Machine Perception

Lecture 3: Range and depth sensing (Part I)

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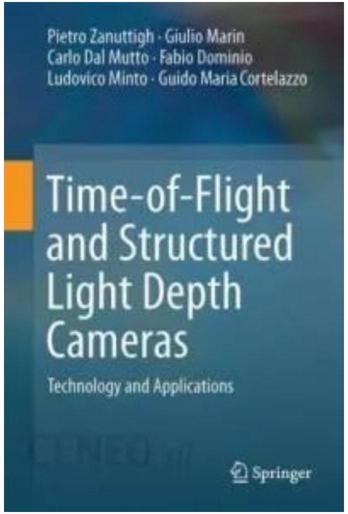
Lecture outline

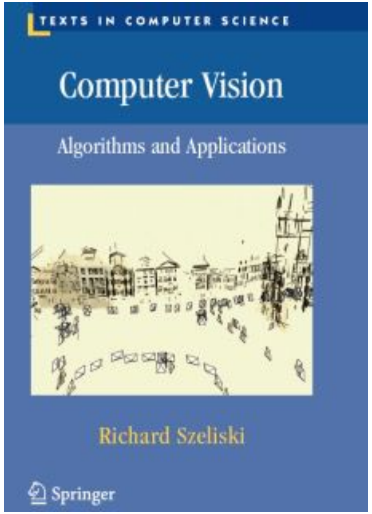
- Laser range sensors (LiDAR).
- Depth cameras: structured light, time-of-flight.
- Image formation, calibration, artifacts.
- Scene representations: depth images and point clouds.

Literature

1. P. Zanuttigh , G. Marin , C. Dal Mutto , F. Dominio , L. Minto , G. Cortelazzo, Time-of-Flight and Structured Light Depth Cameras, Springer, 2016.

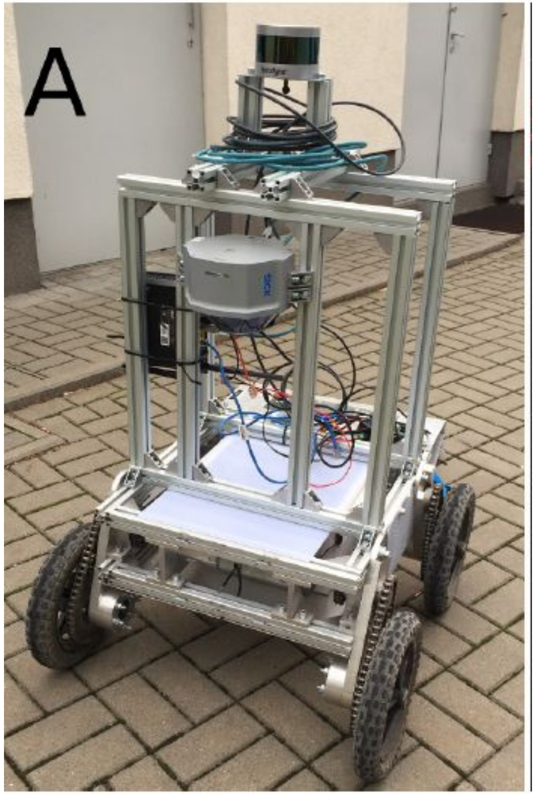
2. R. Szeliski, Computer Vision, Algorithms and Applications, 2nd edition, Spronger, 2022.





