S3 Solid-State Sensor

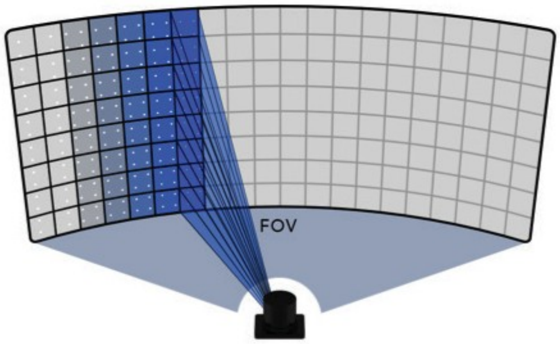
The S3 (Solid-State Sensor) is Quanergy's patented fully solid-state LiDAR sensor for autonomous driving, advanced driver-assistance systems (ADAS) and industrial automation among other applications. The S3 comprises emitters and detectors that are eminently scalable, fully solid-state, and can be mass-produced at a low cost, leveraging the semiconductor industry's mature production capability. The S3 includes a silicon-based optical phased array (OPA) for the emitter, a single photon avalanche diode (SPAD) array and a custom application specific integrated circuit (ASIC) for the detector. The OPA is used for beam forming and steering, and has no mechanical or moving parts, achieving high reliability the auto industry demands. A unique feature of the OPA is its ability to seamlessly collect any pattern of points in the field of view (FOV). This can be used to zoom in on objects of interest, providing situational analysis, confidence in detection, and better judgment.

In this paper, various aspects of the S3 LiDAR sensor are discussed along with how it differs from other LiDAR sensors on the market. This will include why the S3 is a unique, cost-effective, and reliable choice for a wide range of applications.

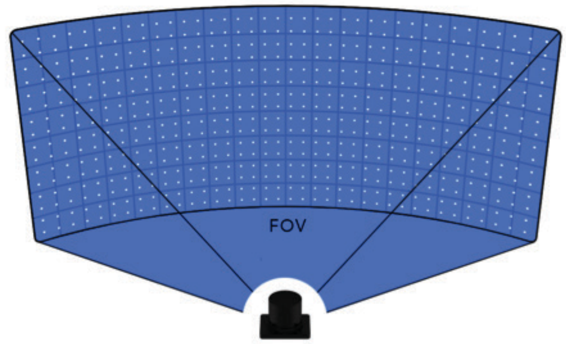
Technology Overview

The S3 is a time-of-flight (TOF) LiDAR. Such a system operates by transmitting light pulses that are reflected off objects and returned to the detector. The time it takes for the signal to travel is a measure of the distance. A 3D point cloud is formed by collecting many such measurements at different directions within the FOV.

Scanning LiDAR and Flash LiDAR, depicted in Figure 1, are the most popular methods in the industry. Scanning LiDARs typically rely on mechanical rotation or oscillation to produce an image of the scene in the FOV. This method can provide high ranges at high optical power density, but at a low frame rate. A Flash LiDAR illuminates the entire FOV simultaneously. It does not rely on any moving parts and can provide high frame rate, however, eye safety restrictions on laser power limit the range of Flash LiDARs. Autonomous vehicles require high performance, long range, low cost, and highly reliability. Mechanical LiDARs can have high performance, but are not reliable and scalable. Flash LiDAR is not very efficient for detecting long ranges, and requires extremely high-powered lasers. Our solution for modern LiDAR needs in autonomous markets is an OPA based solid-state LiDAR, which is reliable, scalable, and a low cost solution.



(a)



(b)

Figure 1: (a) Scanning LiDAR operates by scanning the entire scene using emitter-detector pairs spinning on a base, or MEMS mirrors to steer the light across the scene. (b) Flash LiDAR operates by illuminating the entire FOV, and taking an entire 3D image at once.

Quanergy's solid-state LiDAR has emitters with an OPA to form optical beams and to steer the beams in space flexibly, and a custom-designed detector, which is optimized to the unique capability of the OPA. The OPA can be used as a scanning LiDAR but provides flexibility to collect points in other patterns, enabling "zooming" as depicted in Figure 2. The principle of operation of the OPA, the zoom feature, and the detector are explained in the following sections.

