolution
  - Highly dependent on light conditions
  - Computational cost
  - Short distance
- **Suitable Applications**
  - Smartphone autofocus

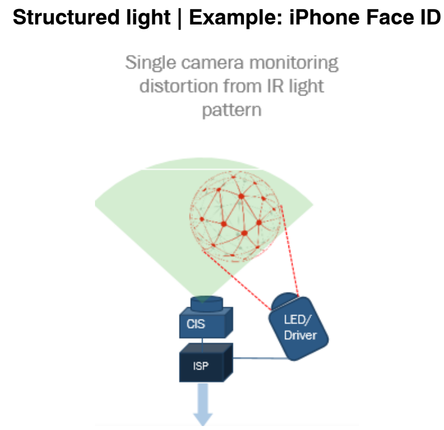


Figure 3. Structured Light

A pattern of received infrared light is analysed by a camera with a traditional CMOS image sensor and the distortion is used to calculate depth in the scene.

Distortion of patterns used to obtain 3D shape of objects.

- **Pros**
  - Suitable for short distance
- **Cons**
  - Active method
  - Sensitive to ambient light
  - Depth error increases with distance
  - Not suitable for long distance
- **Suitable Applications**
  - Face recognition

LiDAR

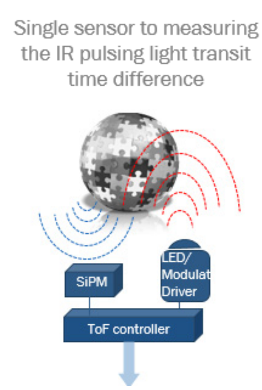


Figure 4. LiDAR

Light Detection And Ranging allows for superior depth sensing to alternative approaches thanks to its high depth and angular resolution, and ability to operate in all light conditions owed to its active approach of using an infrared light transmitter along with a receiver. LiDAR is widely deployed across many different markets for a variety of applications and use cases, including automotive, industrial, robotics, and consumer augmented and virtual reality (AR/VR) applications.

Generally LiDAR refers to the direct Time of Flight (dToF) measurement technique which calculates the time delay between a transmitted signal and its return echo(es). Another approach is indirect time−of−flight (iToF). Both approaches can use pulsed or continuous modulation.

iToF utilizes modulation of image sensor pixels integrating many light pulses in a limited number of bins, typically 2. The timing of the returned pulse is determined by measuring the charge in the different bins.

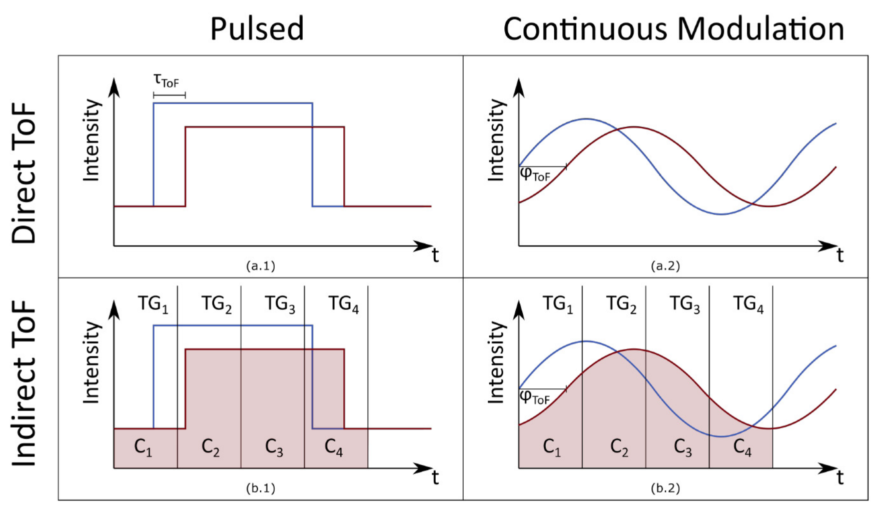


Figure 5. Direct & Indirect ToF Methods

Table 1. TOF METHOD COMPARISON

Parameter	iToF	dToF
Acquisition Speed	Long Integration Time	Fast Acquisition
Range Ambiguity	Yes	No
Detect Multiple Echoes	No	Yes
Pixel Count	Large	Smaller
Data Volume	Small	Larger
Operation in Strong Ambient Light	OK	Good

