Sensing Technologies For Mobile Robotics

AE640A - IITK - 2018-19/II

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The Robotics Pipeline

Sensing the Environment
(this lecture)

Computation Using Various Algorithms

Actuation for Motion

- Computer Vision
- Localization and Mapping
- Motion Planning and Control

Mobile Robotics

- Sub-field of robotics, where robots are not fixed at one physical location
- Locomotion leads to a dynamic (or even unknown) environment, which presents new challenges:
  - Perception and Mapping
  - Localization

  → **S**imultaneous **L**ocalization **a**nd **M**apping (SLAM) (Perception and Mapping + Localization)
  - Navigation and Real-time Decision Making
  - Limited Power Supply
- Active area of research
- Recent increase in interest due to rise of self-driving cars
- Overall applicability is even larger – farming, automated warehouses, defence sector

Popular Sensing Technologies

- Perception
  - Cameras (many types)
  - Laser Scanners
  - Ultrasonic Sensors
  - Radar
- Localization
  - (IMUs) Inertial Measurement Units
  - GNSS Modules
  - Rotary Encoders
- Sensing other environment variables such as temperature, pressure

An Example Mobile Robot

Source: Own work at Team IGVC IITK

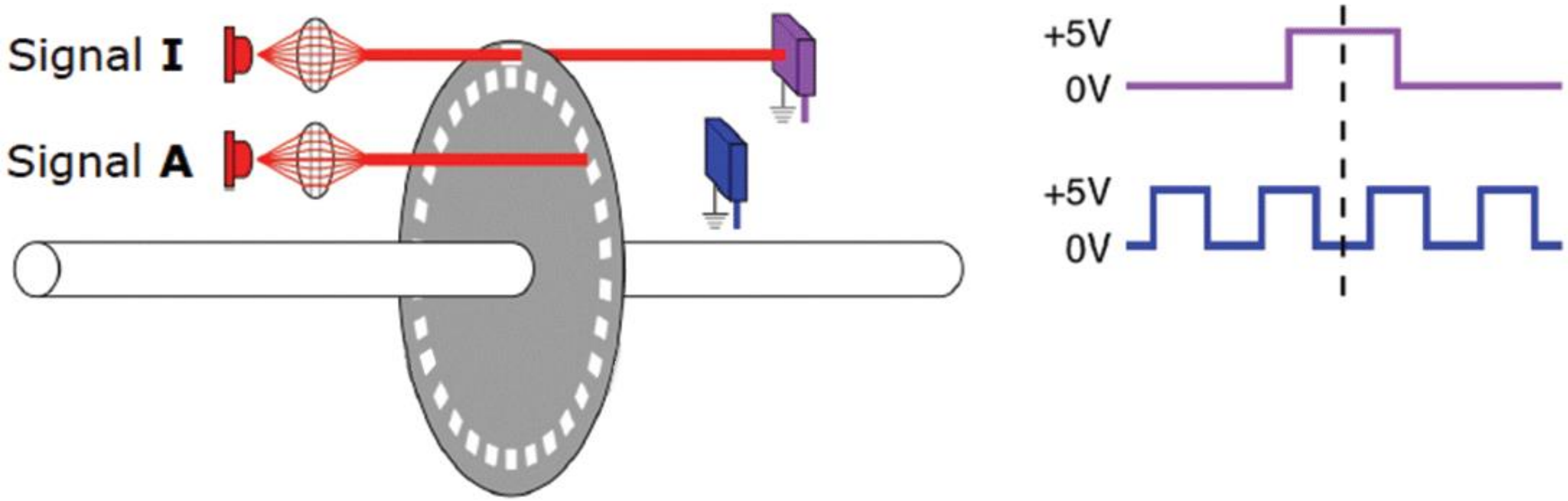
- Stereo Camera
- IMU + GPS
- Laser Scanner
- Rotary Encoders (attached to motor shaft, inside chassis)

Rotary Encoders

- Used to measure rotation of a part precisely (degree level or even sub-degree level precision possible)
  - to calculate the position of a robot from how much its wheels have rotated
  - to know the precise angles of the joints of a robotic arm, so as to control it
- Often embedded into the motors themselves (coupled with the shaft)
- Types:
  - Incremental
  - absolute
- Technology:
  - Optical (most common, more expensive as precision increases)
  - Potentiometer-based (cheap)

