SICK AG WHITEPAPER

LiDAR SENSOR FUNCTIONALITY AND VARIANTS

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SUMMARY

This white paper explores the many areas in which LiDAR can be applied. LiDAR sensors are used worldwide as 1D, 2D, and 3D variants in industrial manufacturing, traffic systems, and logistics. With the rise of automation and automated guided vehicle systems (AGV systems), they are set to play an increasingly crucial role in the near future when it comes to functional safety and the non-contact detection and evaluation of objects.
The latest products equipped with LiDAR include the sensor product families Dx1000, TiMxxx, MRS1000, MRS6000, and NAV from SICK AG. They supplement the company's existing portfolio, which already includes the LMS1xx, LMS5xx, LD-MRS, and LD-LRS.

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Introduction

LiDAR sensors have already been in global industrial use for decades. The sensors protect people and enable process flows to be automated. They work both indoors and outdoors. Port automation, traffic management systems, and object protection systems are just some examples of the potential applications for this technology. Below, we explain the essential functions of the various LiDAR variants. Furthermore, selected examples show the potential applications of non-contact, and often invisible, laser scanners. These examples reveal the importance of LiDAR applications for Industry 4.0.

What is LiDAR?

Sensors that use lasers to perform non-contact distance measurements have become an absolutely integral part of automation engineering. Its development first began in the form of TOF measuring technology. TOF (time-of-flight) has since been largely replaced by the more accurate terms LADAR or, most commonly, LiDAR. The terms LADAR (Laser Detection and Ranging) and LiDAR (Light Detection and Ranging) are, of course, based on the popular term RADAR, which stands for Radio Detection and Ranging.

LiDAR sensors as 1D, 2D, and 3D variants

In their simplest forms, LiDAR sensors work in distance measurement devices and sensors by measuring distance as a series of points. When used to directly measure distance, they are directed toward a certain target or reflector. Sensors that process one dimension (distance) in this way are known as one-dimensional, or 1D sensors.

If the measuring beam is moved or is rotated on one level, this provides an indication of the distance and angle, so the results are in two dimensions. Sensors employed for these kinds of measurements are usually known as 2D laser scanners or 2D LiDAR sensors. They detect measured values in a sequential order, usually at an equal time interval between measurements.

LiDAR sensors operate in the third dimension when they are pivoted. Pivoting provides information about the distance and position along the X-axis as well as positions along the Y and Z-axes. The same information can be obtained about the different space parameters when multiple sender and receiver systems placed at different horizontal angles of a sensor scan while moving. This is now known as a multi-layer scanner.
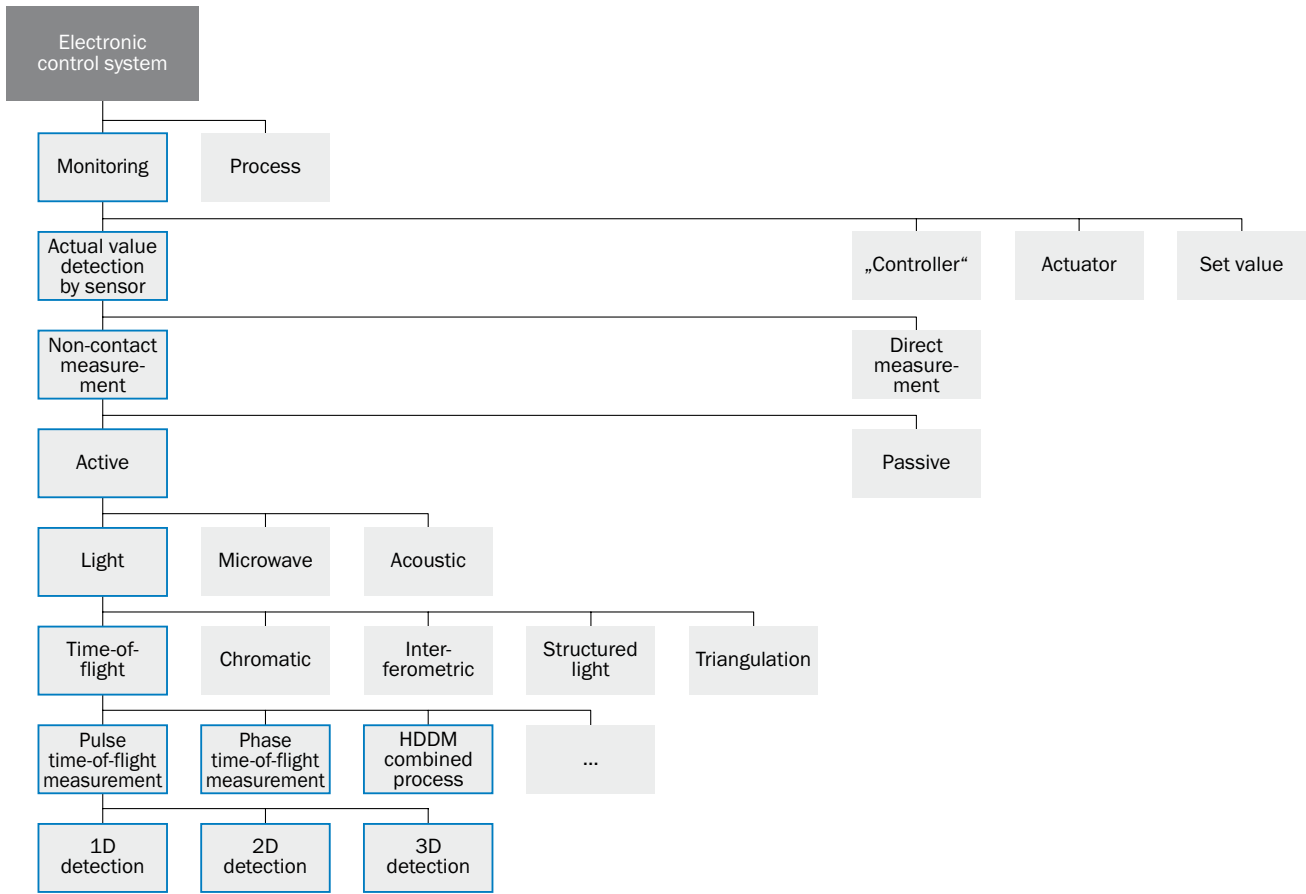
Fig. 1: Structure of an electronic control system