iToF is suitable for shorter range depth sensing applications and use in indoor environments and environments without direct sunlight on the sensor.

dToF is suitable for both short− and long−range depth sensing applications. It offers faster acquisition rates and the ability to measure multiple echoes, allowing for detection of multiple objects in a return path.

The rest of this paper will focus on the pulsed dToF method which can be achieved with a single measurement or by accumulating multiple measurements per reading.

In *single shot* mode a short laser pulse is fired from the transmitter as a timer is activated. When the laser pulse hits an object within the LiDAR system field of view it is reflected back. The returned pulse is detected at the receiver and the timer is stopped. Half this delta in time multiplied by the speed of light provides the distance in meters to the detected object.

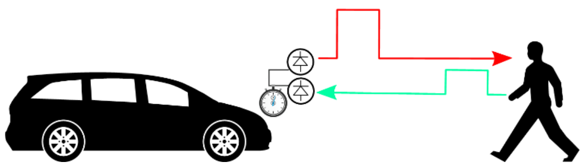


Figure 6. Single Shot Mode

The worst−case target is one far away with low reflectivity, such as a pedestrian wearing black clothes. In this case the returned laser pulse may be hard to discriminate above noise sources such as photons coming from ambient light. A more powerful laser helps to overcome this limitation but the maximum laser power must be constrained within eye safety limits as outlined in IEC−60825−1.

In *multi−shot* mode, the signal−to−noise ratio (SNR) of a LiDAR system is improved by creating a histogram of the time stamps of the detected laser pulses, which can be used to extract the distance of the object(s). This method extends the maximum depth that the system can detect.

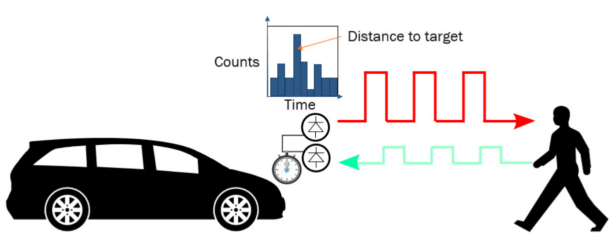


Figure 7. Multi−shot Mode

In this mode, every single photon detection event is correlated in time. The resulting histogram contains a noise level from sources such as ambient photons but the real object in the scene provides more returns at about the same time value, creating a clear peak in the histogram which provides the distance to a target.