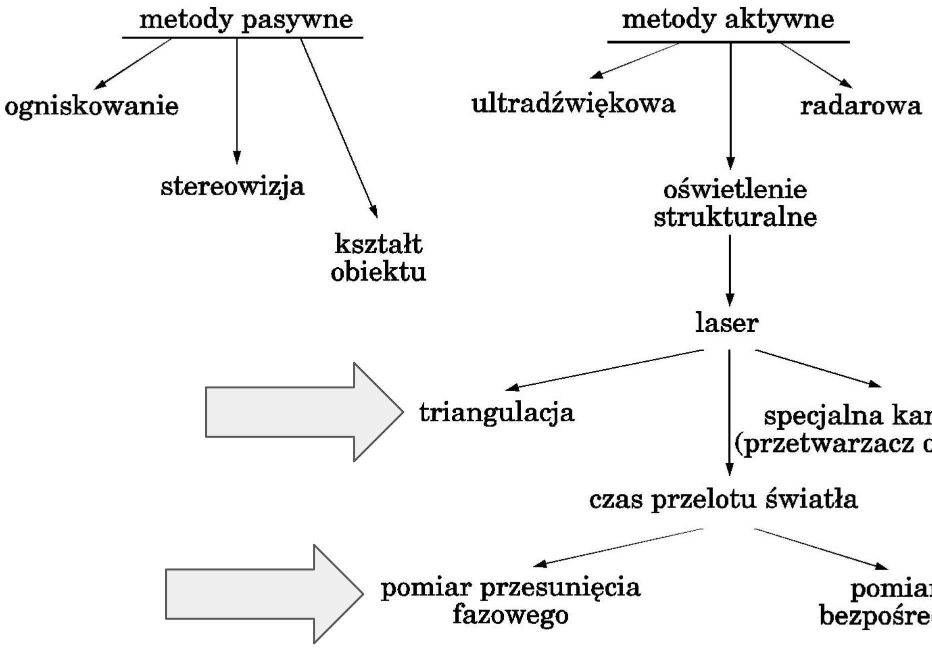
Introduction

Laser scanners and depth cameras are commonly used in robot perception and navigation systems. These are active sensors, radiating light energy in the direction of observed objects and receiving the energy reflected from them. They have a number of advantages over passive vision systems, among which the most significant seem to be their independence from the natural illumination of the scene and their ability to measure distances directly, without complex and time-consuming image processing.



Introduction

- Distance measurements in laser scanners are made by determining the time of flight of a pulse of light reflected from an object. This can be done directly or measuring the phase shift of a modulated light wave reflected from the obstacle.
- Another measurement principle used in laser rangefinders is triangulation.

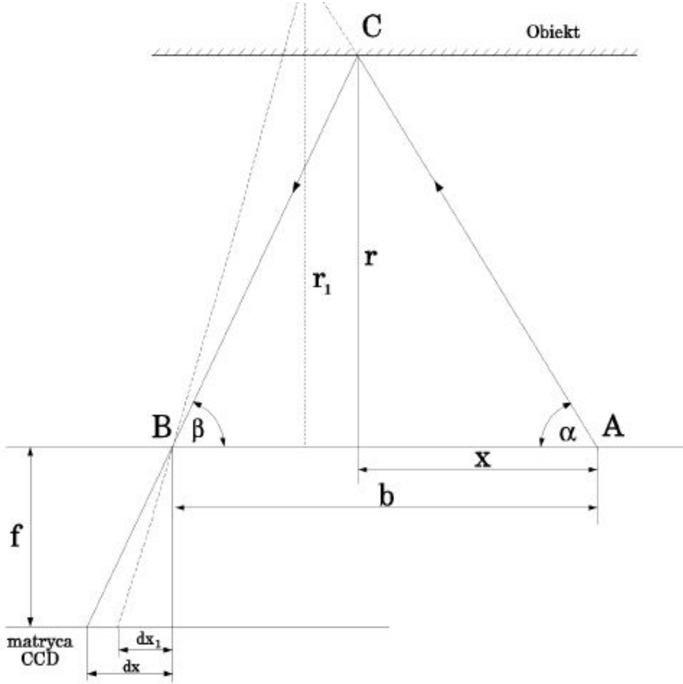


Triangulation-based measurements

The principle of the triangulation rangefinder is explained in The figure to the left. A linear diode array is used as the radiation receiver. A light source (for example, a laser) is placed at point A. The distance between the source (point A) and the detector (point B) is called the base *b*. The collimated light beam sent at an angle creates a trace on the object at point C, which is seen by the detector. Based on the geometric relationship, the distance *r* can be determined:

$$r = \frac{b}{\frac{dx}{f} + \frac{1}{tg\,\alpha}}$$

This method achieves high accuracy when the base b is large relative to the measured distance r.



Amplitude modulation distance measurements

In the method of determining distance by measuring phase shift, the measured distance is proportional to the phase difference between the sinusoidally modulated wave sent by the sensor and the wave reflected from the obstacle. Sensors based on this measurement principle are referred to by the acronym AMCW (Amplitude Modulated Continuous Wave) . Laser diodes, such as GaAs, GaAsAl, or light-emitting diodes (LEDs) with high radiation power are used as transmitters. When modulating the amplitude of the transmitted signal with a single frequency, measuring the phase shift between the transmitted (reference) signal and the reflected signal makes it possible to determine the distance:

$$r = \frac{c}{4\pi f_{AM}} \varphi_d = \frac{1}{2} \lambda_{AM} \frac{\varphi_d}{2\pi}$$

where λ_{AM} is the wavelength of the modulation, and *c* denotes the speed of light. Since the phase shift is measured in the angle interval , the determined distance is unambiguous only in the range .