Rotary Encoders

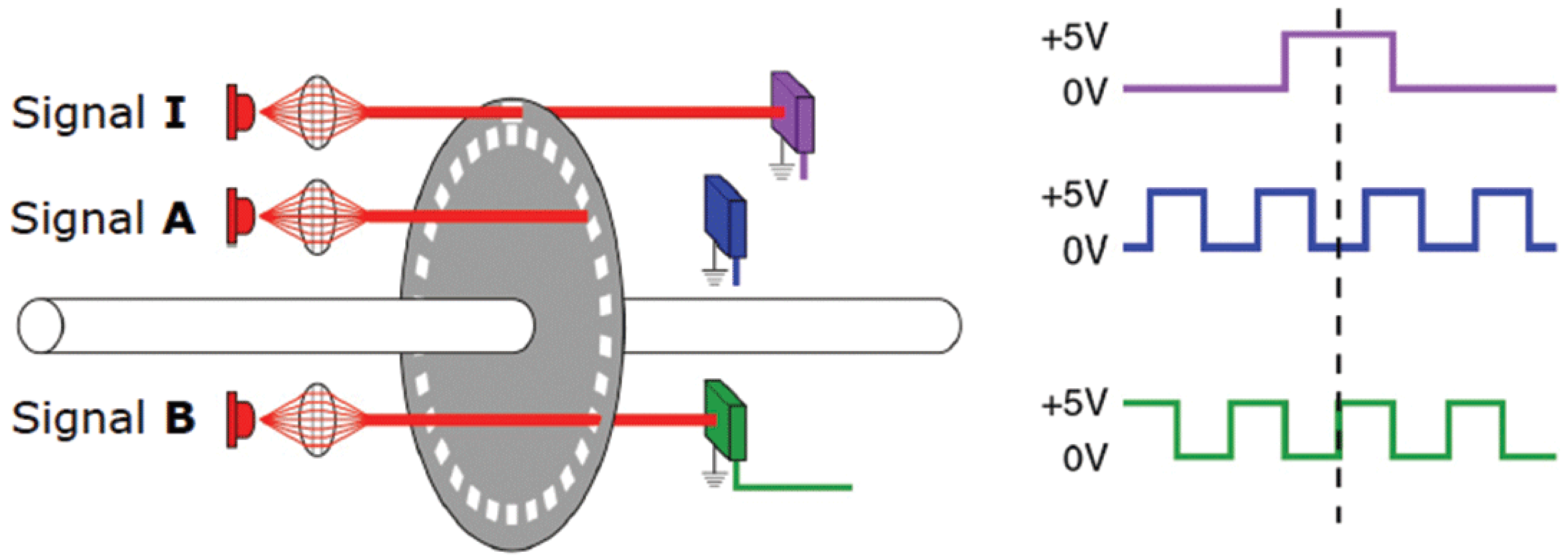
- Most common type – **incremental optical encoder**
  - Consists of a disc with precise holes, that rotates with the shaft
  - A transmitter-receiver pair (LED and photodiode) counts the ‘ticks’ (number of pulses)
  - **Signal A** gives amount of rotation, **Signal I** gives zero-position
  - Direction of rotation?



Source: https://walchko.github.io/blog/Robots/Robot-Wheel-Encoders.html

Rotary Encoders

- **Quadrature encoders** are a special type of incremental optical encoders that consist of two main signals (A and B) offset by 90° to find direction of rotation
  - For one direction, A leads B and for the opposite direction, A lags behind B



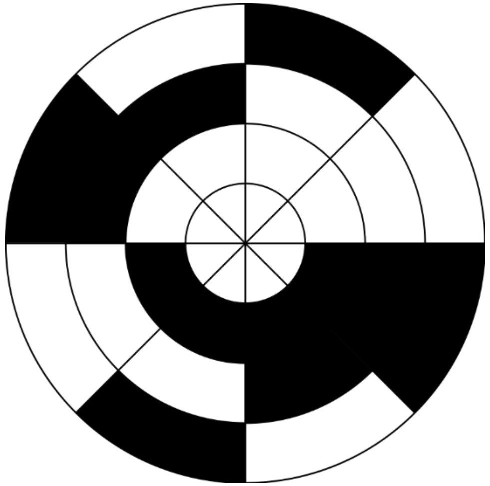
Source: https://walchko.github.io/blog/Robots/Robot-Wheel-Encoders.html

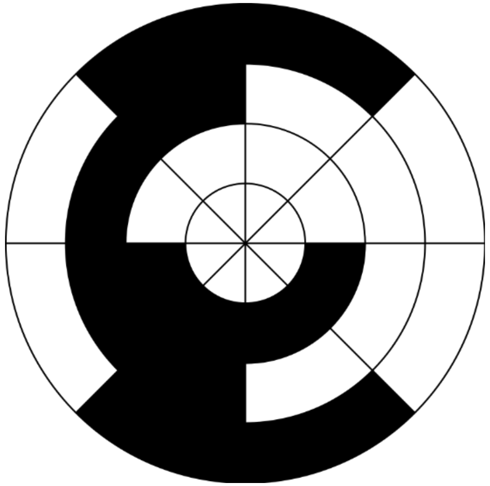
Rotary Encoders

- Problem: Incremental encoders cannot be used for absolute position measurement
  - Only position relative to initial state is known
  - Not really necessary for symmetric objects like wheels
  - But necessary for applications such as a robotic arm or laser scanner (*sensors use sensors too!*)
  - A zero-position (like Signal I in the figure) can be used to get absolute position
  - It is not always feasible to go to the zero-position (restricted spaces, mechanical constraints)
- Solution: Absolute position encoders

Rotary Encoders

- Absolute position optical encoders
  - Multiple signals used: n signals can represent 2^nunique positions
  - Binary Coding: Mechanical and electrical errors can induce false intermediate states (eg: $001 \rightarrow 010$ may momentarily go through 011)
  - Gray Coding: States are assigned such that all adjacent states differ by only 1 bit.

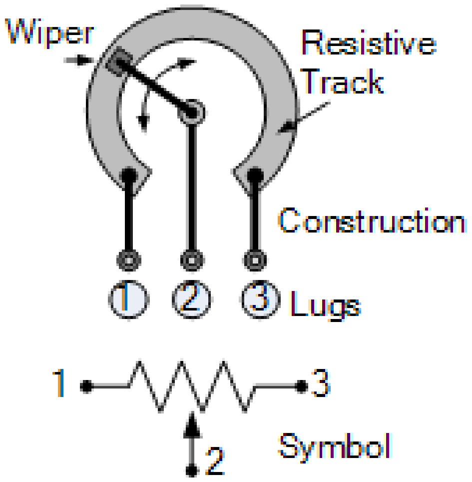




Left – Binary, Right – Gray Code. Source: https://en.wikipedia.org/wiki/Rotary_encoder

