EC4.404: Mechatronics System Design

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General Information

Mechatronics: Study of the integration of mechanical hardware, electrical/electronic hardware with computer hardware and software. Named by Tetsuro Mori from Japan when working with Yaskawa Electric Coorporation.
Applications: Robotics, Aerospace industry, automotive industry, process industry etc.

Course Objective: To introduce the design and development of a mechatronic system.
Instructors: Harikumar Kandath and Nagamanikandan Govindan.

Sensors in Ground Robot

- Wheel Encoder
- Magnetometer
- Inertial Measurement Unit (IMU): contains Accelerometer and Gyroscope.
- Global Positioning System (GPS)
- Range measuring sensor (LIDAR, ultrasonic, camera)

Sensors in UAV

- Inertial Measurement Unit (IMU) contains Accelerometer and Gyroscope.
- Altimeter
- Airspeed sensor
- Magnetometer
- Global Positioning System (GPS)
- Range measuring sensor (LIDAR, ultrasonic, RADAR, camera)

Sensors in Robotic Manipulator

- IMU
- Encoder
- Force-Torque sensor
- Camera

Range Measurement

Applications

- Obstacle Avoidance
- SLAM (Simultaneous Localization and Mapping)
- UAV Landing
- Accurate mapping of a region with elevation
- Distance to the target vehicle
- Atmospheric Physics
- Underwater survey

Major Classification

- Active (LIDAR, RADAR, ultrasonic)
- Passive (Camera)

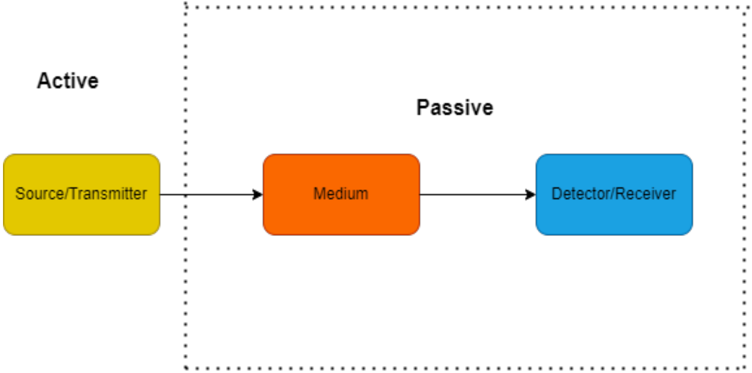


Figure: Structure of a range measuring system

LIDAR

LIDAR: Light Detection and Ranging.

Working principle: Source emits thousands of laser pulses per second and the reflected pulses are detected by the receiver and the time of flight is measured (t_f). Typical wavelengths used 905 nm, 1064 nm, 1550 nm. Lower wavelengths used for water bodies like 532 nm.

$$Range = 0.5 \times (Speed\ of\ light \times\ time\ of\ flight) \tag{1}$$

Types

- Airborne
- Ground-based
- Spatial

LIDAR - Components

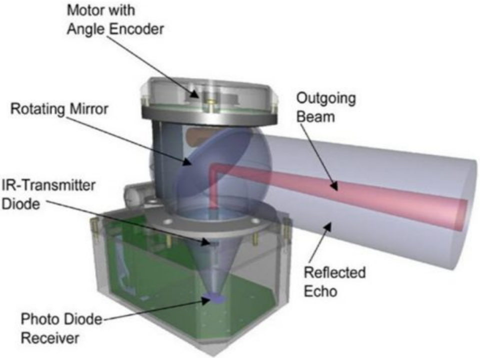


Figure: Components of a LIDAR

LIDAR Transmission

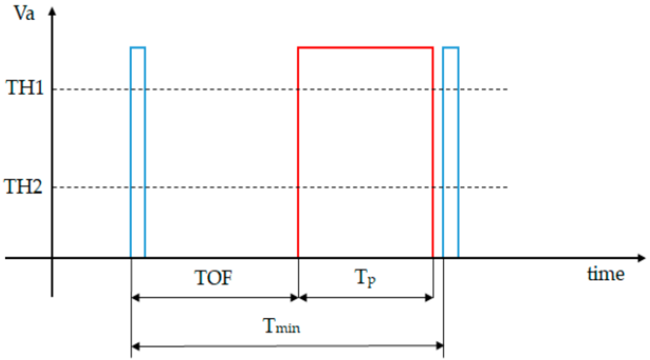


Figure: LIDAR pulse

LIDAR Equation

$$P_R = \frac{P_T A \eta_T \eta_R \Gamma}{2\pi D^2} \tag{2}$$

P_T is transmitted power in watts
P_R is received power in watts
A is the area of the optical sensing element in m^2
η_T, η_R are the efficiency of the transmitter and receiver respectively
D is the distance to the target
Γ is the reflectivity of the target