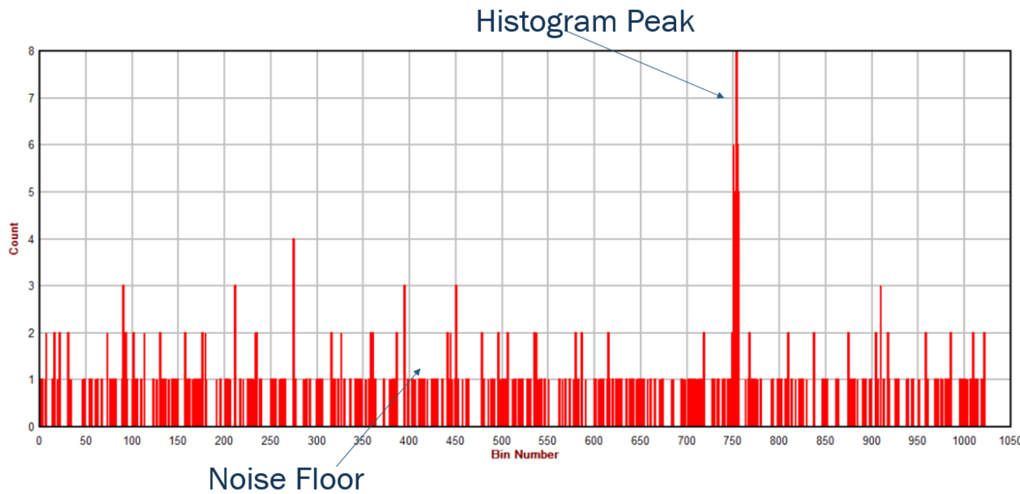


Figure 8. Histogram Peak

In considering the methods described above, it is apparent that a highly sensitive sensor is critical to the performance of the LiDAR system. Example of typical sensors used in dToF LiDAR systems are shown in Figure 3. PIN diodes and Avalanche Photodiodes (APDs) are linear−mode detectors that provide an output proportional to the amount of incoming light, requiring a certain accumulation of photons prior to reaching a threshold that can be correlated as an object reflection. These legacy detectors are fast being replaced with higher performance sensors which are sensitive down to single photon built on single photon avalanche diodes (SPADs). Examples of these sensors include Silicon Photomultipliers (SiPMs), SiPM Arrays, and SPAD Arrays. At **onsemi**, these products are manufactured in a CMOS process offering tight part−to−part uniformity, low voltage operation, and very high gain. These sensor traits are desirable for low−cost and high−performance LiDAR mass production in large volumes.

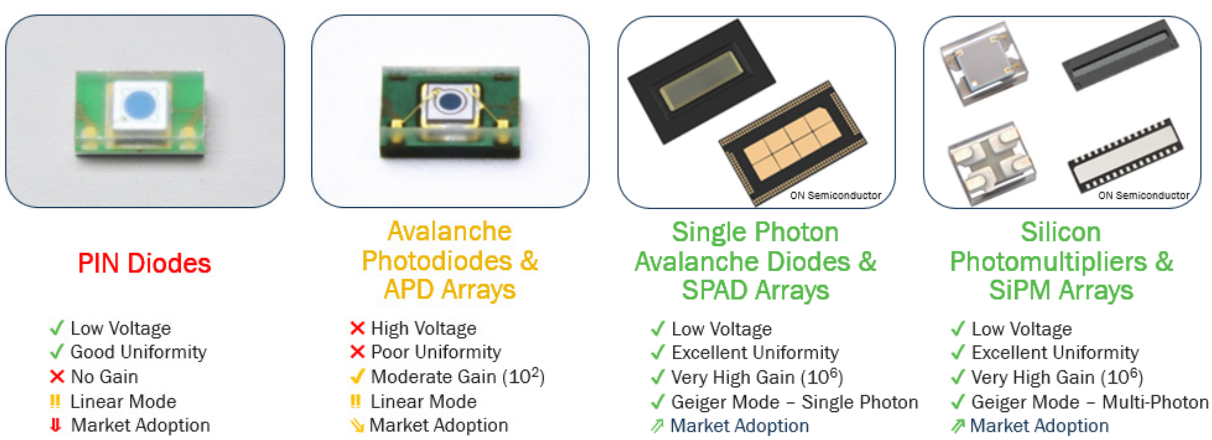


Figure 9. dToF Sensors

The theory outlined so far has described a single point LiDAR system, which can be an effective range−finding tool for single point measurement. But the same architecture can be combined with a scanning optoelectronic system to steer the beams of light and create dense depth point clouds of a scene. Scanning systems also provide more efficient use of laser power, and can consist of mechanical rotating devices which are larger and higher cost. These mechanical beam steering systems are beginning to be replaced with miniaturized systems including micro−electromechanical systems (MEMS) mirrors, liquid crystal meta−surfaces (LCM), and optical phased arrays (OPA).