Rotary Encoders

- Optical absolute position encoders can be a bit expensive
  - A very cheap alternative is to use a resistive potentiometer-based encoder
  - A slider contacts a resistor at a particular location based on angular position
  - Voltage between ends of resistor is fixed
  - Voltage between sliding contact and one end of resistor gives position
  - Used in small servomotors
  - Cannot be used for applications where full 360° rotation is required
  - Accuracy may be lowered by electrical noise



Rotary Encoders

- Problem: Interference
  - Wires carrying encoder signals face large electrical & magnetic interference
  - Happens because they are close to the power carrying wires and magnets in the motors
- Solution:
  - Generate multiple signals: $A, B, \bar{A} = -A, \bar{B} = -B$
  - Transmitted signals: $\tilde{A} = A + \eta$, $\tilde{\bar{A}} = \bar{A} + \eta$, etc. (note that same noise acts over all wires)
  - Getting back original signals: $A = \frac{\tilde{A} - \tilde{\bar{A}}}{2}$

GNSS Modules

- Basic Idea:
  - Use precisely known locations of satellites to calculate location of sensor
- Challenge:
  - Only one-way communication possible (small sensors do not have enough power to transmit signals all the way to space)
- Solution:
  - Satellite signals send position of satellite and the receiver calculates the distance travelled by the signals (called pseudo-range) based on time difference

$$
\begin{aligned}
(X_1 - U_X)^2 + (Y_1 - U_Y)^2 + (Z_1 - U_z)^2 &= (c\Delta t_1)^2 \\
(X_2 - U_X)^2 + (Y_2 - U_Y)^2 + (Z_2 - U_z)^2 &= (c\Delta t_2)^2 \\
(X_3 - U_X)^2 + (Y_3 - U_Y)^2 + (Z_3 - U_z)^2 &= (c\Delta t_3)^2
\end{aligned}
$$

GNSS Modules

- Challenge:
  - Receiver clock may not be accurately synced with satellite clock
- Solution:
  - Introduce another variable to represent the error and use one more satellite for another equation

GNSS Modules

- Challenge:
  - Satellite clocks run faster than clocks on earth due to relativity
- Solution:
  - Design satellite clocks to run slower so as to compensate

GNSS Modules

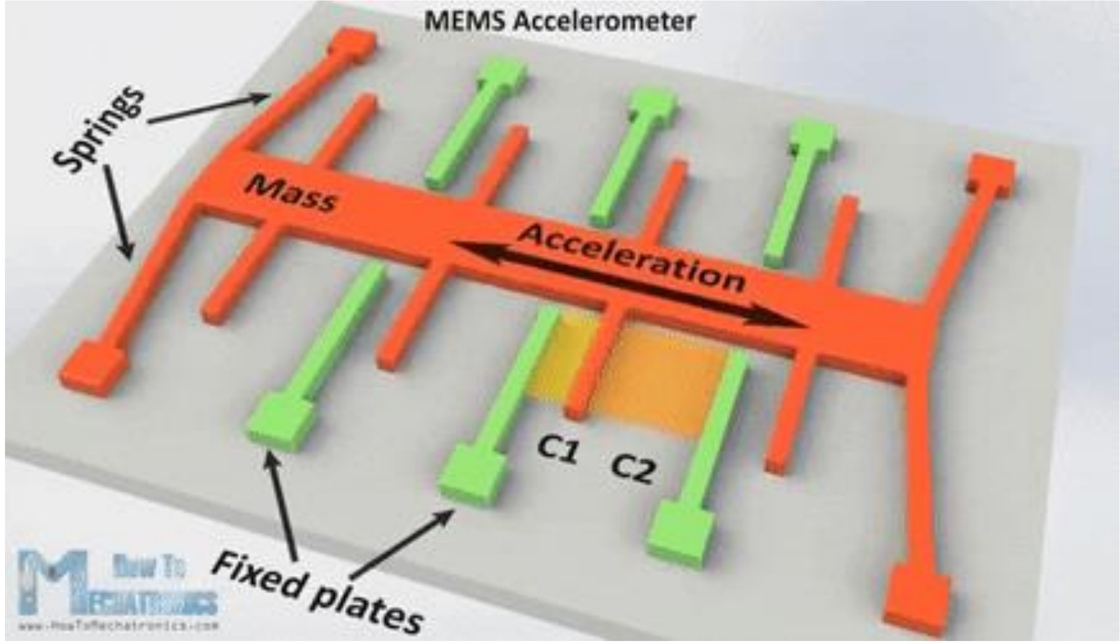
- Cold start and Hot start
- GNSS is the name of the technology, there are multiple satellite constellations such as GPS, GLONASS, Galileo, BeiDou, NAVIC

IMU

- Consists of:
  - Accelerometer (acceleration, including that due to gravity)
  - Magnetometer (magnetic field)
  - Gyroscope (angular velocity)
- Usually accurate for orientation (absolute measurement of roll, pitch, raw)
- Acceleration can be integrated twice to get position but it is not very accurate (no absolute measurement of x, y and z co-ordinates of position)

IMU

- Accurate for orientation, bad for position
- Small IMUs are manufactured using MEMS technology (**M**icro **E**lectro-**M**echanical **S**ystems).
- Eg: Accelerometer