LiDAR sensors are most commonly used in conventional industrial control systems. LiDAR sensors used in quality assurance applications will be examined on another occasion.
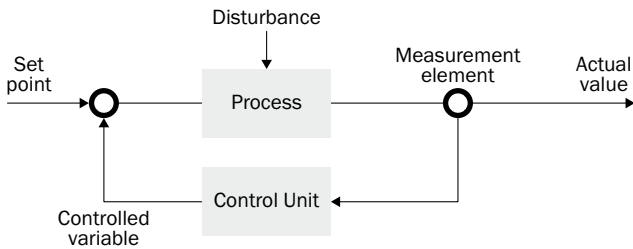
Control system

Fig. 2: Schematic circuit diagram of a control system

In a conventional control system, LiDAR sensors offer the advantage of detecting actual values without contact at the work process output by using the measurement element. Using a non-contact measurement process, they avoid the need for applying any mechanical or other pressure on the measured object. This means that the process has no impact on the object and provides a reliable, demonstrable measurement result for the subsequent control system loop.

Measuring with lasers: A range of measurement processes

Using a laser involves actively illuminating the measured object. When objects are illuminated in this way, sensor receivers can take advantage of being aligned with the sender source in any measurement situation. The sensor operates independently of external light sources and can be employed at night, in the daytime, in tunnels, etc., all with the same level of efficiency, whether used outdoors or with artificial light sources.

The focused, consistent light afforded by a laser provides other benefits, too. For example, it means that the sender signal used to detect an object can be focused with high spatial precision. Where lasers are involved, it is important that the sensors are eye-safe and meet the legal requirements on permitted output power. Focusing emitted laser beams in 2D and 3D provides high resolution, which means that objects with fine structures or that are a long distance away can be scanned.

When measuring with lasers as the sender source, a suitable receiver must also be used. The sender and receiver, combined with the evaluation unit and its high temporal resolution, are at the heart of every LiDAR sensor. The subsequent electronic circuits are important when it comes to using the obtained measurement data. Data on the mechanical alignment of the sender and receiver units is combined here with data about adapting the performance to the sensor application.

Non-contact measurement requires the measuring object to be physically detectable based on the sensor's measurement principle. When using lasers, the laser beam must therefore be directed to and from the object without interference along the direct line of sight. This is where non-contact laser measurements come into their own: They work on measuring objects with virtually any physical properties. As a result, they offer a huge scope of potential industrial applications in non-contact detection using lasers. Laser-based measurement sensors are used, for example, in logistics, including as part of transport processes, detecting traffic flows on roads, and automated loading and unloading procedures for containers at ports.

The reflected light output of a laser pulse is directly linked to the distance and physical properties of the measuring object. The right-angled, surface diffusion of the laser pulse in the sending direction, i.e., the divergence, means that less light output reaches the object per unit area, according to the distance. The same diffusion conditions are true for the reflected light. In addition, the surfaces that are being evaluated are not necessarily aligned in such a way that all the reflected light returns toward the sensors. Usually, only a fraction of the reflected light reaches the LiDAR sensor receiver.
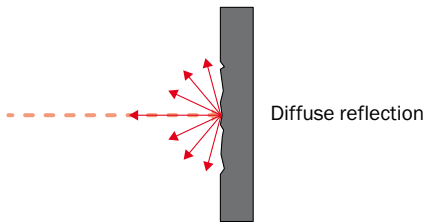

Diffuse reflection

Fig. 3: Reflection of the beam from the surface of the object

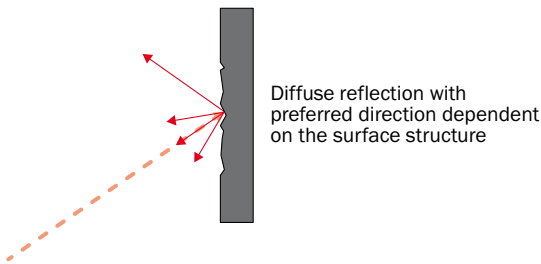Diffuse reflection with preferred direction dependent on the surface structure

Fig. 4: Reflection angle

The amount of reflection from the object depends directly on the object's properties. This is what is known as 'remission'. The gloss and reflectiveness of the object will determine this value. Levels of remission are provided in a table as percentages based on the Kodak Standard. Remission for coal is approximately 5 %, while for matte black shoe leather it is around 10 %, and for a white drywall the figure is about 90 %. Retro-reflectors that reflect light directed toward the source achieve reflectance values of up to 10,000 %, while reflective tape achieves an additional 3,000 %. The reflection properties of objects that are detected directly in front of the sensor and at long distances from it present a challenge to the sensor receiver dynamics. By optimally coordinating laser transmitters, pulse energy, and receiver sensitivity, LiDAR sensors can reliably measure objects even with low remission and positioned at long distances away.

When a laser is used to perform a distance measurement, it detects the shortest distance between the object and the sensor directly in its path. This is a major advantage since measurements at the speed of light prevent any further deflection and thus no additional magnification can occur. However, in a few applications this can also be a disadvantage. It can pose problems when measuring objects placed behind a pane of glass or film packaging. LiDAR sensors do not "see" around corners and generally cannot see through objects, even where this would be desirable in specific applications. In most cases, transparent objects cause interference in the measured value, but can often be reliably filtered out in the application using technologies such as multi-echo.
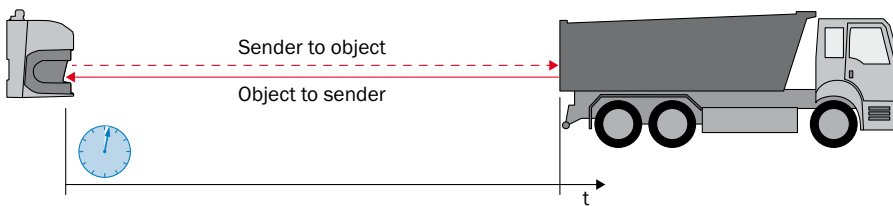

Fig. 5: Distance measurement using pulse time-of-flight-measurement

By selecting an appropriate measurement procedure, LiDAR sensors can be optimized to the relevant application.