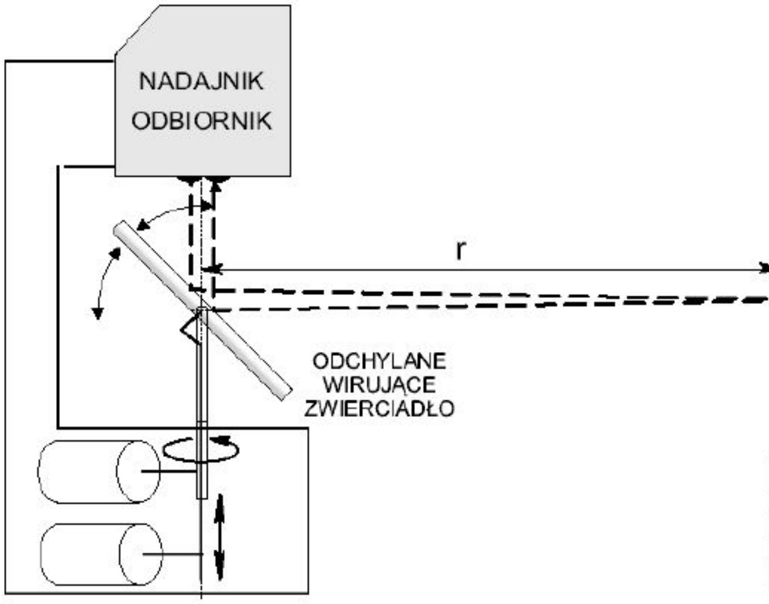
$$r_{ua} = \frac{1}{2} \lambda_{AM}$$

AMCW sensor example

As an example, we use a scanner that uses an AMCW rangefinder from *Pepperl & Fuchs GmbH*. The source of the MHz modulated waveform is an LED operating in the infrared range (880 nm). With the amplitude modulation frequency used, the range of unambiguous measurements is 18.75 m. However, the range of the rangefinder used, resulting from the power of the transmitter and the sensitivity of the receiver, is much shorter and is (according to the manufacturer) up to 5 m for a surface with a reflectance of 90%. The resolution of the distance measurement is 10 mm, and the scanner takes 280 measurements over an angular range of 360º. The scanner is characterized by the existence of a strong relationship between the results of distance measurements and the intensity of the returning signal. The dominant component of distance measurement uncertainty is systematic error. The value of this error depends not only on the measured distance, but also on the angle of incidence of the measurement beam on the observed surface and on the optical properties of the surface itself. These dependencies make the calibration of the AMCW sensor, which consists in determining the dependence of the actual distance on the measured distance, insufficient. A serious disadvantage of the sensor is the lack of a channel for measuring the intensity of the returning signal, which makes it impossible to use methods known from the literature for compensating for the bias and estimating the standard deviation of measurements based on the amplitude of the reflected signal.

AMCW sensor example

In the presented sensor, the wave is amplitude modulated at a frequency of 8 MHz. When the amplitude modulation frequency is 8 MHz, the range of unambiguity of measurements is 18.75 meters. However, the range of the rangefinder used, resulting from the power of the transmitter and the sensitivity of the receiver, is much shorter, ranging (according to the manufacturer) from 30 to 5000 mm for an area of 200 mm x 200 mm and with a reflectivity of 18% to 90%, respectively. The nominal resolution of the measurement is 10 mm (the results are read in centimeters). The maximum repetition rate of distance measurements does not exceed 100 Hz



AMCW scanner example

It is a 2D scanner using the AMCW distance measurement principle with dual amplitude modulation. It is much smaller and lighter than the Sick LMS-200 scanner, and communicates with a computer via a USB connection. It allows measurement over a wider range of angular field of view than the LMS. However, it is characterized by lower measurement accuracy, and shorter range.