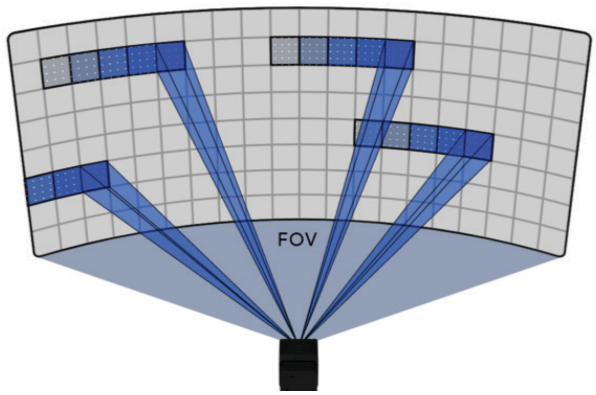


Figure 2: The OPA-based LiDAR as depicted here, can be used as a scanning LiDAR, but provides flexibility to collect points in other configurable patterns enabling zooming.

Optical Phased Array (OPA)

A silicon-based OPA makes true solid-state LiDAR possible in a reliable and cost-effective design. The OPA is an optical version of a phased array. Phased-array technology is often used for radar devices in radio frequency (RF). Instead of RF, the OPA uses optical spectrum waves, particularly near infrared (NIR). This means that antenna elements in the OPA need to be scaled down in size significantly compared to those in a phased array radar.

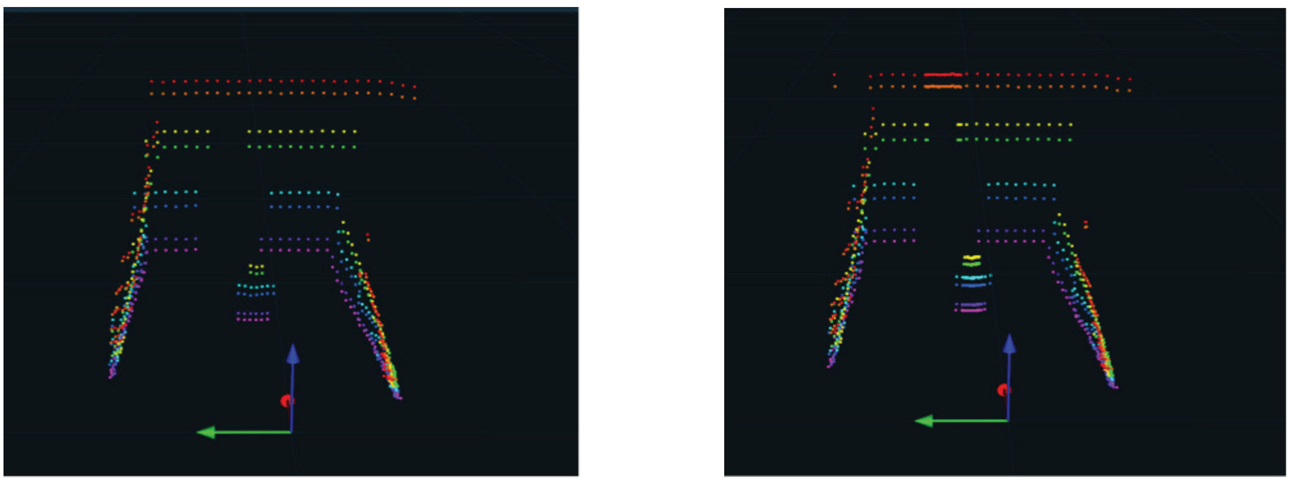
The phased array in the S3 has an array of antenna elements that emit NIR waves. The NIR waves from many antennas will then interfere with each other and create an interference pattern. By controlling the phase of the NIR wave from each antenna element, specific interference patterns can be generated. For LiDAR applications, beam shape patterns can focus the NIR energy in a particular direction where the range measurement can be done efficiently.

To realize the dimensions required for optical phased arrays, Quanergy's patented OPA is designed using silicon photonics. With this technology, the miniature antenna array, phase controllers, and other structures are integrated in a single silicon chip. Mature silicon industry technology gives performance, reliability, and cost structure that scales very well with volume manufacturing. Another unique feature made possible by the OPA is the ability to zoom in and out. Even though the FOV is typically covered via scanning, the emitter does not have any moving parts, so the FOV and angle can be changed on demand, as explained in the next section.