Phase correlation measurement process
The phase correlation measurement process is also described in the white paper HDDM+ (8022027). It is a part of standard distance measurement techniques. A continual laser beam is assigned a signal with a specified frequency. The difference in the time-of-flight phase measurement between the emitted and received beam is then detected in the receiver and assessed by the evaluation unit. The phase difference correlates to the distance between the sensor and object. A systematic disadvantage of this process is that when measuring the phase difference, if the value is greater than 360° it is no longer possible to obtain a clear indication of the distance. This is also known as an unambiguous range of < 360°. In one-dimensional systems, one solution is to use sensors that switch through various frequencies of different wavelengths, achieving a large scanning range with high levels of accuracy by performing a logical comparison of the measured values.

Pulse time-of-flight-measurement process

The pulse time-of-flight measurement process has enabled LiDAR sensors to successfully operate with scanning ranges of up to several hundred meters. In the meantime, sensors have been developed that can detect times-of-flight in an area of a few centimeters by using a meter. The pulse time-of-flight measurement process uses the pure time-of-flight of a light pulse between the sender, object, and receiver. If an object reflects a laser pulse, then the measurement detects the shortest distance between the object and the sensor. By measuring at the speed of light, the measured values obtained by LiDAR sensors based on the pulse time-of-flight measurement process are extremely reliable and have outstanding levels of availability.
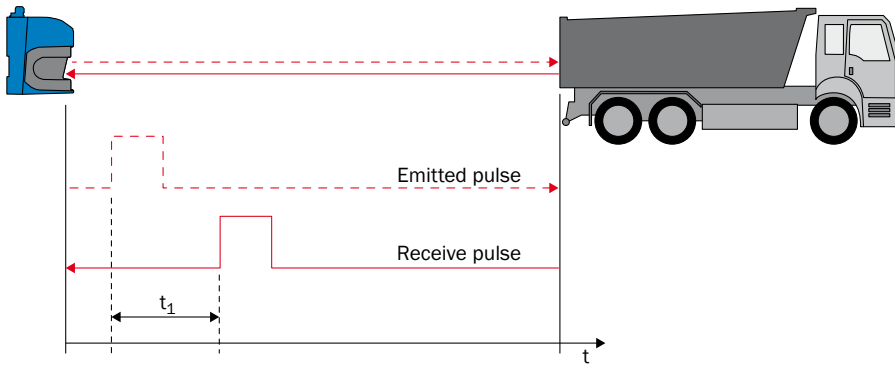
Fig. 6: Principle of operation of time-of-flight measurement

HDDM+ measurement process (statistical evaluation):

High Definition Distance Measurement Plus (HDDM+) is a statistical approach. It is described in more detail in the white paper HDDM+ (8022027). This process uses the effect of many individual pulses, which are then grouped together again using the known transmission pattern and by way of statistical approaches, providing information on distance and echo signals.
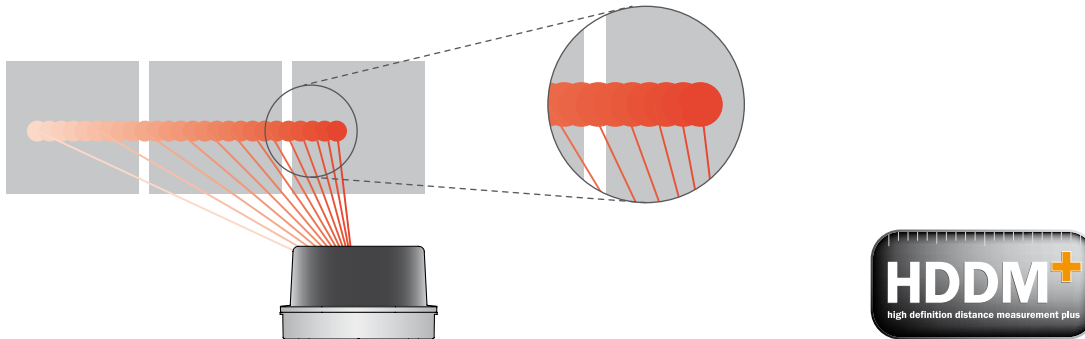
Fig. 7: Gap-free detection of the scanning area with the MRS1000 LiDAR sensor from SICK

Evaluating multiple receiving pulses in the measuring beam

In practice, a laser pulse cannot be infinitely short nor can a light spot be infinitely focused (small) in the direction of diffusion, and these facts result in physical effects. A sensor can make use of these effects to calculate a measured value. The best-known of these effects are returning echo signals, which can be used to perform multiple sampling. If the laser spot is larger than the measuring object, with part of the spot on an edge, then part of the light pulse will be reflected from the first measuring object and another part will be reflected from the surface behind it, if applicable. This effect can occur multiple times and result in further measurements. The aim now is to develop a process that can put these apparent interference effects to use in the application. The sensor provides the customer with distance and echo values about the reflected echoes at the relevant angle. In 1D sensors, up to eight echoes are considered useful, and in scanning sensors it is up to five. By emitting multiple echoes, LiDAR sensors can also be used in outdoor areas. The multi-echo technology reliably filters out interference in measured values caused by rain, snow, dust, and hail in the viewing area.
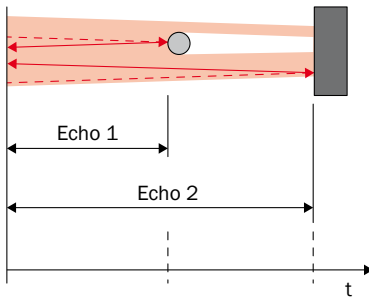