It is also possible to get a dense point cloud without the use of any beam steering by using sensor and emitter arrays together and flashing the scene. Flash−based LiDAR can be used with large arrays of SiPMs or SPADs to create true solid−state solutions. Flash LiDARs are suitable for shorter to medium range applications due to the dispersion of laser power across the scene and eye safety requirements limiting the amount of emitted photons incident on each point in the sensor field of view.

Examples of scanning methods can be seen in the figures below.

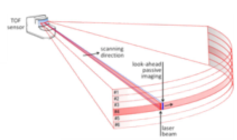
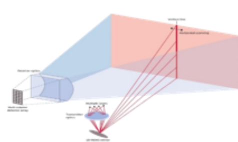
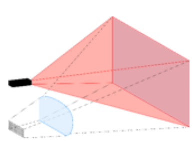
		Scanning Methods	Challenges/Benefits
Rotating		• Mechanical • Galvo • Raster Scan	• System Alignment • Auto Qualification • Popular today
Beam-Steering		• MEMS | LC | OPA • Scan on transmit & receive • Scan on transmit only	• Angle of View tied to sensor • "Solid state" / solid state • Efficient for long-range
Flash		• Staring transmit & receive • VCSEL array + SPAD array • Flash with no scanning • Flash "electronic scanning"	• Highest angular resolution • True solid state • Shorter range

Figure 10. Beam Steering Methods

onsemi LiDAR Reference Designs

After the photon return, LiDAR system signal chains can use either Analog−to−Digital Converters (ADCs) or Time−to−Digital Converters (TDCs) to digitize the detected laser echo(es). ADC−based systems allow for full pulse digitization, which provides additional information on the target such as its reflectivity which can be inferred by the pulse shape. However, there are cost and power advantages to the TDC−based method as the discrimination circuits are relatively simple to implement, and this approach is compatible with narrow pulse width lasers. This means that higher peak power can be used per pulse without affecting eye safety limits.

The reference designs in this paper are based on a TDC signal processing approach with multi−shot histogram output to extract depth. They have been developed to allow LiDAR ecosystem customers and partners to leverage **onsemi** products and system solutions in building their own designs.

SiPM dToF LiDAR Reference Platform

The SiPM dToF LiDAR Reference Platform is available for purchase and is also a full reference design by **onsemi**. This is a near turnkey solution of a single−point LiDAR system containing the laser transmitter, optics and sensor and readout receive chain including FPGA code to measure depths from 1 m up to 23 m.

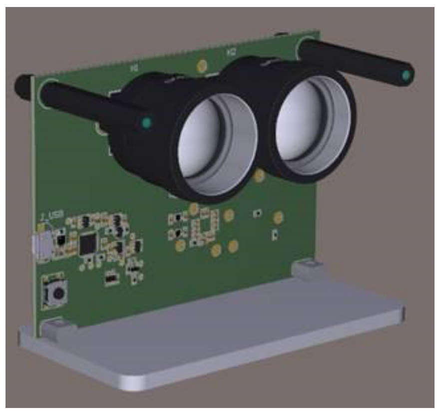


Figure 11. SiPM dToF LiDAR Reference Platform

The transmitter uses an OSRAM SPL PL 90_3, 905 nm laser diode to transmit the laser pulses to a target. Within the transmit lens, a MicroRB−10010−MLP−TR reference SiPM is used to detect the outgoing laser pulse and create the start signal for the TDC.

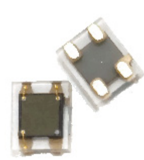


Figure 12. RB−Series SiPM Sensor

On the receiver, a second MicroRB−10010−MLP−TR SiPM is used to detect the reflected pulse from the target. An amplification stage ensures that low intensity reflected laser pulses are detected. The output of the amplifier provides the stop signal to the TDC.