Zoom

Collecting a point with the OPA involves forming the beam at a specific location in space. Each time the beam is formed, it is completely independent and the beam can be formed at any location in the field of view. Any other scanning mechanism, especially mechanical scanning has inertia that prevents smooth scanning at will, and in random fashion. This allows for a completely unique scanning capability as the sensor can be used to collect the exact data that is of interest for the application. For instance, the scan can be setup to have a particular "coarse" resolution over the full FOV and a "fine" resolution near the center of the FOV. Increasing the resolution in the center of the FOV allows detecting smaller objects, extends the range at which objects are detected, and can help improve the classification accuracy.

The zoom feature is not constrained to the simple fine/coarse FOV scenario, however. Objects of interest can be zoomed into as they are detected. This type of adaptive zoom can be used, for example, to get more points on lane markers or curbs or obstacles (e.g., the person in the center of the room in Figure 3). This can allow for more accurate tracking and provides additional information for classification. Even individual points can be recollected to increase confidence of detection. All of these concepts are impossible with mechanical LiDARs with moving parts of any scale.



(a) (b)

Figure 3: The zoom functionality of the S3 is available for demonstration. The demonstration includes a GUI that allows direct control of the zoom functionality through an API. A user can control the zoom window location, size, resolution (of coarse and fine areas) and the frame rate. Additional demonstrations show object tracking through the same API. Here, in (b), the zoom window is focused on the person in the center of the room revealing a denser point cloud.

Detector

The detector includes a custom-designed SPAD array and a readout ASIC. SPADs are highly sensitive diodes that produce digital pulses in response to incident photons. SPADs are sensitive to single photons, and exhibit low noise and jitter. Silicon SPADs can detect wavelengths in the 300 nm to 1100 nm range, and can have high photon detection efficiency (PDE). By using standard CMOS technology to fabricate the high-density SPAD array, we achieve scalability and reliability at low cost, while integrating complex in-chip readout circuitry. The readout circuitry performs direct TOF measurement implementing complex analog time-to-digital converters (TDC) with high precision.

We use a custom-designed 905 nm laser as our light source to enable photon detection by our SPADs. As discussed earlier, distance is determined by the time it takes from the start of laser pulse emission to the SPAD-triggered stop upon detection of photons. Under low ambient light conditions, the high sensitivity of SPADs enables excellent images with high-precision depth/distance/range information. Like all photon detection apparatus, in high ambient noise condition such as a sunny day, since the sun also emits light in a wide optical spectrum as shown in figure 4, the signal-to-noise ratio (SNR) deteriorates. We implement a multitude of noise filtering mechanisms to optimize daytime performance.

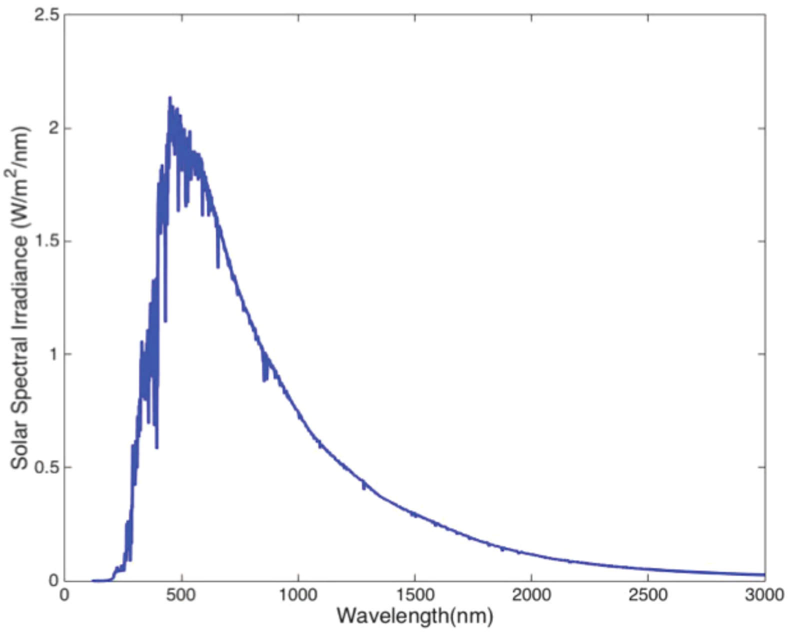


Figure 4: Solar Spectral Irradiance has a wide optical spectrum. Solar radiation in the NIR spectrum is significant. The S3 uses several filtering mechanisms to mitigate solar irradiation.