Fig. 8: Object is smaller than the laser beam diameter
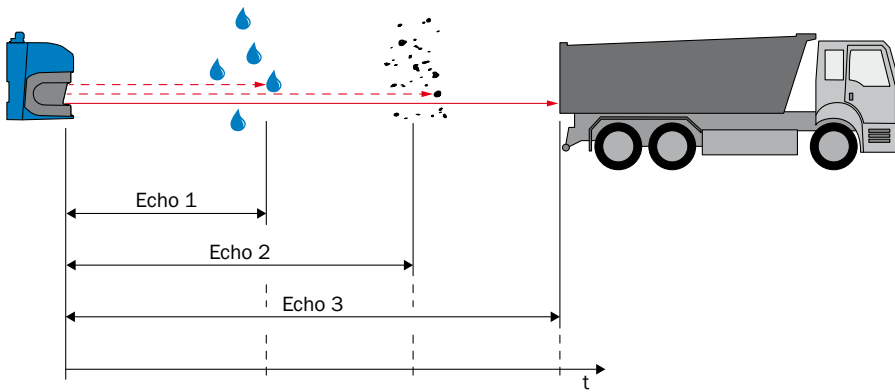

Fig. 9: Effects of multiple echoes in the measuring beam

LiDAR sensors can detect one measured value or, in multi-echo systems, multiple measured values, at different distances for each angular step. This measured value can be passed on for internal evaluation or for external data output. If a measured value is detected on a given angle, the pulse time-of-flight measurement process ensures that an object is present on this measuring beam. If a LiDAR sensor is placed on a vehicle, please do not assume that two consecutive measurements relate to the same object. It is important to carry out an evaluation for the subsequent application to determine whether the measured value is part of the application or whether it should be discarded, e.g., due to a part falling across the field of vision. When using measuring laser sensors, customers have the freedom to install the filter that suits their application. In addition, sensors often have configurable, attachable filters. The sensor data scans have time stamps to determine the time of the measurement. These time stamps can be synchronized with external data sources.
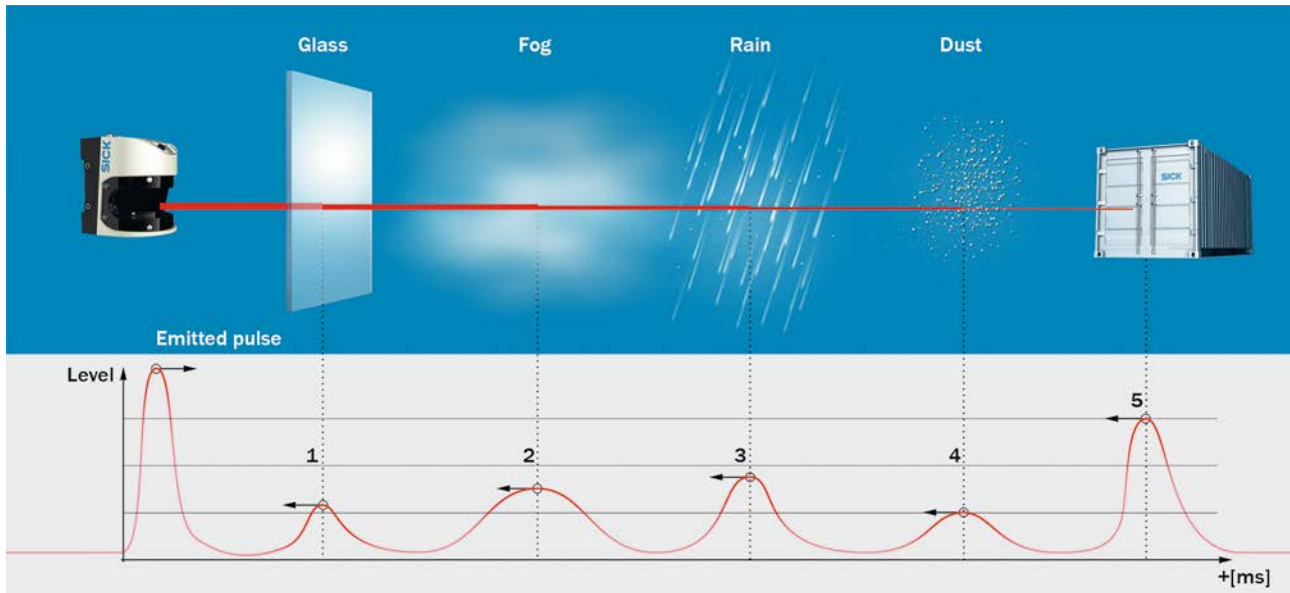

Fig. 10: Multi-echo analysis by LMS5xx

Measurement process in 1D, 2D, and 3D sensors

Linear measurement sensor (1D)

Distance sensors such as the Dx1000 scan in a linear, one-dimensional direction toward the measuring object. This enables them to detect distances and changes in distance to defined targets (with up to 100 % remission) or reflectors. They can achieve a scanning range of up to 1,500 m (DL1000) when performing measurements on reflectors. Linear measurement sensors can be used to position objects such as large cranes at an accurate distance, enabling them to perform gripping and unloading processes. By optimizing the measurement cycle time to suit the application, the sensors can detect large distances and rapid distance changes reliably and with outstanding precision. For further details, please see the operating instructions for the Dx1000 (DE: 8019330; EN: 8019329), which is a 1D sensor typically used in modern measurement processes.

Sensors measuring surfaces (2D)

2D sensors were developed in order to maintain the outstanding measurement properties offered by laser systems and to harness these in a sensor that performs measurements on surfaces. The method used here, whereby a laser beam is deflected across a rotating mirror, seems like a simple one. But the devil is in the detail. Many scanning sensors are in the form of coaxial measuring systems, with the emitted beam at the center of the received beam. In this case, it is deflected using a rotating mirror. All the described properties that make laser measurements so outstanding still apply in this case, such as the large scanning range and the capacity to measure even extremely dark objects.

In LiDAR sensors, the sequential order of the laser pulses is synchronized with the rotation frequency of the motor and the desired angular resolution. Generally, the motor rotation speed is determined by the maximum emitted pulse frequency of the laser source and the desired angular resolution. During a rotation, the number of pulses generated cannot exceed the number permitted by the wiring of the laser.

Scanning sensors offer exceptional angular resolution and angular accuracy in the pulse sequence, combined with high measuring frequency (motor rotation speed).