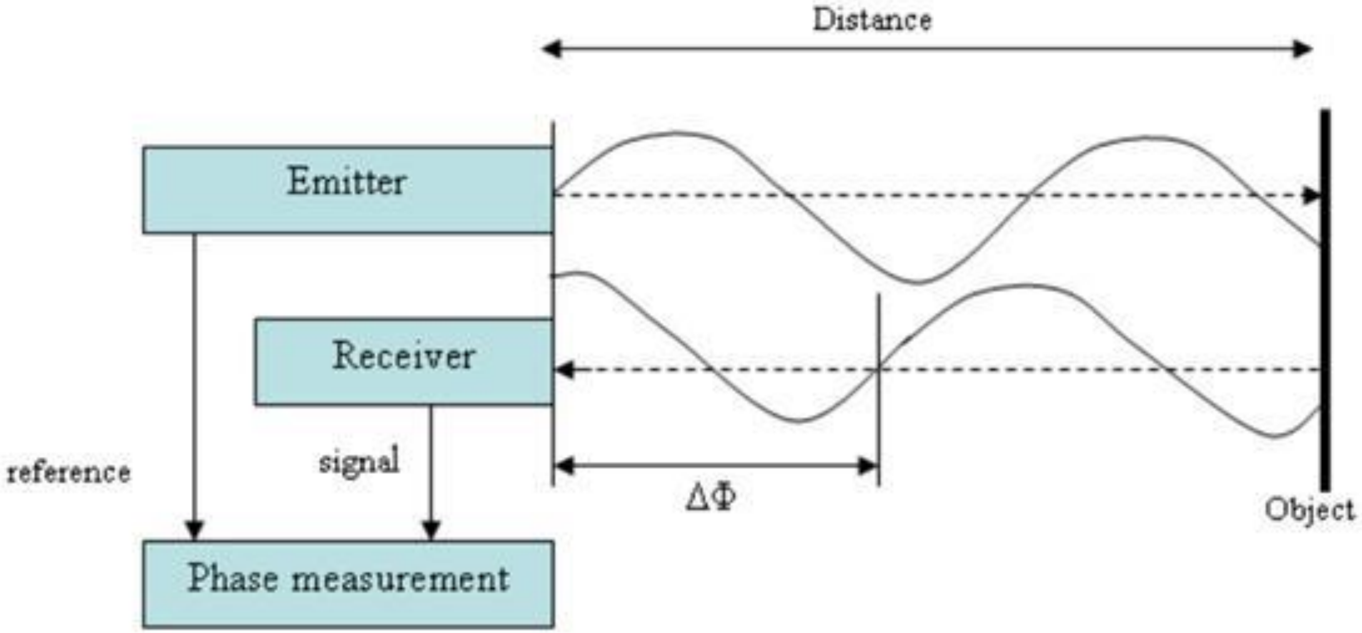
Source: https://howtomechatronics.com/how-it-works/electrical-engineering/mems-accelerometer-gyrocope-magnetometer-arduino/

Laser Scanners

- Based on LiDAR Technology (**Li**ght **D**etection **a**nd **R**anging)
- They consist of one or more rotating transmitter-receiver pairs
- Distance measurement not usually done using time of flight (light travels 0.3m in 1 nanosecond, but we need cm-level accuracy)

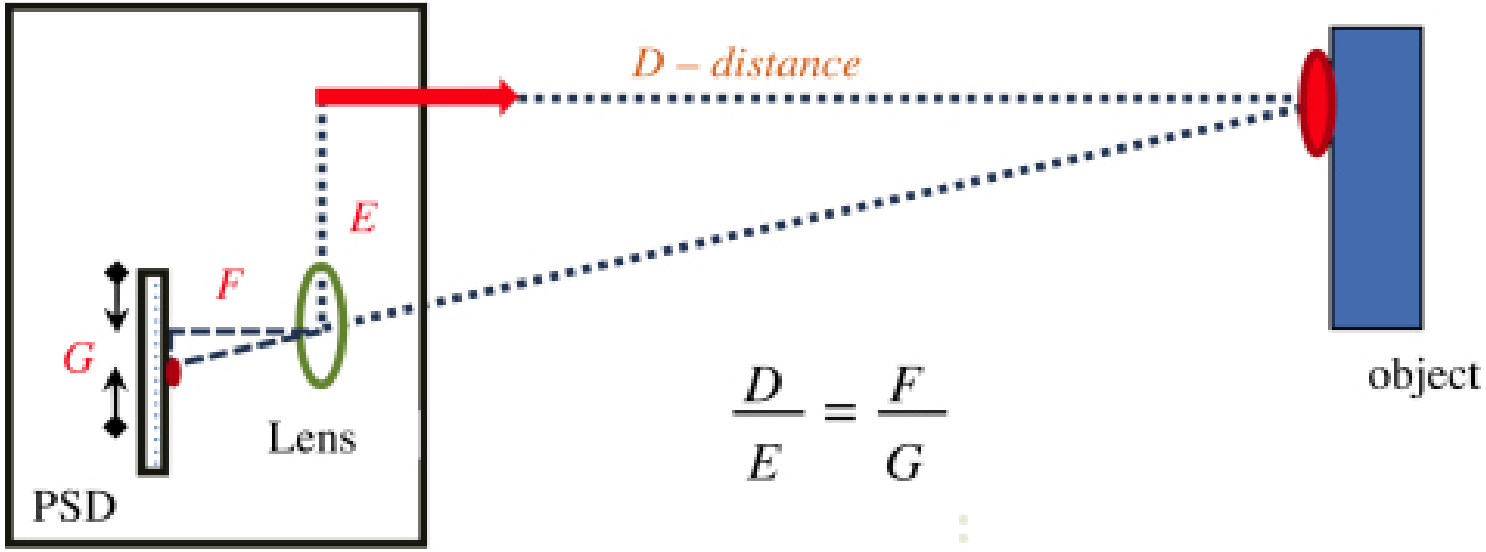
Laser Scanners

- Phase based measurement
  - *Multiple possible locations – solution: use two frequencies*