LIDAR Mapping

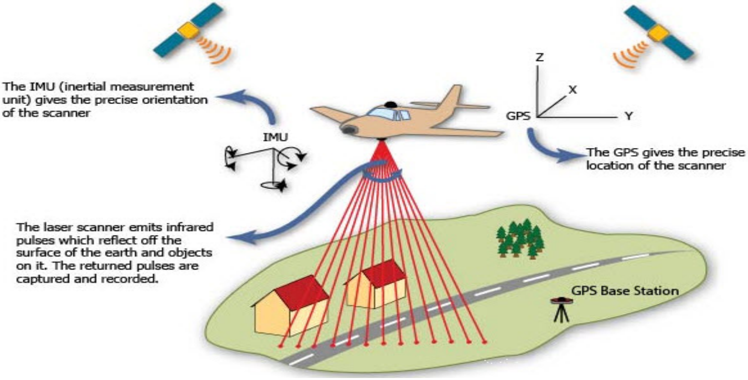


Figure: LIDAR based mapping

LIDAR Parameters

- Detection Range
- Field-of-View (FoV)
- Scan Pattern
- Cross Talk Immunity
- Detection Range
- Multiple Returns
- Range Precision and Accuracy

RADAR

RADAR: Radio Detection and Ranging (detection range higher than LIDAR).

- Transmitter
- Waveguide
- Antenna
- Receiver

RADAR Frequency Band

Radar Band	Frequency (GHz)	Wavelength (cm)
Millimeter	40–100	0.75–0.30
Ka	26.5–40	1.1–0.75
K	18–26.5	1.7–1.1
Ku	12.5–18	2.4–1.7
X	8–12.5	3.75–2.4
C	4–8	7.5–3.75
S	2–4	15–7.5
L	1–2	30–15
UHF	0.3–1	100–30

RADAR Equation

$$R^4 = \frac{P_t G_t G_r \lambda^2 \sigma F^4}{64\pi^3 P_r} \tag{3}$$

R is the range to the target (m).
P_t, P_r is the transmitted signal power and the received signal power respectively (w).
G_t, G_r is the gain of the transmitter antenna and the receiver antenna respectively.
λ is the signal wavelength (m).
σ is the scattering coefficient of the target (m^2).
F is the pattern propagation factor (depends upon the medium).

Ultrasonic Range Measurement (SONAR)

- Utilizes sound waves with frequencies higher than human audible limit (typically above 18 KHz).
- Main component is piezoelectric material that undergoes deformation when a voltage is applied (transmitter) and also can convert a deformation into an electrical signal (receiver).
- Applying a sinusoidal voltage with a specified frequency vibrates the piezoelectric material with the same frequency, resulting in the generation of ultrasonic waves through the medium.

$$Range = 0.5 \times (V_s \times t) \tag{4}$$

V_s= speed of sound (m/s), t = time elapsed between sending and receiving (s).

Frequency Response

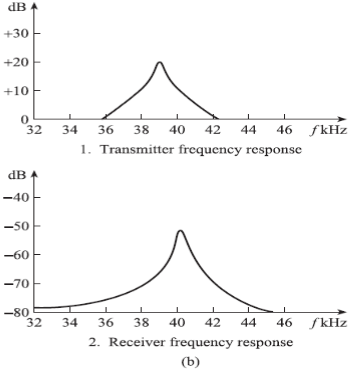
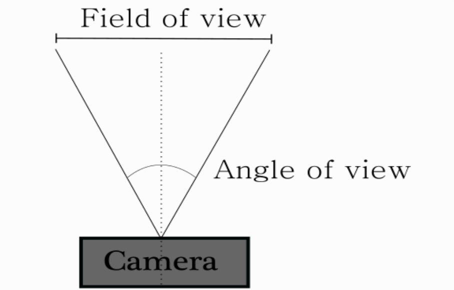


Figure: Transmitter and Receiver Frequency Response

Camera

- Day/ Night
- RGB/ Monochrome
- Mono vision/Stereo vision
- FOV (field of view)- narrow/ wide angle
- FPS (frames per second)
- Image resolution (pixel size)

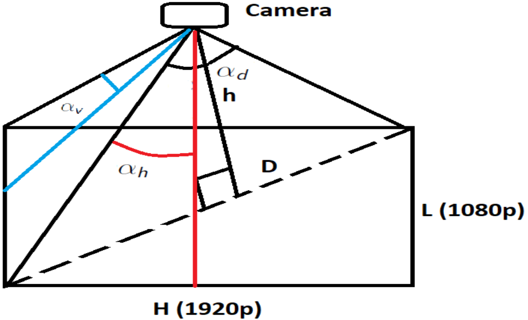


Camera FOV

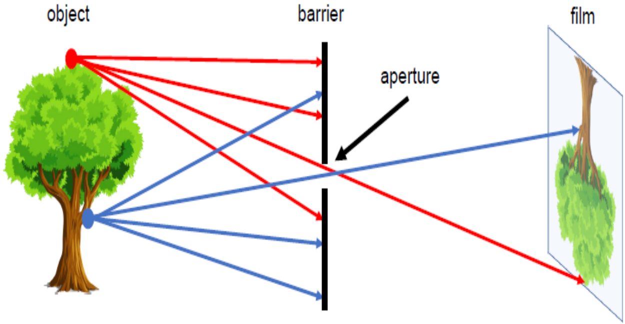
Diagonal FOV (α_d), horizontal FOV (α_h) and vertical FOV (α_v).