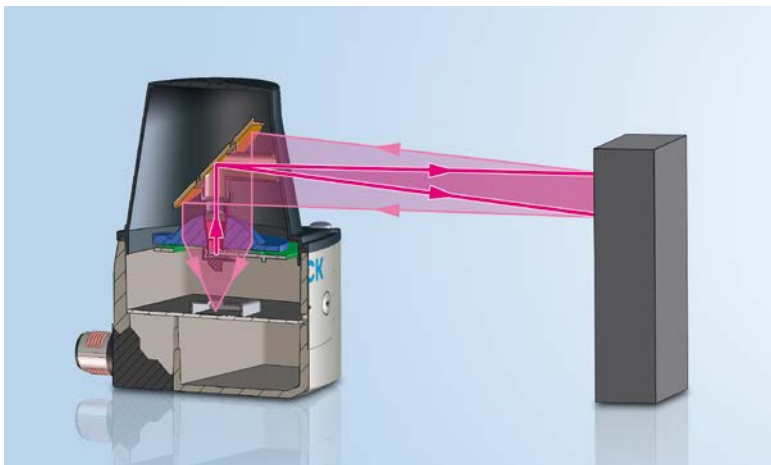Deflecting a laser beam using a mirror requires high mechanical precision.

Fig. 11: Principle of operation of a 2D LiDAR sensor

This diagram shows the side of the sender polygon. The light received on the receiver polygon is guided to the side receiver using a converging lens. By using a polygon, low motor frequencies achieve high scan rates. This is because deflection using a mirror creates a scan for each polygon facet. As a result, the visual field is physically limited to below 100°, or 70° in the LMS4000, depending on the number of facets and the mechanical structure of the sensor.

①

Sender/receiver unit   Rotating mirror

Object

②

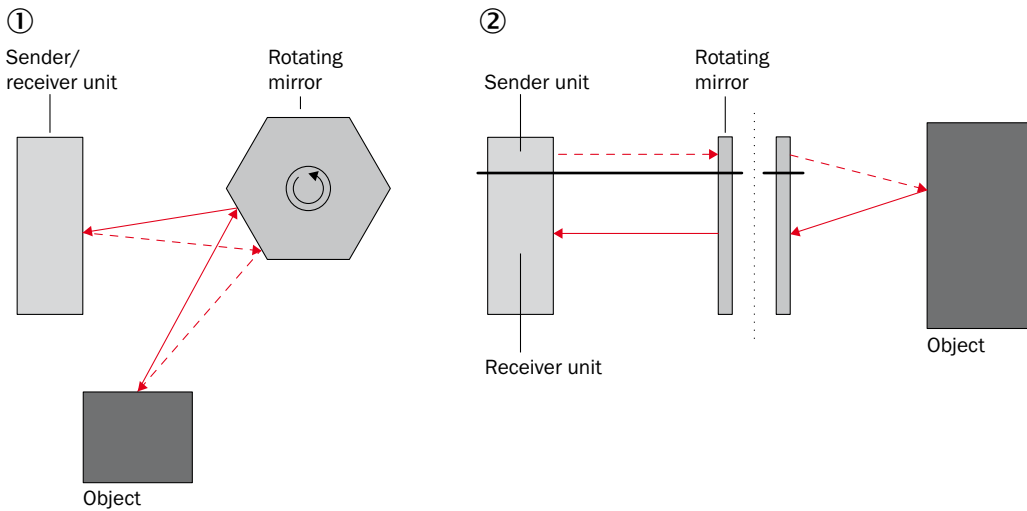Sender unit   Rotating mirror

Object

Receiver unit

Fig. 12: Setup of LMS4000, ① = View from above; ② = View from the side

As discussed earlier, scanning frequency is a crucial feature of LiDAR sensors. This sampling frequency can be increased by using multiple senders and receivers. The LMS1000, the latest LiDAR sensor from SICK, has four sender and receiver modules rotating around its axis in a cross formation (when viewed from above). In effect, this means it has four laser sensors scanning the same level at a phase distance of 90° between each sensor. If the motor rotates at 50 Hz (20 ms per full rotation), each 90° section will be scanned in ¼ of the 20 ms rotation. The complete 360° rotation is covered by four modules, each one of which only needs to scan 90°. This means that the 360° field of vision is scanned in 5 ms: In other words, the sensor works with a 200 Hz sampling rate.

In the case of LiDAR sensors that measure surfaces, the angular resolution is a relevant aspect in the scan plane. It contains the information as to whether a surface can be fully scanned without any gaps. To this end, many sensors offer an optimum angular resolution for the relevant application. For example, the LMS511 can vary the angular resolution with the aid of the scanning frequency. Its laser spot is larger than the angular resolution of the sensors, enabling it to scan the area without any gaps. The effective scanning range ranges from 10 m to 80 m, depending on the scanner. Scanners can achieve these levels in spite of challenging retro-reflection properties, including where remission is just 10 %.
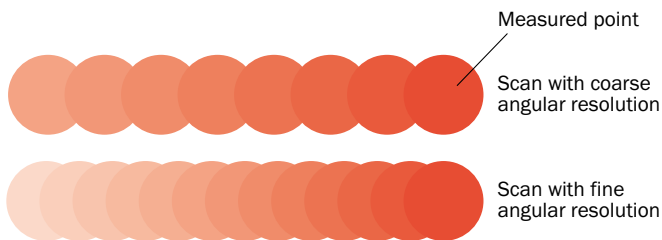
Measured point