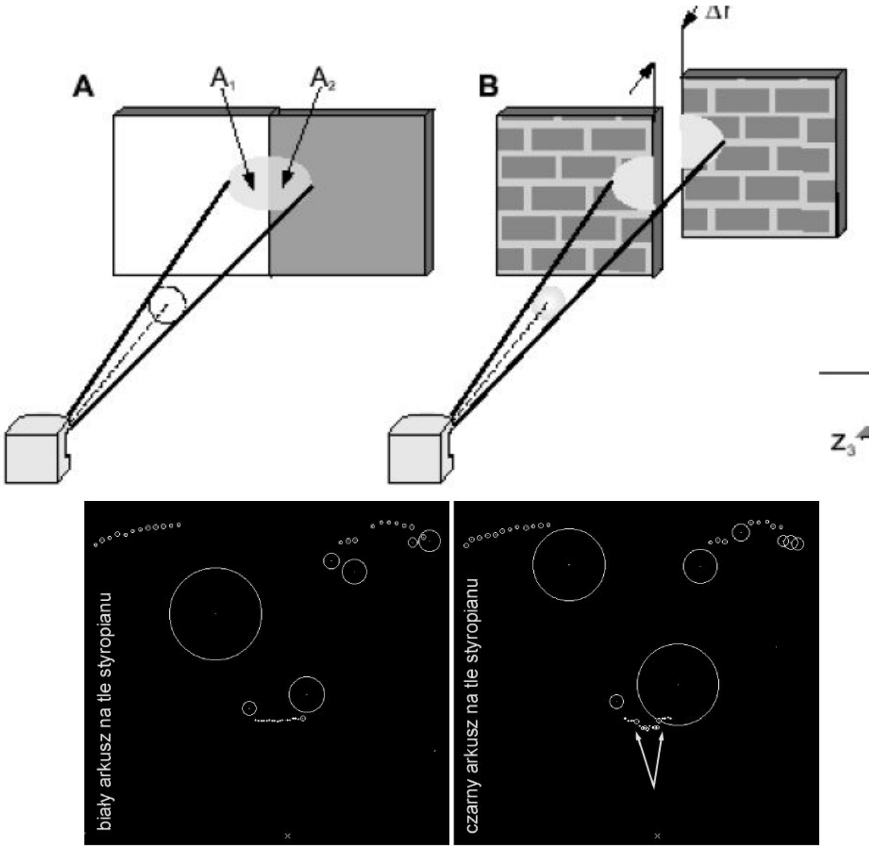
AMCW scanner example

It is a 2D scanner using the AMCW distance measurement principle with dual amplitude modulation. It is much smaller and lighter than the Sick LMS-200 scanner, and communicates with a computer via a USB connection. It allows measurement over a wider range of angular field of view than the LMS. However, it is characterized by lower measurement accuracy, and shorter range.

Skaner	Sick LMS 200	Hokuyo URG-04LX
Zakres pomiarowy	100° lub 180°	240°
Krok pomiarowy	0.25°,0.5° lub 1°	0.36°
Maksymalny zasięg	80m	5.6m
Czas skanu	13.33ms do 53.33 ms	100 ms
Rozdzielczość pomiarowa	10mm	1mm
Długość fali promienia	905nm	785nm
Moc promienia	b/d	do 0.8 mW
Napięcie zasilania	12V do 24V	5V
Pobór prądu	b/d	500 mA, rozruch 800mA
Pobór mocy	30W	2.5W
Komunikacja z PC	RS232 lub RS422	RS232 lub USB 2.0
Maks. prędkość transmisji	500kbps(RS422)	9Mbps(USB)
Wymiary(mm)	156x155x210	50x50x70
Waga(mm)	4.5kg	160g

Measurement errors

A phenomenon characteristic of laser scanners is the formation of completely erroneous distance measurements in situations when the laser beam sent by the sensor falls on a surface with inhomogeneous optical properties, or when it reflects from two (or more) surfaces located at different distances from the sensor. This phenomenon is called mixed pixels or mixed points in the English-language literature.



Direct time-of-flight measurements

In the direct time-of-flight method, the time elapsed between the transmitter sending the light pulse and receiving it is measured. Such scanners are TOF (Time of Flight) class devices. Short pulses of light are obtained by using pulsed lasers. Based on the measurement of the time from the emission of the pulse to the return of the pulse reflected from the observed object, the distance to the object can be determined:

$$r = \frac{1}{2} c t_{TOF}$$

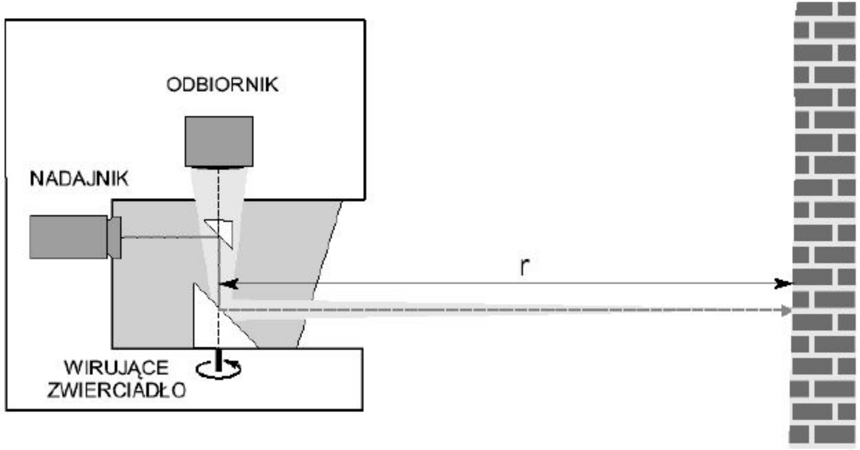
Since the transmitted pulse travels at the speed of light, for short distances (a few meters) and resolutions of the order of centimeters, it is necessary to measure time with picosecond accuracy, which is a fundamental technical difficulty in the construction of TOF laser scanners. Analog timing systems based on charging a certain capacitance with a constant current over a given time interval or digital systems counting pulses of a reference oscillator are used . Despite its conceptual simplicity, due to the difficulty and high cost of implementation, the principle of direct timing was inferior in popularity to the AMCW method in robotics applications . This situation changed with the advent of mass-produced TOF scanners, and designed mainly for industrial automation (safety barriers) and construction and transportation. Currently, TOF laser scanners are sensors with the best performance in the considered class.

Time-of-flight laser scanner

The Sick LMS-200 scanner, which is popular in robotic applications, will serve as an example. The laser scanner type LMS 200-30106 made by Sick AG is designed for precise distance measurements, determining the dimensions of objects and monitoring areas. The results of distance measurements with the LMS 200 scanner depend little on the optical properties of the observed surface, and the systematic error does not exceed 20 mm . The beam deflection system of this scanner allows measurements in the horizontal plane in the range of 180º. Sick LMS scanners (and the older PLS model) are now widely used in research on mobile robots. In the LMS 200 scanner, a 1 mW laser diode operating in the infrared range (905 nm) generates a light pulse of 3.5 ns duration. At this point, a timer is triggered. The reflected pulse hits a photodetector through a mirror, whose output is compared with a threshold value that is a multiple of the average noise level. When the amplitude of the returning signal exceeds the set threshold, the timer is stopped and the measured distance is calculated.

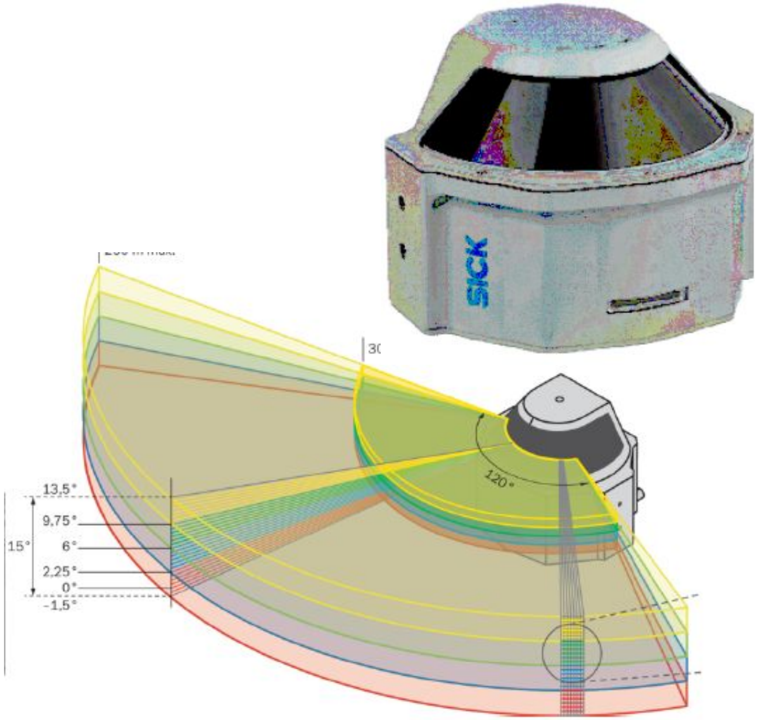
Time-of-flight laser scanner

A beam deflection system with a 45o inclined mirror spinning at 75 rpm allows scanning in the horizontal plane and over a 180º range. The Sick LMS 200 is a programmable sensor. Communication with the device via a serial link is enabled by a set of commands (so-called telegrams), allowing the user to select the range of distance measurements (range and resolution), angular resolution and scanning angle range. The physical angular resolution of the scanner is fixed at 1º. Higher resolution scans are obtained by rotating the mirror twice or four times over the entire scanning angle range. Data processing in the sensor itself makes it possible to average the results from several series of measurements before sending them to a host computer.