Laser Scanners

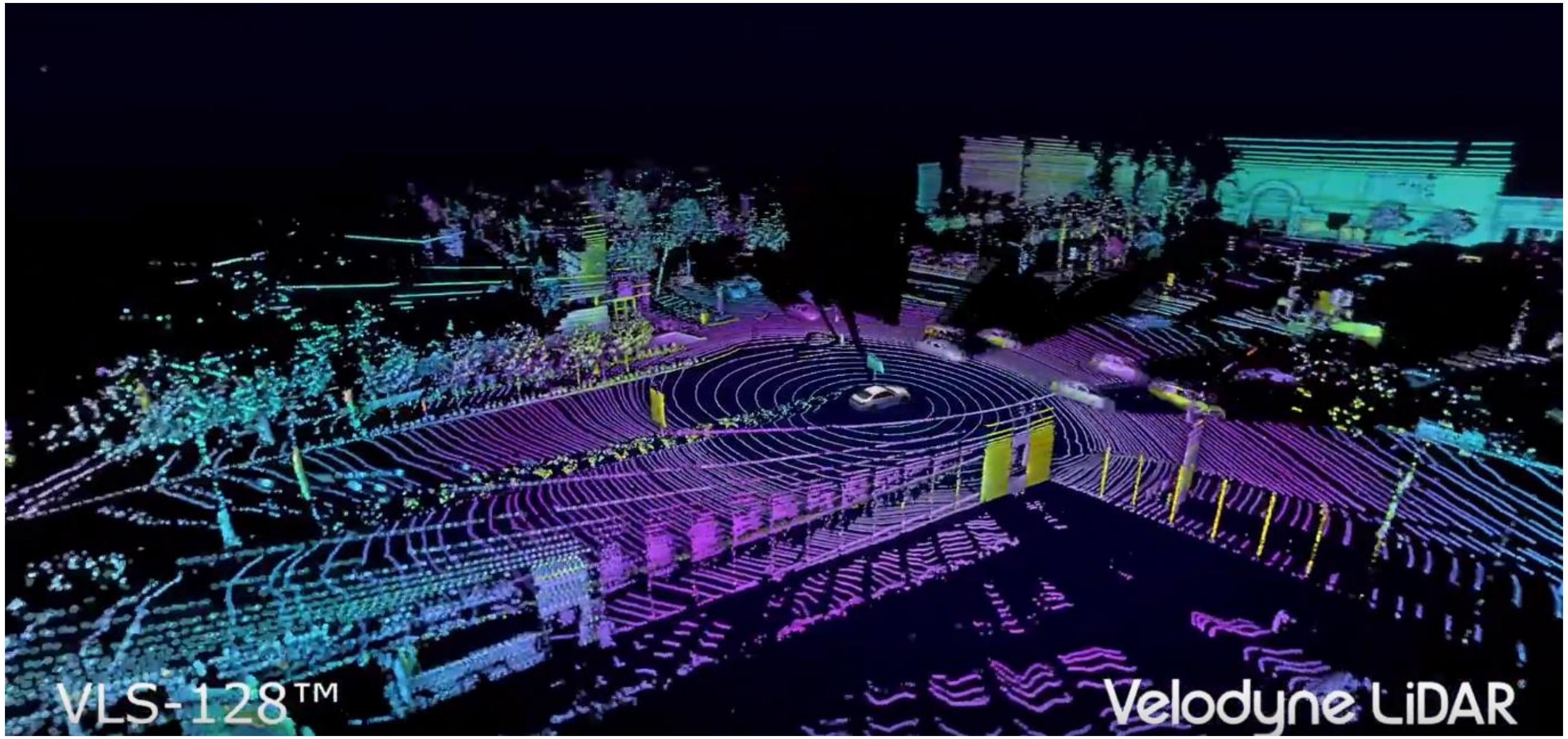
- Laser triangulation:



Triangulation sensor

$$\frac{D}{E} = \frac{F}{G}$$

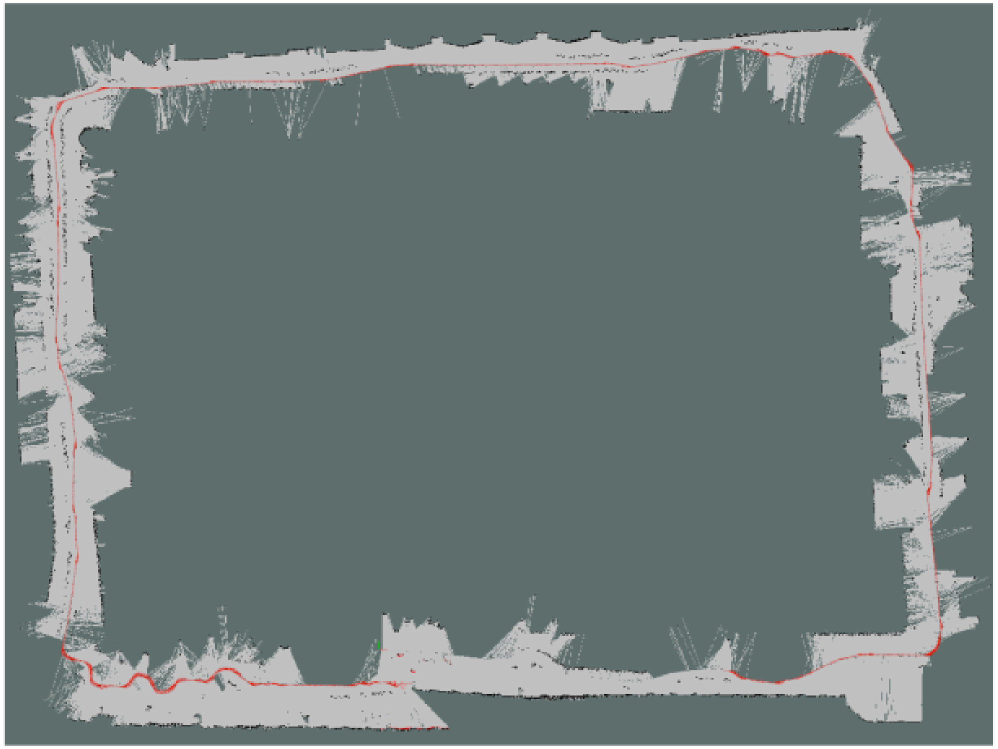
3D Laser Scanner



Source: Velodyne YouTube Channel

- Generate high density point clouds
- Laser reflections used to get distance
- Precise rotation leads to high cost (Velodyne Puck: $8000)

Source: RPLiDAR A2 Website



Source: Own Work

2D Laser Scanner

- Cheap but still gives most necessary information for ground vehicles
- Generates 2D maps similar to floor plans
- Cheaper (RPLiDAR A2: $400)

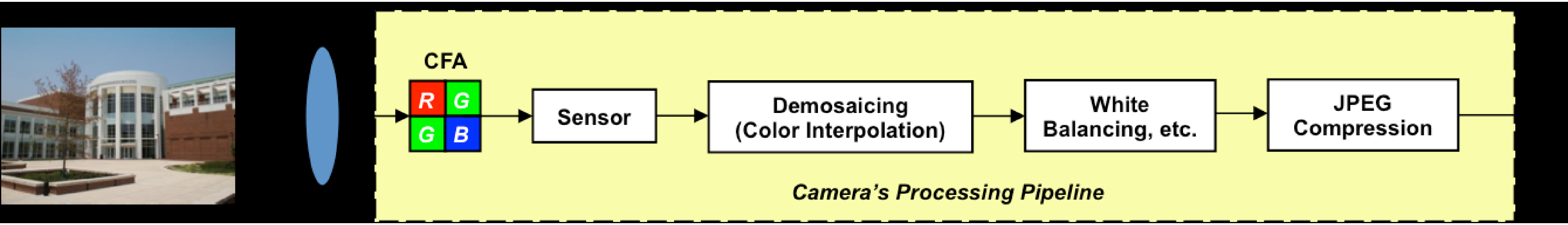
Source: Velodyne Website

Solid State Laser Scanner

- Uses electrically controlled refractive index to transmit light pulse in different directions
- No moving parts – low cost

Cameras

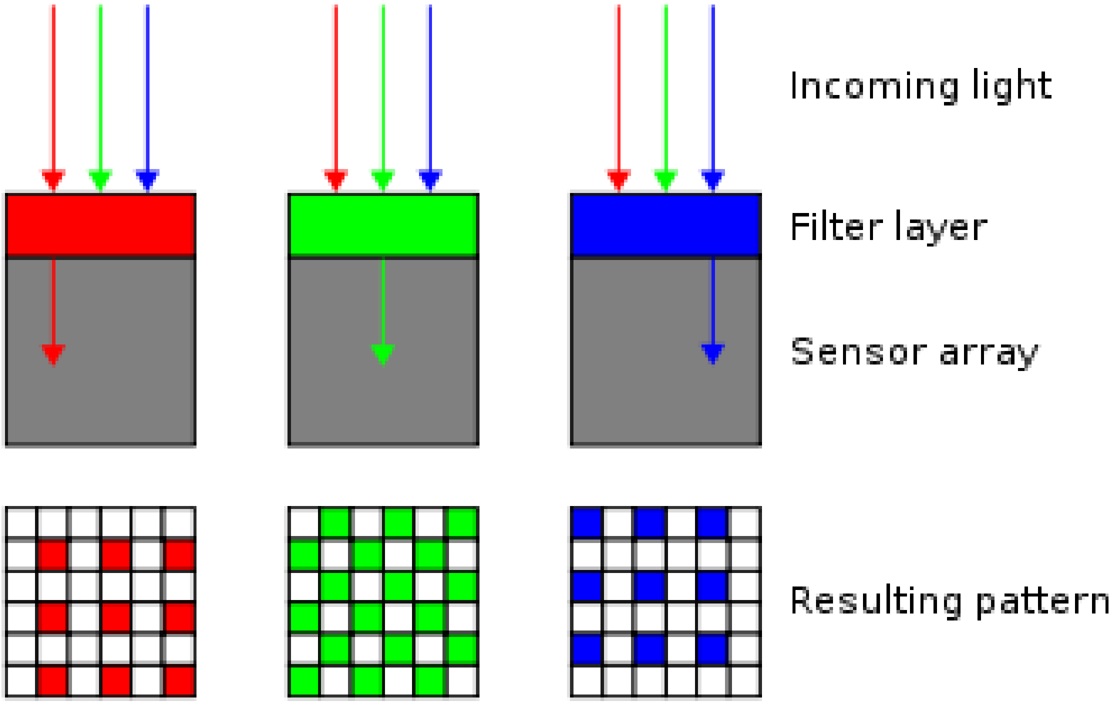
- 3D information is projected onto a 2D sensor (array of photodiodes) through a small opening (aperture)
  - Colour Filter Array (CFA) used since photodiodes do not sense colour



Source: http://signalprocessingsociety.org/sites/default/files/uploads/get_involved/docs/SPCup_2018_Document_2.pdf