Scan with coarse angular resolution

Scan with fine angular resolution

Fig. 13: Example: LMS5xx
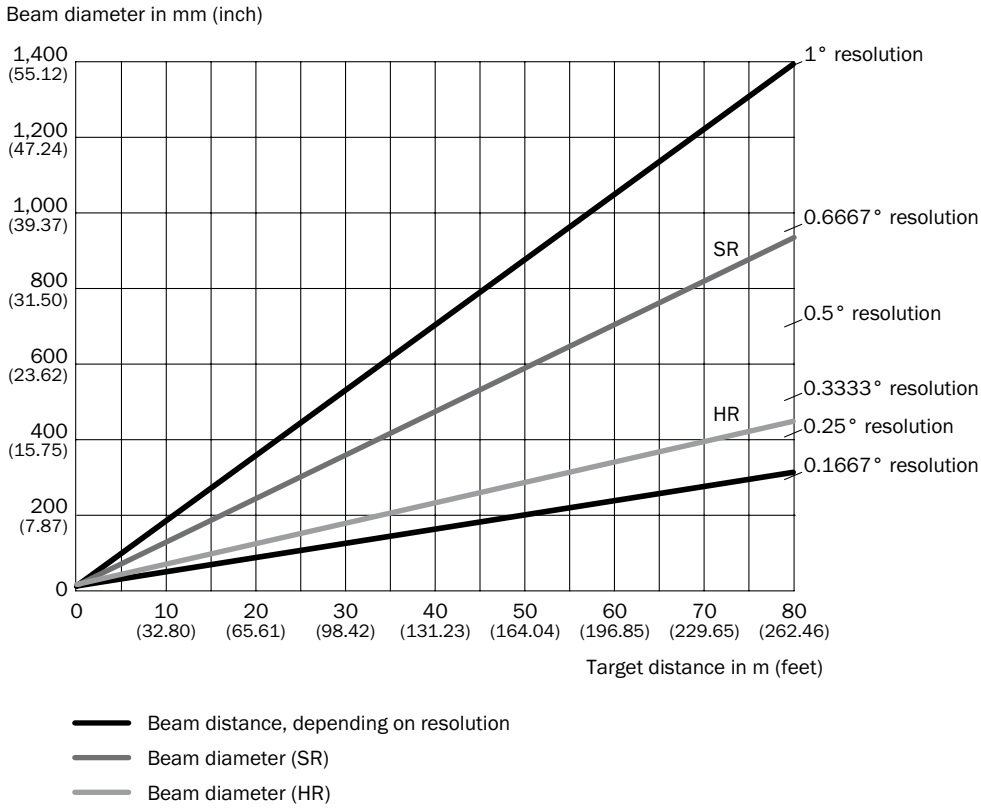
Beam diameter in mm (inch)

Fig. 14: Beam diameter and distance between the measured points of the LMS500 at 0 m to 80 m

Sensors measuring space (3D)

Having described the principle for LiDAR sensors that measure surfaces, this white paper will now examine how objects can be measured in three dimensions.

In order to generate a 3D image from the measurement data of a 2D LiDAR sensor, the standard outgoing telegram for the data must also be accompanied by the mechanical application point of the sensor in the customer's chosen coordinate system. The scans are provided with time stamps and indexing so that the customer can create an image of the output scans in a logical way with the correct times and locations. A 3D image of moving objects can be created by firmly securing a sensor to a frame or mast. Logically, a speed vector of the independent object movements is required here in order to synchronize the scanning frequency of the recording with the actual distance of individual scans performed on the object. This also means that the sensor can measure the length of the object passing underneath it. This method is used, for example, in vehicle toll collection systems. These provide accurate information about the vehicle class using laser sensors. It is also used in volume measurement systems that measure the sizes of unusually wide vehicles or objects.
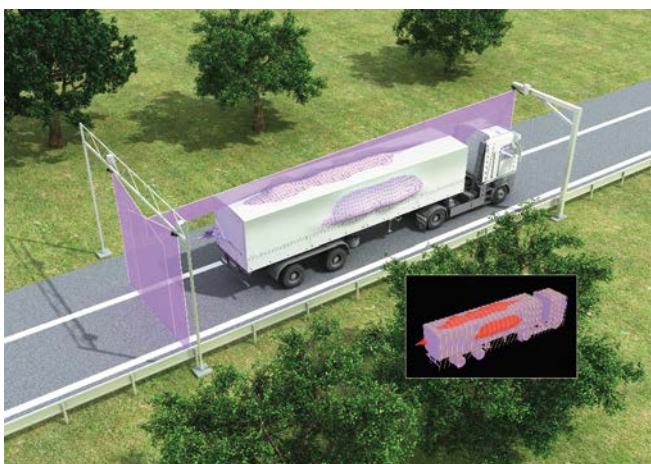

Fig. 15: Measuring the profile of a truck using 2D LiDAR sensors

By using the information provided by the sensor measurement data, every laser sensor from SICK can be automatically repositioned. This is carried out either on swivel mechanisms or by creating 3D "distance images" of the objects using linear axes. The objects in this type of application are usually stationary. Examples include volume measurement systems and automated loading equipment used to load containers. Thanks to their rugged design, sensors from SICK can resist different movements with ease, including swiveling, acceleration, and braking.
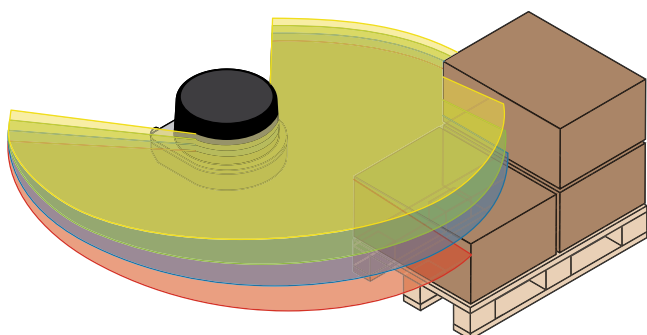
Multi-layer scanner

Fig. 16: LiDAR sensor with four scan planes

The latest 3D LiDAR sensor classes offer yet more features. By using multiple senders or receivers, or a combination of both, sensors can be produced with the capacity to scan multiple planes simultaneously or at offset angles. This means that the sensors of device generation LD-MRS, MRS1000, and MRS6000, in addition to the horizontal 2D plane (which is the 0° plane in a horizontally positioned sensor), can scan further planes tilted up or down.