$$D = 2h \times tan\alpha_d,\ H = 2h \times tan\alpha_h,\ L = 2h \times tan\alpha_v \tag{5}$$

$$tan^2\alpha_d = tan^2\alpha_h + tan^2\alpha_v,\ \frac{tan\alpha_h}{tan\alpha_v} = \frac{1920}{1080} \tag{6}$$

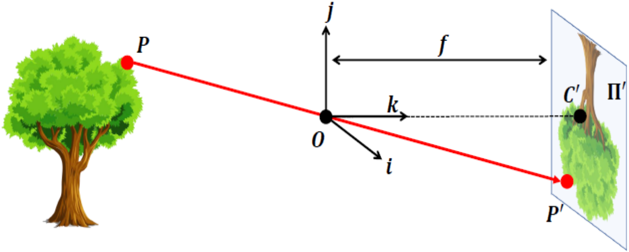


Pinhole camera model (PCM)



NB: Object is seen inverted in the image plane.

Coordinates in PCM



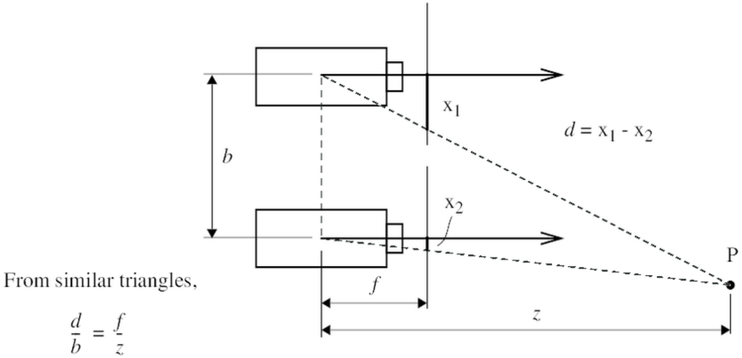
(x_i, y_i) coordinates in the image plane of the point P whose real world coordinates is (x, y, z).

$$x_i = f\frac{x}{z}, \;\; y_i = f\frac{y}{z} \tag{7}$$

Stereo Vision

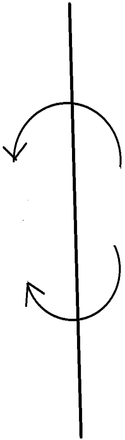
Pixel coordinates x_1, x_2 and real world coordinates x_{r1}, x_{r2}
Distance between 2 cameras

$$b = x_{r1} - x_{r2} = \frac{zx_1}{f} - \frac{zx_2}{f} = z\frac{d}{f} \implies z = \frac{fb}{d} \tag{8}$$



Gimbal

Stabilizing camera from the oscillations of the robot.



Altimeter

Altitude measurement using pressure sensor (more accurate than using GPS)

$$\delta pressure = -\rho g \delta h \tag{9}$$

NB: Pressure reduces as altitude increases.

$$pressure(ground) - pressure(h) = -\rho g(0 - h) \tag{10}$$

$$h = \frac{pressure(ground) - pressure(h)}{\rho g} \tag{11}$$

Airspeed Sensor

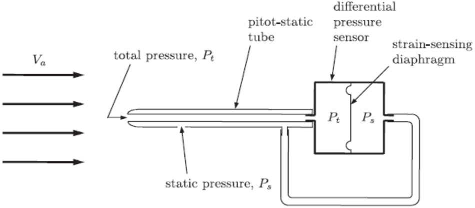


Figure: Pitot Tube

$$P_t - P_s = \frac{\rho V_a^2}{2} \tag{12}$$

P_t - total pressure (N/m^2), P_s - static pressure (N/m^2), ρ - density of air (Kg/m^3), V_a - airspeed in m/s.

GPS Speed & Airspeed

(x, y, z) is the coordinate in NED frame.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} -s\phi c\lambda & -s\lambda & -c\phi c\lambda \\ -s\phi s\lambda & c\lambda & -c\phi s\lambda \\ c\phi & 0 & -s\phi \end{pmatrix} [\begin{pmatrix} (N+h)c\phi c\lambda \\ (N+h)c\phi s\lambda \\ (\frac{b^2}{a^2}N+h)s\phi \end{pmatrix} - \begin{pmatrix} (N+h_0)c\phi_0 c\lambda_0 \\ (N+h_0)c\phi_0 s\lambda_0 \\ (\frac{b^2}{a^2}N+h_0)s\phi_0 \end{pmatrix}] \tag{13}$$

GPS Speed (ground speed) (V_g)

$$V_g = \sqrt{\dot{x}^2 + \dot{y}^2} = V_a \tag{14}$$

NB: $V_g \neq V_a$ when wind speed is non-zero.

THANK YOU