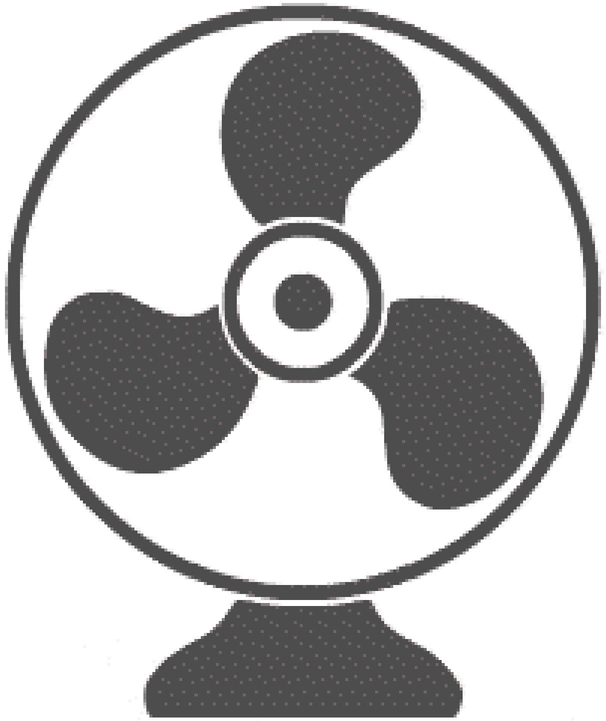
Cameras

- Demosaicing interpolates RGB subsamples to get colour image



Cameras

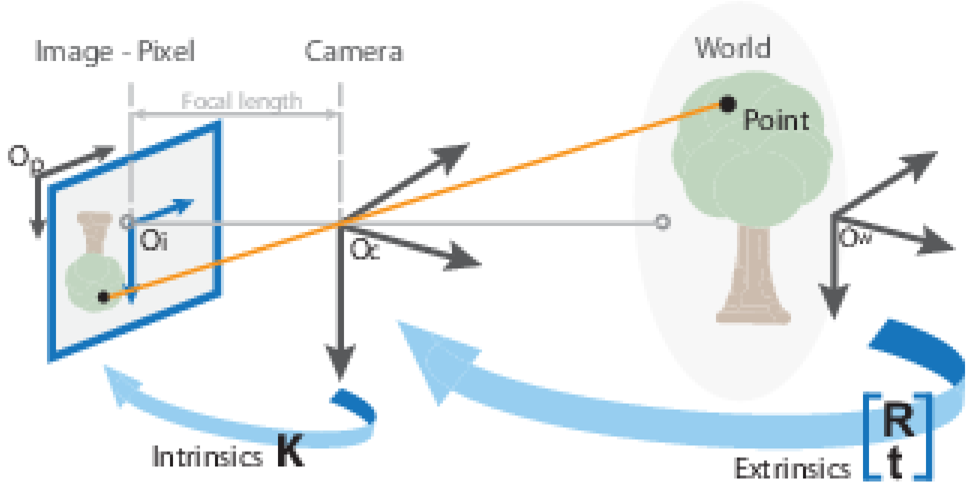
- Rolling Shutter Effect

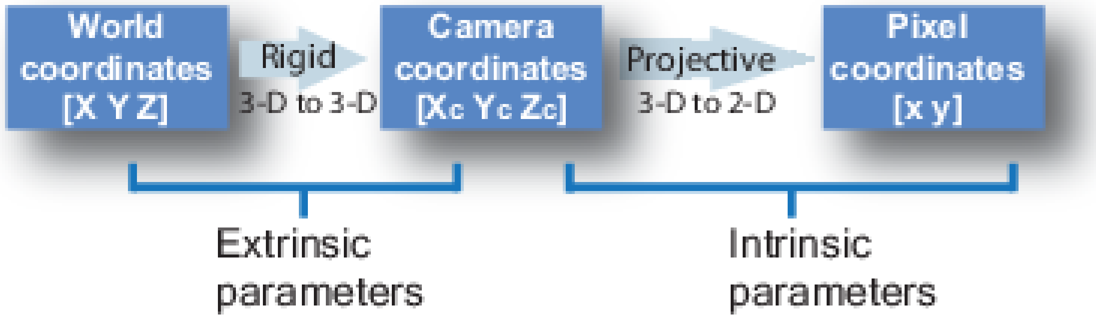


Source: https://thinklucid.com/tech-briefs/understanding-image-sensors/

Cameras

- *Basic equations for projection:*
- $\begin{bmatrix} x' \\ y' \\ w \end{bmatrix} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$
- $x = \frac{x'}{w}, y = \frac{y'}{w}$