Time-of-flight laser scanner

The Sick MRS6000 is a 3D scanner that uses laser beams to scan the environment. The device uses polar coordinates to describe the space around the sensor. The Sick MRS6000 uses 24 scanning layers to scan the space in three dimensions, where measurements are taken 6 layers at a time. The device uses wizzles emitted by a laser diode. To create 24 scanning layers, four polygonal rotating mirrors are used. If the beam reflects off an obstacle it is then picked up by the scanner. Based on the time of flight of the beam (Time of Flight), it is possible to calculate the distance from the obstacle.

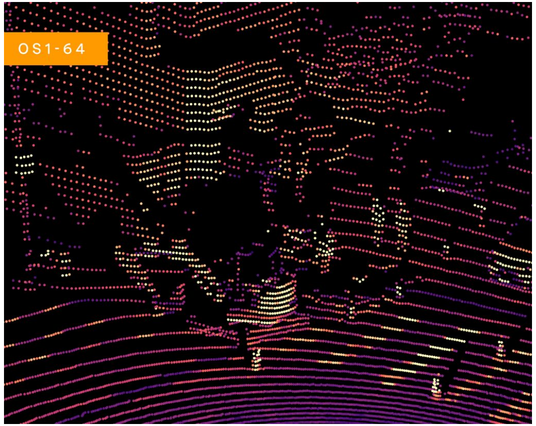


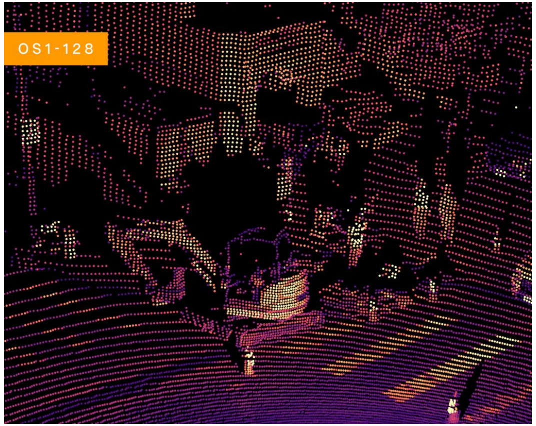
3D laser scanners (LiDAR)

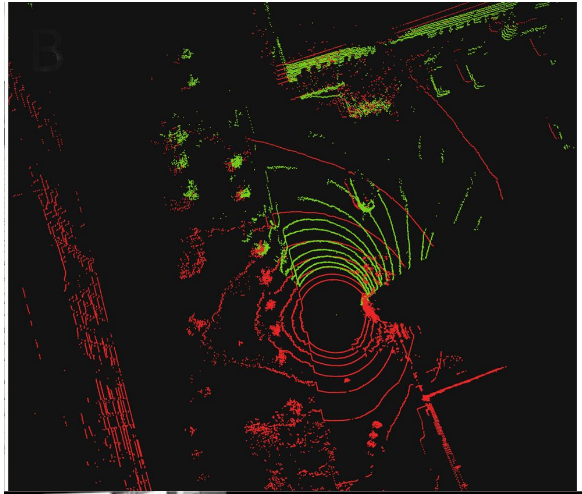
LiDAR (Light Detection And Ranging) sensor measures distance by illuminating a target with laser light and measuring the distance at multiple points with a sensor. Differences in the return time of the laser beam can then be used to create a three-dimensional model of the environment. Lidar is used to create high-resolution maps used in surveying, geodesy, geomatics, archaeology, geography, geology, geomorphology, seismology, forestry, atmospheric physics, laser guidance, aerial laser mapping and laser altimetry. The technology is also used in navigation for some autonomous cars and robots.