The S3's high-density SPAD array can locate the returning beam in space, as it is uniquely emanating in response to a specific angular beam by the OPA, performing spatial filtering function. The SPAD array thus acts as a noise filter to achieve better SNR under brightly lit conditions. In order to further improve the dynamic range, we use concurrence on the detector, where a multitude of photon hits are considered as signals, achieving temporal filtering. We use match filtering to match the coded emitter signal to the received detector signal which further improves SNR. These techniques, combined with newer signal processing methods, will achieve even further background light suppression, extending the dynamic range.

S3 Product Description

S3 is our high performance, automotive-grade, smart sensing solution that is ideal for a wide variety of applications in transportation, ADAS, industrial automation, security, data analytics and mapping. The sensor's economical price point enables high volume deployment of 3D LiDAR, while the compact packaging allows seamlessly integrating it into consumer vehicles.

The S3 operates using a 905 nm wavelength laser for light emission. The beam is steered via a custom-designed ASIC that resides on each individual optical phased-array chip. The returned light is projected onto the detector for direct TOF measurement. This data is processed for frame collection and 3D point cloud generation. The current generation of S3 has eight emitters that sweep horizontally with a 100^o FOV, with dynamically adjustable, non-linear beam position and control at an angular resolution of 0.1^o - 0.5^o, an adjustable frame rate from 10 Hz - 60 Hz, and a range of 30m under bright sunlight or over 100m at night or indoors. The outdoor daytime range is expected to reach 50m in the near term, then 100m and 150m.

Multiple S3 LiDAR sensors can be integrated into the design of any vehicle providing a 360^o FOV. We use a unique (patent pending) optical signal processing method to mitigate the interference between the multiple S3 units, or different units on other vehicles. Each emitter sends a unique optical code at a unique frequency. The detector that receives the returned light can differentiate signal from interference based on the unique emitter code. As LiDAR sensors are increasingly incorporated into consumer vehicles, this unique feature will produce more reliable data.

Technology Benchmarks

Autonomous and semi-autonomous vehicles will use a variety of sensors to understand their dynamic environment, in order to localize and navigate in all weather and traffic conditions. There are three main sensors that will work in cohesion to achieve autonomy: LiDAR, RADAR, and cameras. In this fusion of sensors, each sensor is used in accordance with its advantage over the other sensors. RADAR systems are common, inexpensive, and work well in light, dark, and all weather conditions, but with significantly poorer resolution than LiDAR sensors, and work best on dense materials (e.g., metal, concrete) and objects that are moving. Cameras are inexpensive, give color and contrast, but the performance degrades in low ambient light, in the distance (perspective effect), and in close proximity assessments. Since cameras are passive sensors, there are circumstances where it is difficult to distinguish lighter objects against bright skies or large moving vehicles. LiDARs provide true 3D information at a high resolution in any lighting condition, but do not detect color or have the data density of cameras, and are well-positioned to fill the gaps that other sensors cannot. The quest to achieve full-autonomy has led to a mushrooming of LiDAR companies and the market is saturated with competing LiDARs. In this section, we benchmark various LiDARs on today's market against the S3 based on the components that make up LiDAR sensors.

Wavelength

LiDARs need a light source, and typical implementations use laser diodes that emit light at 1550 nm, 905 nm, or the less common 850 nm wavelength. In determining the wavelength of the laser, eye safety limits, detectability, and fabrication costs are important factors. A 1550 nm laser diode is farther away from the visible spectrum, and has a higher eye safety threshold. Extremely high-powered fiber lasers at 1550nm that achieve very long ranges are not camera safe, are bulky, expensive, and may not be stable in vibrating conditions. In order to detect light at 1550 nm wavelength InGaAs photodiodes are required. The material cost of GaAs is three orders of magnitude more expensive than Si, even in volume production. 1550 nm is a high-powered, brute force, and expensive approach that is not suitable for high-volume production.

Eye safety becomes more of an issue at 850 nm than at longer wavelengths, which makes high-powered laser pulses unsafe. Si-based photodiodes can detect 850nm wavelength. At 850 nm, there is more ambient light interference as shown in Figure 4. This means that there is more noise, and the detector is highly sensitive to both signal and noise, deteriorating SNR, and making high-powered lasers necessary.