The TDC is implemented within an FPGA. This is used to timestamp the start and stop signals. Histogram processing takes place on the FPGA to calculate the depth to a given target.

A graphical user interface is included with the SiPM dToF LiDAR Reference Platform. This allows the user to view the histogram data and to configure the laser range finder for single shot or multi−shot mode. The GUI also allows the user to set the SiPM sensitivity by changing its bias voltage.

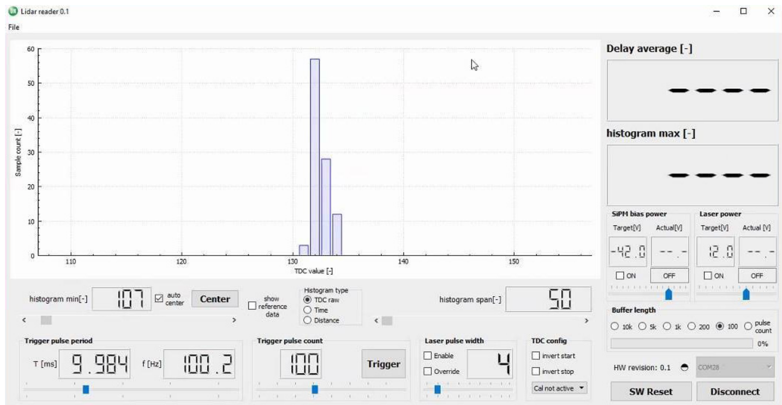


Figure 13. User Interface showing Depth Histogram

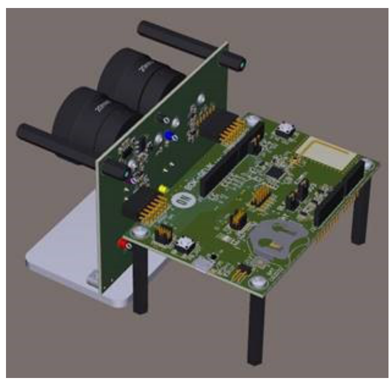


Figure 14. SiPM dToF LiDAR Reference Platform

The LiDAR Reference Platform can be configured to connect to other sensors within the **onsemi** IoT platform.

SiPM dToF Reference Platform Includes:

- Eval Kit
  - SiPM dToF LiDAR Reference Platform
  - Universal Power supply & cable
  - Software GUI
- Reference Design Documentation
  - Full description of the design
  - Implementation advice
  - Interface command library

* Package Release
    * FPGA code
    * Gerber files
    * Cadence files
    * Eagle files
    * Full BOM

Please contact depthsensing_questions@onsemi.com for more information on our SiPM dToF LiDAR Reference Platform.