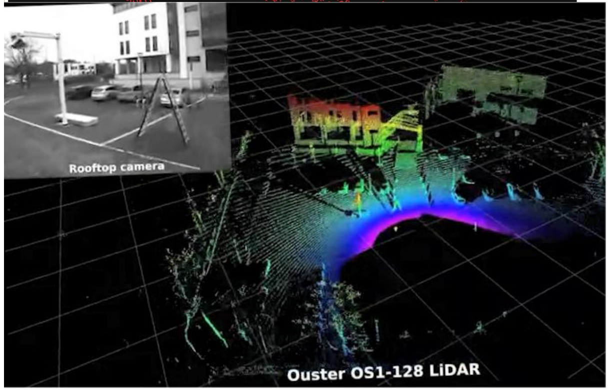
3D laser scanners (LiDAR)

- Sick MRS-6124 (green) and Velodyne VLP-16 (red)
- Ouster OS0/OS1/OS2 (32, 64,128 beams)
- Comparison of an image and a point cloud from OS1-128



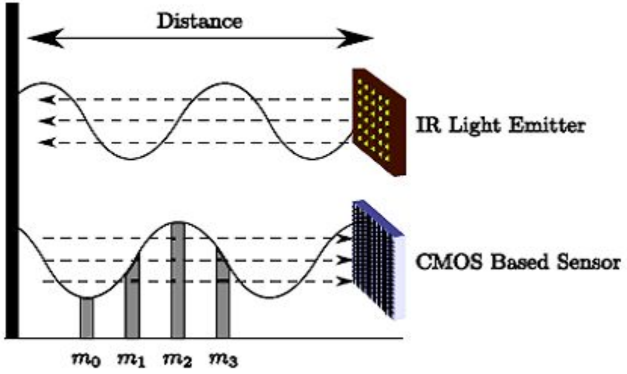






Active depth cameras

A group of sensors using the principle of indirect ToF measurement, differing in technological solutions and parameters. The principle of operation of these sensors is based on measuring the time between the moment the transmitter sends a pulse of light and the detection on the detector of the light reflected from the obstacle, and at the receiver the phase difference of the transmitted sinusoidal signal (usually) relative to the reflected signal is calculated.

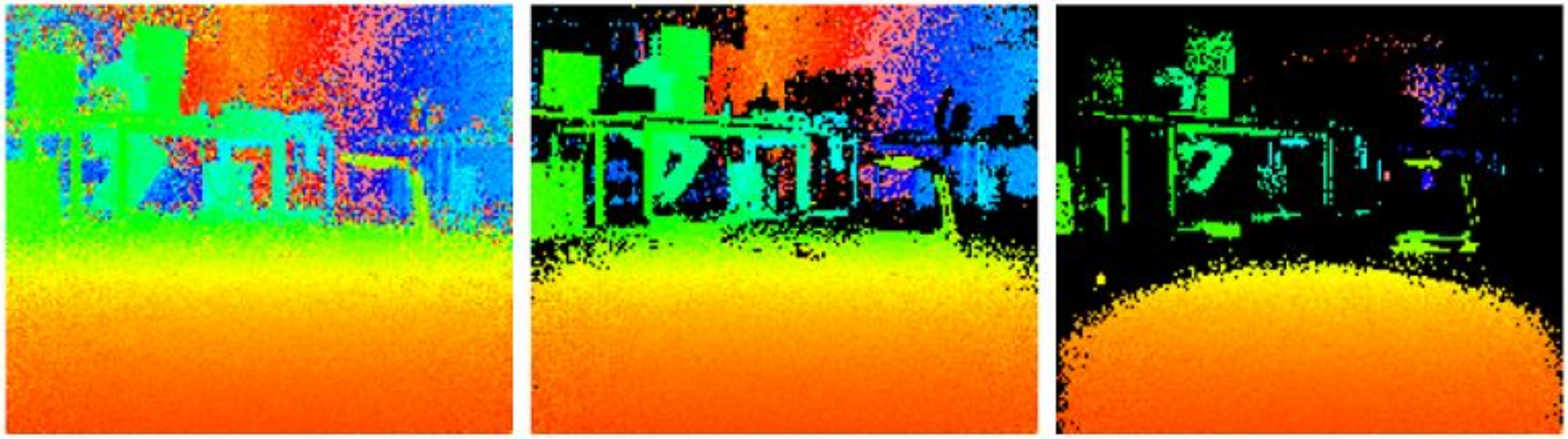


The phase difference of the signals is calculated by integration after time, which leads to delays in depth image estimation or image blurring associated with camera movement. ToF cameras typically use light sources that operate in the infrared and are invisible to the human eye.