At 905 nm, the ambient light interference lies between 850 nm and 1550 nm, sensitivity in Si is lower than 850 nm, and is eye safe at detection ranges of interest for autonomous vehicles. The S3 uses 905 nm as it offers a reasonable compromise in terms of affordability, performance, and scalability. The next step is to sweep this light across the FOV.

Beam scanning

Mechanical rotation, MEMS-mirror based steering, and Flash are the most common scanning mechanisms. In this section, we compare these and other mechanisms to Quanergy's patented OPA-based scanning. MEMS-based sensors are cost-effective, however, moving vehicles can impede the precise motion of the MEMS mirrors introducing uncertainty in the beam direction, and therefore object location. Some implementations of the MEMS sensors appear to not detect objects at close ranges, an absolute necessity for collision avoidance. Other implementations include large mm-scale mirrors to steer light. Flash systems require high-powered lasers to extend range, but work well at close ranges, and at a faster frame rate. These high-powered lasers tend to be very expensive as well. Mechanical scanning systems cannot achieve compact form, a lower price point, and meet automotive reliability standards. Another method that has recently become popular is called multi-beam flash, where an array of laser diodes forms an emitter. This emitter can be turned on and off in a particular scan pattern, or in random fashion, and appears to have the all the advantages of an OPA. Such emitters are based on Vertical Cavity Surface Emitting Laser (VCSEL) arrays packed in a chip. VCSEL lasers usually have lower output power compared to other type of high-power laser types used in LiDARs. It will take high electrical power to pump a VCSEL array, necessitating an efficient heat sink, which compromises the form and compactness of the system, and at an added cost. Yet another approach on the market uses prism-based scanning, where a tunable laser light passes through prisms and changes direction achieving scanning. These systems can only steer light by a few degrees, and are used to steer the beam in the vertical FOV. For the horizontal FOV, some other mechanism is used. The cost saving in such systems is in using a single laser source as opposed to multiple laser diodes for the vertical FOV. The overall system performance is not improved, and the tunable laser performance has a temperature dependence that is difficult to control. Quanergy's S3 uses an entirely solid-state approach achieving optimum performance, reliability, scalability, compactness, cost-effectiveness, and situational analysis as depicted in Figure 5. After selecting a light source, and a means of scanning it, the next step is to measure the returned light to form a 3D depth image. In the next section we describe two popular techniques.