MRS1000 3D LiDAR sensor

Height in m (ft)

Scanning range in m

■ Max. scanning range	① Layer 1
■ 90 % Remission	② Layer 2
■ 10 % Remission	③ Layer 3
	④ Layer 4

Typical scanning range

Radius in m (ft)

■ Scanning range max. 64 m

■ Scanning range for objects up to 90 % remission 30 m

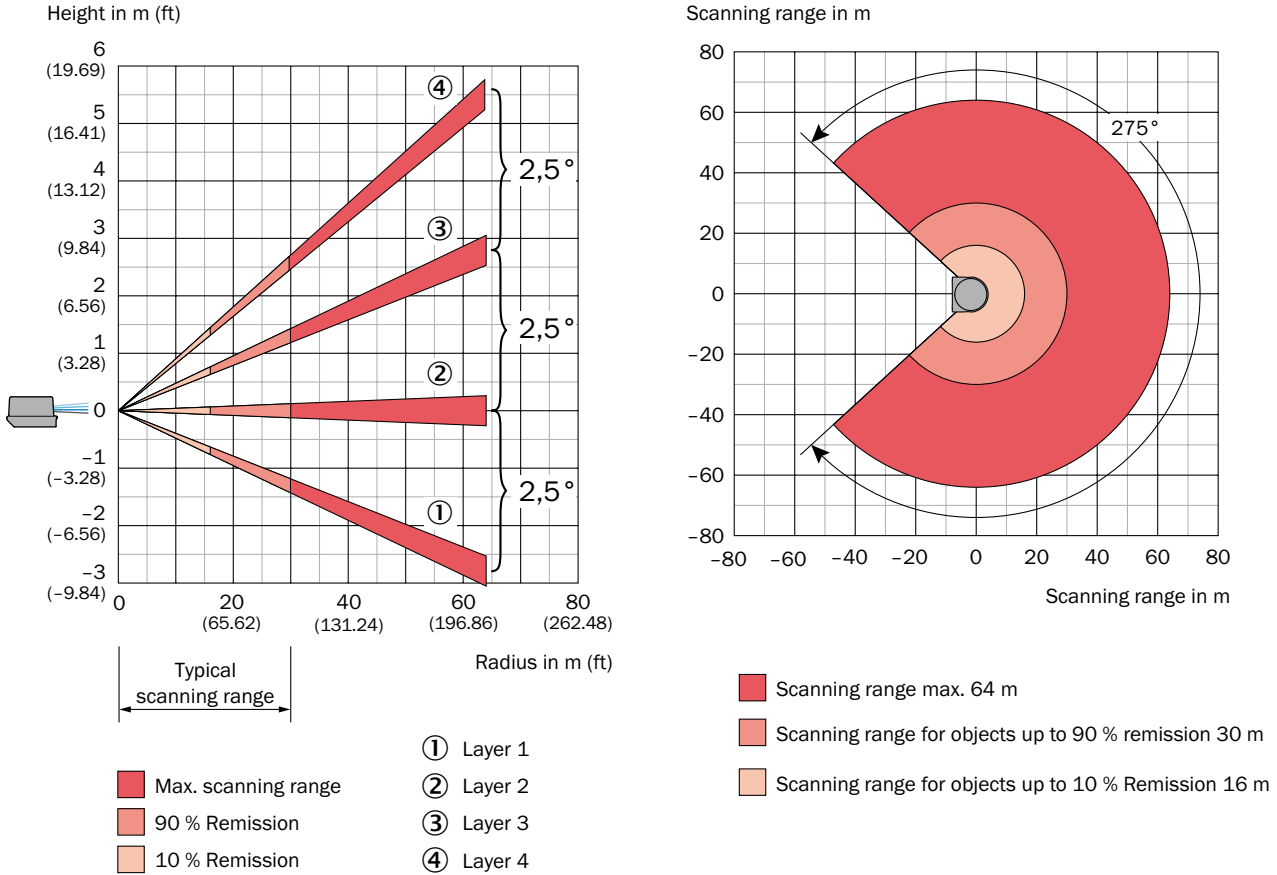■ Scanning range for objects up to 10 % Remission 16 m

Fig. 17: Example diagram: MRS1000

The advantages to the customer are clear. Rotation results in more measured points. Additional information must also be collected on distance, angle at the horizontal level, and angle at the different levels of the three-dimensional space. Using these three spatial coordinate values, the positions of an XYZ measured point can be determined in the original coordinate system. This measured value demonstrates largely the same availability as is customary for sensors from SICK AG, including its 1D and 2D sensors. The MRS1000, for example, has four scanning planes that are each tilted by 2.5°. Compared to 2D sensors, it can scan more measured points over the same duration. The mechanical multi-layer structure also offers higher scanning speeds.

Multi-layer systems are available in a range of different designs. In the MRS1000, the internal sender and receiver modules are tilted to achieve tilted planes. As a result, each module scans one section with 90° of rotation. Objects that are visible in more than one plane are therefore scanned in a quarter of the time it takes to complete a full rotation.

3D sensors and the measurement principle of using a mirror to deflect the field of vision of the sender-receiver pathway maintain the advantages of laser-based measuring. If modules are additionally oriented at different angles, then object measurements, in addition to the distance and angle of the scan direction, can also detect the angle at the object level, or the XYZ spatial coordinates. When measuring at all levels, customers retain the advantages of high sensitivity and a large scanning range.
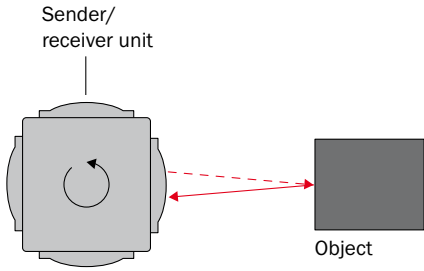
Fig. 18: Structure of MRS1000

At a distance of around 16 m, the MRS1000 achieves a lateral coverage of approximately 2 m. The tilted planes are conical in shape.

By mounting a sensor to a driverless vehicle, such as an AGV or automated guided cart (AGC), the sensor will scan object surfaces as it passes. The scanning range can be changed by tilting the sensor. Tilting the planes in a close proximity of under 5 m results in a scan approximately 0.5 m wide. This caters for a quick response at close proximity, as even small objects are detected on every plane. With the sender-receiver module offset by 90°, scans are four times faster than with the rotation frequency of an individual module.