16−Channel LiDAR Reference Design

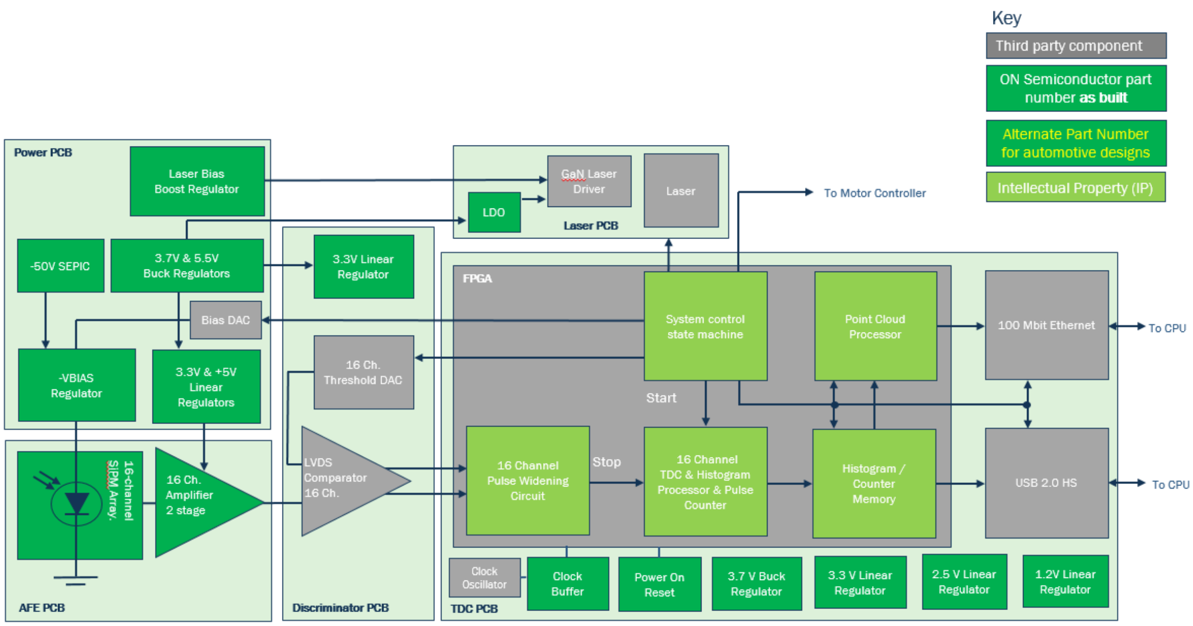


Figure 15. 16 Channel Reference Design Block Diagram

The 16−channel LiDAR Reference Design is suitable for scanning LiDAR applications including automotive and industrial markets. It consists of a software release package for the design files of several printed circuit boards, designed as modular sub−block components:

* Power PCB
* Laser PCB
* Analog Front End (AFE) PCB
* Discriminator PCB
* TDC/Processing PCB

Each of these sub−blocks of the reference design has been built, tested, and verified. The design encompasses all electronic functionality for generating the laser pulses, detecting the return signal and generating point cloud. Note that the system optics, scanning hardware and motor control are outside of the scope of this design.

The reference design can be used in its entirety with an optomechanical sub−system to make a complete LiDAR system, or individual blocks can be leveraged as part of a design when used as intended with **onsemi** parts.

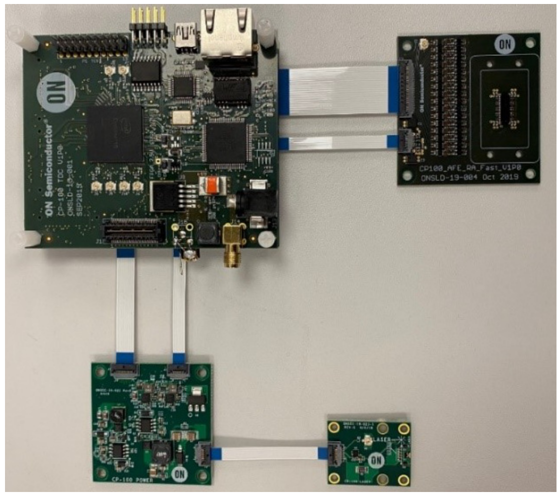


Figure 16. Physical PCBs

The power PCB covers the SiPM boost converter to step the 12 V input up to 50 V. The SiPM bias supply can be modified over SPI communication to control its sensitivity. A boost converter is also used to supply the laser PCB.

The optical transmitter is a single laser emitter @ 905 nm wavelength. This edge emitting laser source uses a discrete GaN based laser driver to achieve 75 W peak power lase pulse in a 3 ns pulse width.

The AFE board contains the detector and the front−end electronics. The detector is the ArrayRDM−0116A10−DFN, which is a 16 channel linear array with industry−leading photon detection efficiency (PDE) of 16% at 905 nm. Each channel of the SiPM array is read out in parallel to provide 16 depth points simultaneously. The detector connects to an amplification stage, which provides the gain required to observe single photon events.