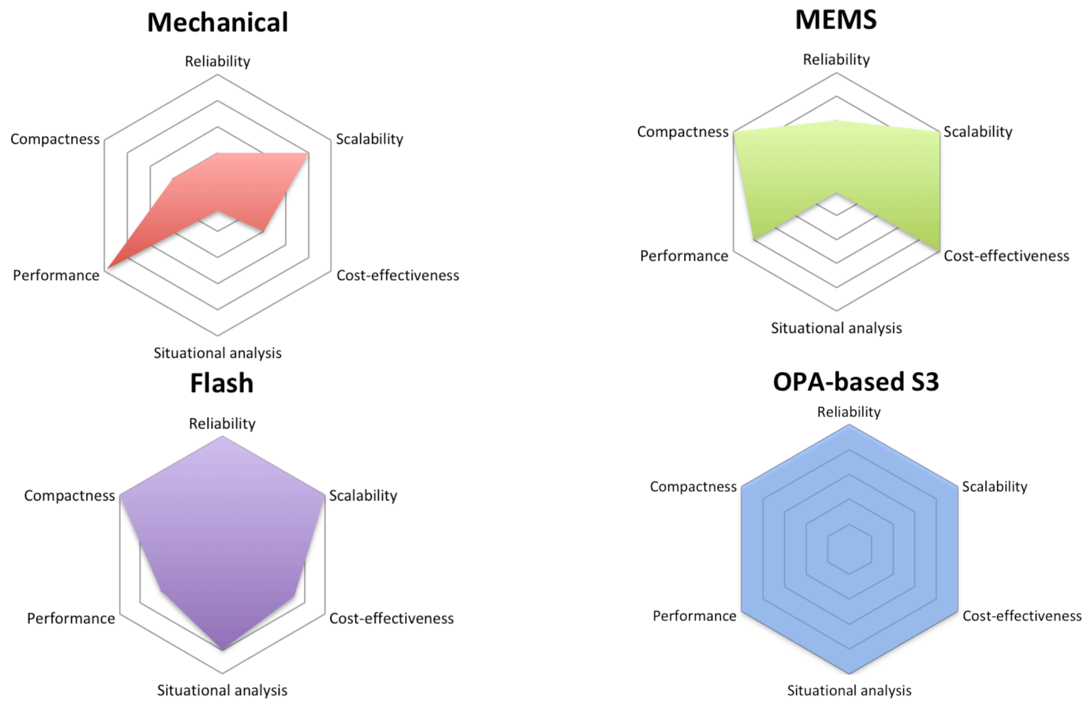


Figure 5: The S3 uses an entirely solid state approach to the emitter, the detector and the OPA-based scanning mechanism. The S3 achieves superior performance on various metrics as illustrated here. Performance metrics includes range (close and distant objects), object recognition, power consumption, immunity to interference, and safety.

Pulsed mode vs. Continuous mode (FMCW)

Most LiDARs use TOF to measure the distance of objects. Typically, an emitter drives the laser diode to transmit short, narrow optical *pulses* that are reflected off objects and measured by the receiver. This is *pulsed operation*. These narrow pulses pack high peak optical power (within eye safety limits) to overcome ambient light, and return a strong enough signal that can be detected over noise. It is challenging to generate such precise, narrow, repeatable, and high-powered pulses. This requires robust, tightly controlled drivers, and heat sinks.

Another method to measure TOF that circumvents the need for high-powered optical pulses is to operate the laser in continuous mode, popularly known as frequency modulated continuous wave (FMCW) LiDAR. In this method, the laser operates in *continuous mode*, and the target is continuously illuminated, thereby operating at a lower power compared to the peak power of pulsed laser systems. The laser frequency is constant, but the frequency at which the amplitude changes is linear, called up chirp when the frequency is linearly increasing, and down chirp when it is decreasing. A target that is chirped returns a chirp back, and the emitted and returned chirps are mixed to generate a beat frequency, which is a measure of the distance. There is a Doppler shift in the beat frequency when the target is moving, and this shift is captured by sending an "up chirp" and "down chirp". The Doppler shift affects the beat frequency differently in up and down directions, and by combining the two, an accurate estimate of range, and velocity is obtained. To achieve good SNR, the mixer that mixes the emitted and reflected chirp to generate the beat frequency has to have high linearity across the dynamic range of the signal. The photo detectors must be balanced, and must be followed by complex analog gain, filtering, signal processing circuitry, and precision ADCs to achieve good SNR. This dictates the use of an analog photo detector, precluding SPADs. While FMCW LiDARs measure velocity, in sensor fusion system RADAR sensors already provide velocity information. The S3 utilizes TOF to achieve requisite performance without the use of complex processing circuitry, which would add processing time, cost, and complexity to the system design. Next, we examine various scanning mechanisms that are compatible with FMCW method.

Even though the FMCW method uses lower optical power, implementing FMCW with the flash method will lead to a very complex and expensive system. The returned light from flash systems is typically detected by an array. As described earlier, the complex circuitry behind each 'pixel' and the signal processing to pick the signal from noise is resource intensive and time-consuming. An array that can process all of this data in parallel will be expensive, and difficult to implement without slowing the frame rate. Any other form of scanning mechanism will have disadvantages discussed in earlier sections. FMCW can be implemented with Quanergy's OPA scanning mechanism for best results. However, the S3 is designed with a SPAD array and our unique emitter pulse patterns to achieve the requisite performance with TOF, and without the use of complex analog front ends, heavy signal processing, and the added cost and complexity of such a system. Next, we discuss the density of data generated by LiDAR sensors, and describe how the S3 is optimized for objection detection and classification while balancing other tradeoffs.

Point Cloud Density

Point cloud images and demonstrations are a popular metric to measure the effectiveness of LiDAR sensors against each other, however it is insufficient, and does not weigh the cost of achieving a dense point cloud. While dense point clouds are great for research and development, there are a lot of practical issues in implementing these systems for the consumer market. These systems are generally expensive, consume a lot of power, generate huge amounts of data that in turn requires processing power, and most importantly are not necessary for object recognition and collision avoidance. On the processing side, these systems often use Deep Neural Networks (DNN) that have been developed over the years for 2D cameras. This is an easy and quick way to get a system up and running but these networks don't take full advantage of the 3D data. While there is some research on DNNs for 3D data, it is very early stage at this point. In addition, it is not clear how DNNs will be certified to the ISO 26262 standard for functional safety, which is a requirement for the auto industry.