Device	MESA SwissRanger 4000
Technology	Time-of-Flight
Range	0.8 – 8.0 m
Resolution	176 × 144 pix
Frame Rate	30fps
Field of View	69° x 56°

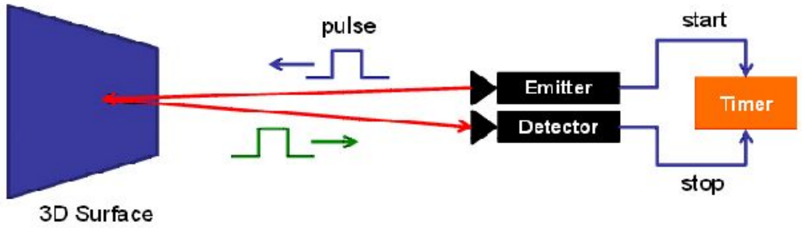
Active depth cameras

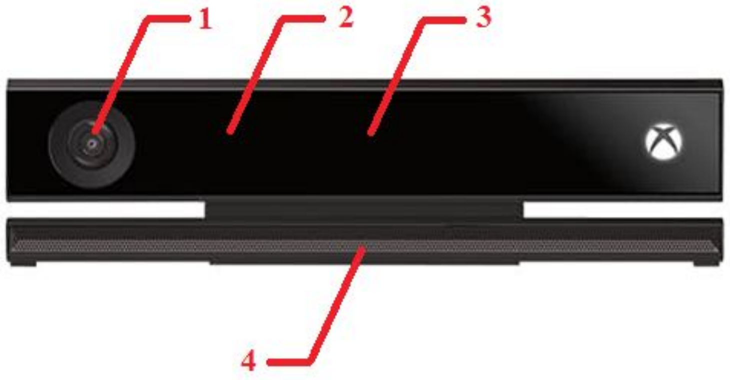
3D ToF cameras can be used both indoors and outdoors, but different calibration is often required for different lighting conditions and depth measurement ranges. 3D ToF sensors are sensitive to the optical properties of the observed surfaces. Measurements of distance to light-absorbing (dark) surfaces have larger errors.



Active depth cameras

Kinect 2.0 was developed by Microsoft as an add-on for the Xbox One console, allowing users to interact with it using body gestures as well as voice commands. In addition, drivers have been made available on the manufacturer's official website, allowing the device to be operated on a Windows computer. As a result, its capabilities can also be used in robotics. The sensor is equipped with an RGB camera with a resolution of 1920 x 1080. The depth measurement camera transmits an image of 512 x 424 px. The Kinect 2.0 uses the ToF technique. This system was originally patented by Canesta. It uses modulation of light in the infrared range with a rectangular wave. The time it takes for the light to travel from the transmitter to the observed object and then from the object to reach each pixel of the depth sensor is evaluated indirectly by detecting the phase shift between the modulated transmitted wave and the return signal received by each pixel of the sensor array.





1 - RGB camera, 2 - depth measurement camera (under the housing), 3 - infrared sensors (under the housing), 4 - panel with microphones

Active depth cameras

Device	PMD CamCube 2.0[1]
Technology	Time-of-Flight
Range	$0 - 13.0$ m
Resolution	200×200 pix
Frame Rate	up to 80 fps
Field of View	$40^\circ \times 40^\circ$

Device	Kinect V2
Technology	Time-of-Flight
Range	$0.5 - 4.5$ m
Resolution	512×424 pix
Frame Rate	30 fps
Field of View	$70^\circ \times 60^\circ$

Device	MESA SwissRanger 4000
Technology	Time-of-Flight
Range	$0.8 - 8.0$ m
Resolution	176×144 pix
Frame Rate	30fps
Field of View	$69^\circ \times 56^\circ$

Device	MESA SwissRanger 4500
Technology	Time-of-Flight
Range	$0.8 - 9.0$ m
Resolution	176×144 pix
Frame Rate	30fps
Field of View	$69^\circ \times 55^\circ$

Device	Creative Senz 3D
Technology	Time-of-Flight
Range	$0.15 - 1$ m
Resolution	320×240 pix
Frame Rate	60 fps
Field of View	$74^\circ \times 58^\circ$

Device	SoftKinetic DS325
Technology	Time-of-Flight
Range	$0.15 - 1$ m
Resolution	320×240 pix
Frame Rate	60 fps
Field of View	$74^\circ \times 58^\circ$

Outcome of the lecture

- A brief review of the active range sensing technology used in robotics and similar areas (self-driving cars, drones).
- Physical principles used in active range sensors shape the practical properties of these sensors (range, accuracy, errors, speed of data acquisition)
- Classic 2D range sensors (laser scanner) used in simple mobile robots (indoor, industrial AGV)
- Modern 3D laser scanners - LiDARs used in self-driving cars, some drones
- Depth cameras used in AR, consumer applications.

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