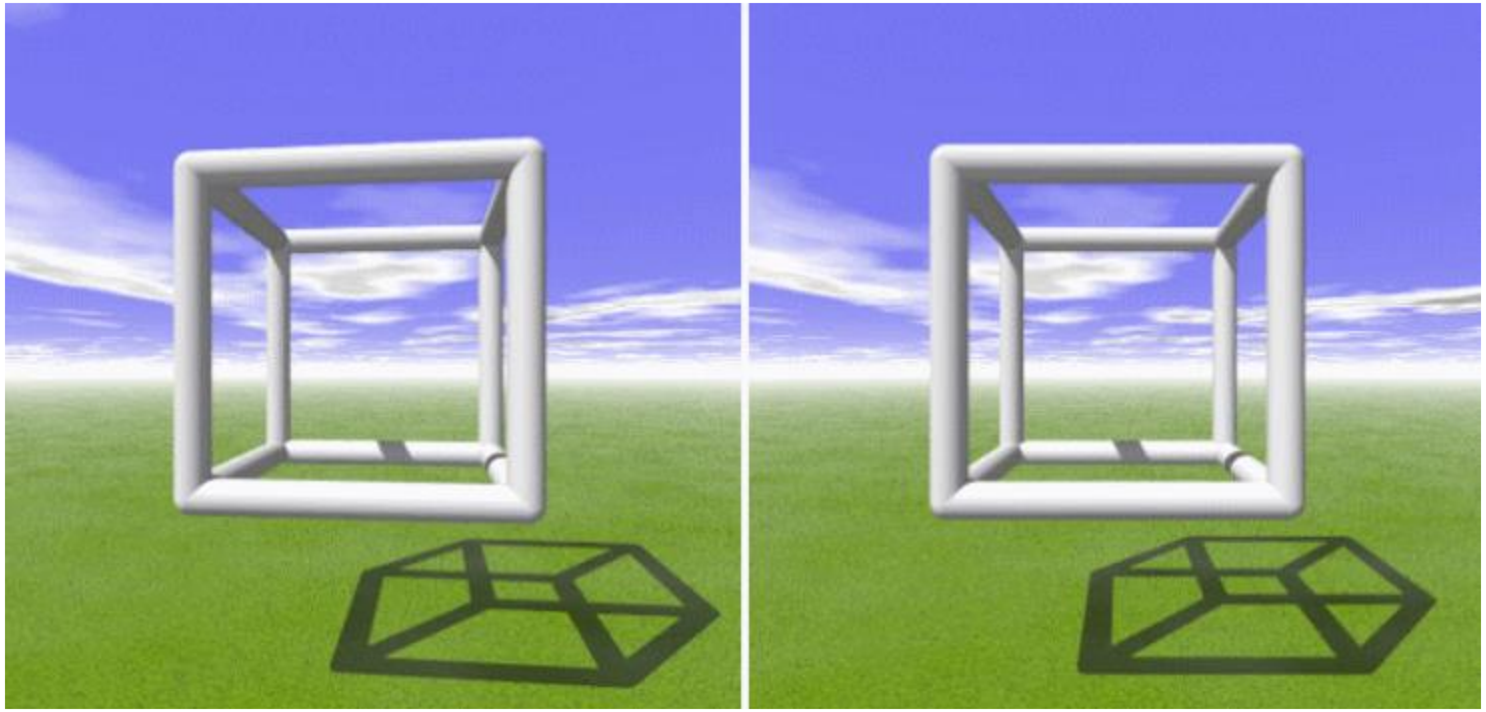
Source: https://in.mathworks.com/help/vision/ug/camera-calibration.html

Cameras

- Images are 2D and are therefore fundamentally insufficient to create an environment map
- 3D information can be obtained from cameras in many ways:
  - *Stereo Cameras*
  - *IR Projection/Light Coding Technology*

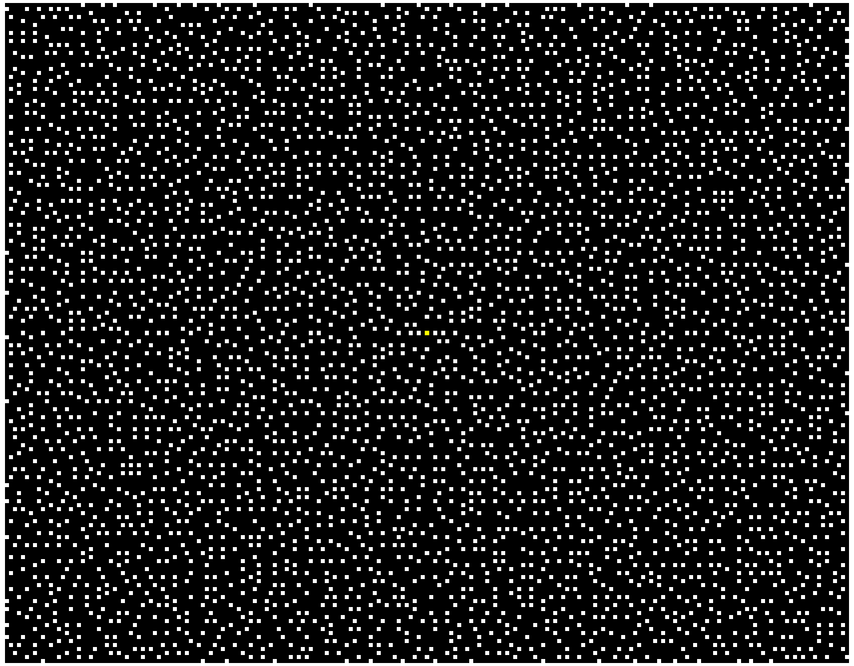
Stereo Cameras

- Image matching used to find correspondence
- Intersection of 2 lines used to get 3D location
- Fails for uniform images, images with many similar features
- Relies on natural illumination, so bad for nighttime



Source: http://www.f-lohmueller.de/pov_tut/stereo/stereo_400e.htm

Source: Stereolabs' (manufacturer of ZED Camera) Website



Source: Kinect Documentation

IR Projection

- Used in Microsoft Kinect, iPhones
- Distortion of projected pattern used to calculate distance
- Requires power for IR projection
- Fails in high IR-noise conditions – bad for daytime

Event Cameras/ Dynamic Vision Sensors (DVS)

- Very low latency required for SLAM applications – a car at 30 m/s covers half a meter in one frame (at 60fps)
- Event cameras transmit only change in intensities, leading to very low data transfer per frame, leading to lesser latency

Source: https://www.youtube.com/watch?v=kPCZESVfHoQ