The S3 is built from the beginning to go into a production vehicle. The S3 hardware development is about continually improving the performance. The software development approach similarly is focused on the ultimate product. The S3 does not use DNNs for automotive sensors, but instead utilizes sophisticated algorithms that go point-by-point through the data to extract the most possible information. We've found that with reasonable horizontal density, we can perform good detection, tracking, and classification with only one beam on the object. The S3 is optimized to generate point cloud data that is discernable by its intelligent software without high-powered processing units to achieve classification, performance and safety, as illustrated in figure 6.

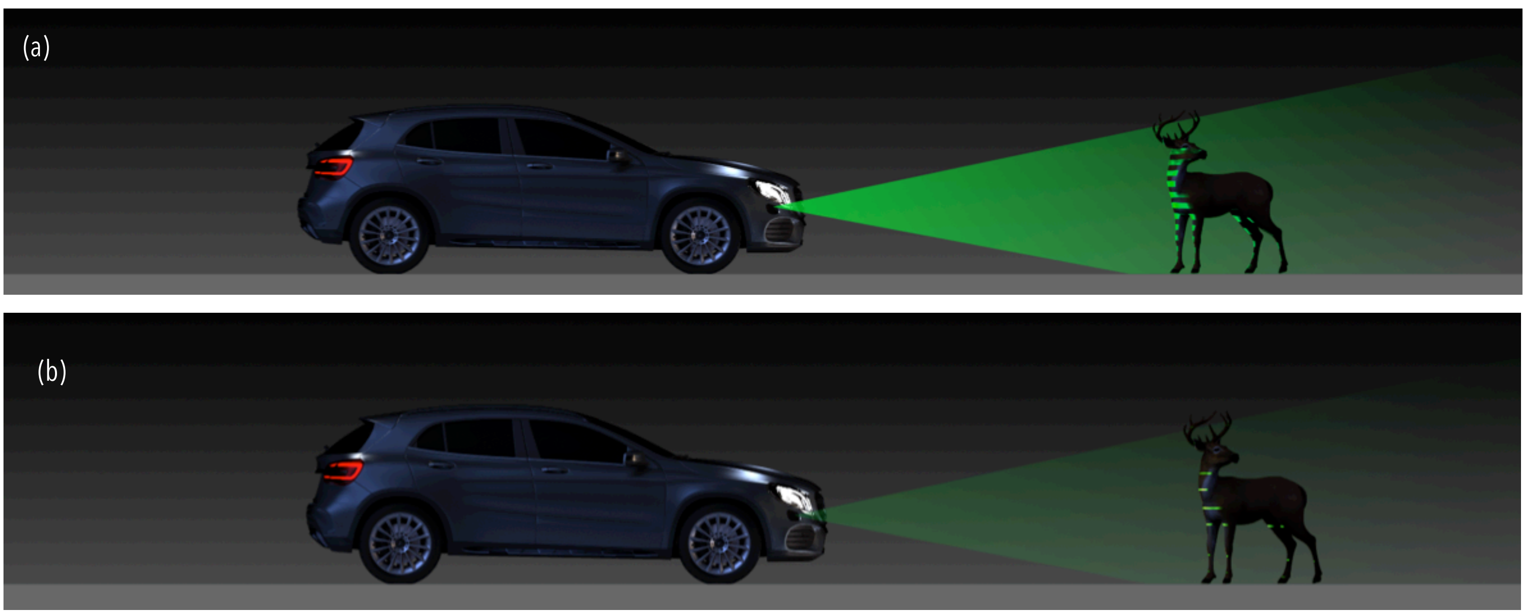


Figure 6: (a) Systems using high-powered lasers produce a dense point cloud at significant cost in terms of power, processing capacity, and safety. (b) The S3 is optimized to produce point cloud data to achieve object recognition and collision avoidance reliably, safely, and in a cost-effective way.

Conclusions

Quanergy's S3 solid-state family of LiDARs contains no moving or vibrating parts on either a macro or micro scale. This enables the highest level of performance, longevity and cost efficiency with increasingly smaller footprints that require lower power levels. In addition, the S3 is capable of electronic beam steering, which creates an entirely new paradigm for 3D LiDAR sensor functionality. As a result, sensor scanning can change dynamically based on real-time situational analysis to provide unsurpassed awareness of the surrounding environment, making S3 the best LiDAR for the automotive market.