MRS6000 3D LiDAR sensor

The MRS6000 uses the polygon mirror effect and allocates multiple senders one over the other. This is an alternative principle used to generate more than one measuring level with a single scanner. Each polygon mirror is used to tilt one sender output of 6 beams, thus achieving a complete rotation of the polygon with 4 polygon sides and 24 planes. The MRS6000 offers gap-free scanning of the entire horizontal aperture angle. It has a horizontal aperture angle of 120° and a vertical aperture angle of 15°.
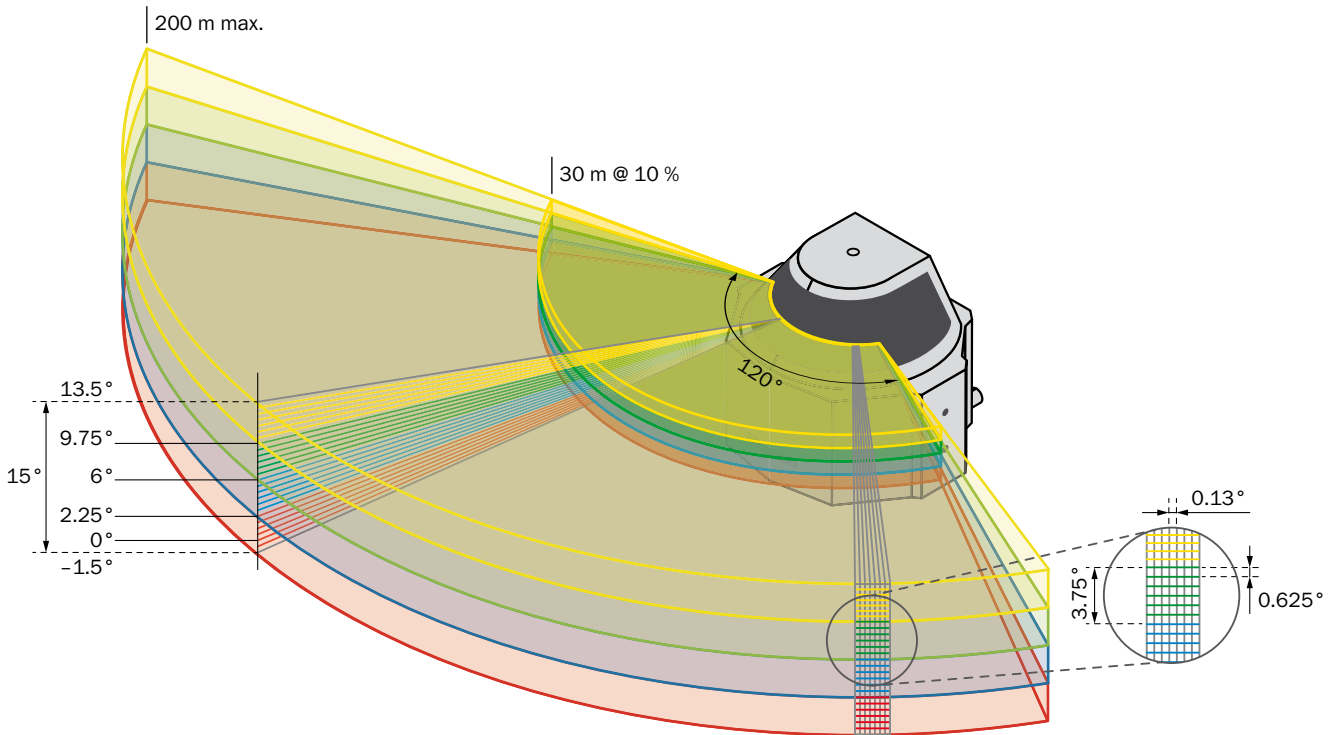

Fig. 19: Principle of operation, 3D representation

LD-MRS 3D LiDAR sensor

The multi-layer LD-MRS scanner achieves large scanning ranges of up to 100 m with its four to eight planes, and the MRS1000 achieves scanning ranges of up to 30 m in AGV systems.

In the sensors of the LD-MRS product family, two superordinate laser diodes are used as the senders. The receiver signal is further divided to two receivers. This means that the LD-MRS becomes a sensor with four planes. Its mechanical structure is similar to the MRS6000 polygon scanner, which has a polygon with two facets: The front and rear of the deflector mirror.
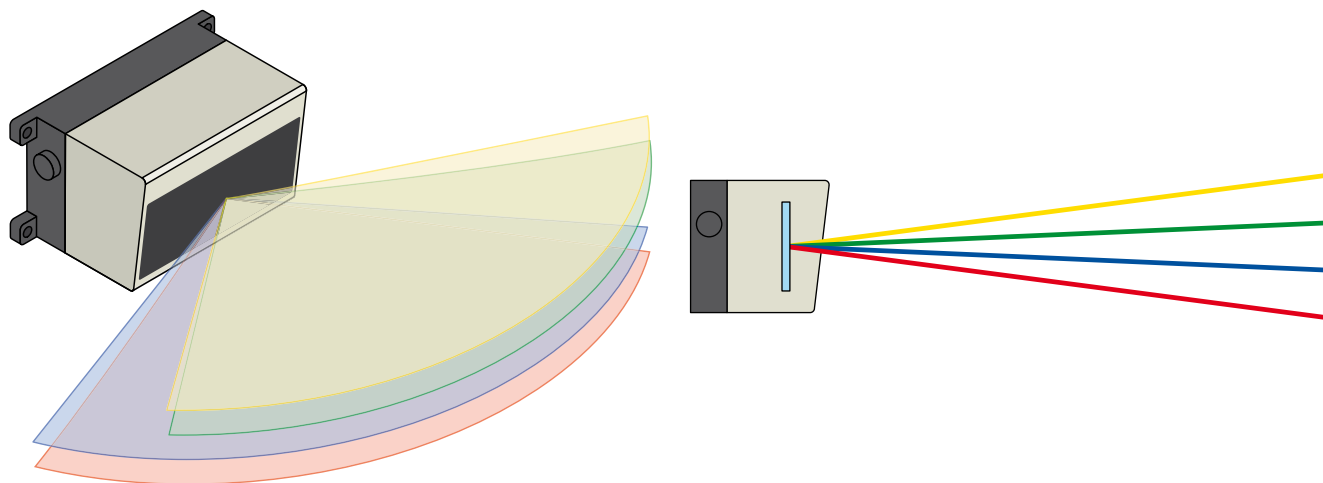

Fig. 20: Layer structure of the LD-MRS

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➜ www.sick.com/2D_LiDAR_sensors
➜ www.sick.com/3D_LiDAR_sensors