Figure 17. ArrayRDM−0116A10−DFN

The discriminator PCB contains a comparator for each channel of the SiPM array. The SiPM signal is compared to a reference threshold to generate the stop signals for the TDC. The comparator threshold can be controlled via an SPI−controlled digital−to−analog converter (DAC).

This reference design features a 16−channel TDC−based readout for digitizing the return pulses across the one−dimensional detector array simultaneously. The TDC is implemented on an Intel® Cyclone® 10 LP FPGA. This FPGA also generates the timing histogram and 3D point cloud data, as well as providing system control and timing signals for the laser and motor control functions.

Target LiDAR systems may scan the single laser beam across the field of view to create a high resolution 3D depth map.

Please contact depthsensing_questions@onsemi.com for detailed information on this reference design.

Additional Features

- Fast, high dynamic range TDC with low deadtime
- TDC resolution programmable between 31−250 ps
- Max TDC range of 150 m (4096 bins)
- Serial and USB interfaces (Ethernet coming soon)
- Automotive Grade components used where possible

Automotive Requirements

Automotive applications require high performance sensors and devices that can operate reliably in challenging conditions and across wide temperature ranges. To meet these challenges and cusomter requirements, **onsemi** now has several SiPM and SiPM array products designed specifically for automotive applications. This includes the ArrayRDM−011A16−DFN used in this reference design.

Please contact depthsensing_questions@onsemi.com for more details on our SiPM and SiPM Array products.

These are the first automotive−qualified SiPM sensors available on the market today. To achieve automotive qualification of these products, **onsemi** has qualified its labs and design centers to the IATF16949 manufacturing standard. Prior to mass production release, these products undergo qualification stress testing to the applicable Automotive Electronics Council (AEC) standard AEC−Q102 specifically for optoelectronic semiconductors like SiPMs.

16 Channel LiDAR Reference design Includes:

- Reference Design Application Note
  - Full description of the design
  - Implementation advice
  - Hardware test results
  - Interface command library

* Package Release
    * FPGA code
    * Gerber files
    * Cadence files
    * Eagle files
    * Full BOM

Target Applications

Table 2. TARGET APPLICAITON

Application	Recommended Reference Design	
	Laser Rangefinder	**16−Channel LiDAR Ref Design**
AUTOMOTIVE		
Long/Short Range LiDAR	Yes + Scan Mechanism	Yes + Scan Mechanism
Turn Assist/Blind Spot Detection	Yes + Scan Mechanism	Yes + Scan Mechanism
ADAS	Yes + Scan Mechanism	Yes + Scan Mechanism
INDUSTRIAL/CONSUMER		
Fill Level Monitoring	Yes	Yes
Storage Retrieval	Yes	Yes
Stack Height Control	Yes	Yes
Measuring the Thickness of Metal, Ceramics, Wood etc.	Yes	Yes
Distance Measurement	Yes	Yes
Distance Monitoring	Yes	Yes
Position Feedback in Industrial Automation	Yes	Yes
Level Control, e.g. in the Packaging Industry	Yes	Yes
Exact Positioning of Stacker Cranes, Gantry Cranes, and Conveyors	Yes	Yes
Safeguarding Minimum Distances	Yes + Scan Mechanism	Yes + Scan Mechanism
Verifying Occupancy Conditions	Yes + Scan Mechanism	Yes + Scan Mechanism
Overhang, Gap, and Compartment−occupied Checks	Yes + Scan Mechanism	Yes + Scan Mechanism
Avoidance of Collisions for AGVs, Suspended Conveyor Systems, or Freely Navigating Platforms	Yes + Scan Mechanism	Yes + Scan Mechanism
Object Detection and Classification	Yes + Scan Mechanism	Yes + Scan Mechanism
Safety/Proximity	Yes + Scan Mechanism	Yes + Scan Mechanism
Security	Yes + Scan Mechanism	Yes + Scan Mechanism
People Counting	Yes + Scan Mechanism	Yes + Scan Mechanism

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