Logistics

Paper Presentation Form:

- Please fill in by TODAY
- https://forms.gle/rJwnEBUeTudToegC9

Office Hours:

- 4:15pm – 5pm after each lecture, same zoom link

Mid-term Project Presentation:

- Oct 27 Friday 4:15pm – 5:30pm

Piazza:

- https://shenlong.web.illinois.edu/teaching/cs598fall21/

Video Recording:

- https://mediaspace.illinois.edu/channel/CS+598+Fall+2021+Advanced+Topics+in+Robot+Perception/

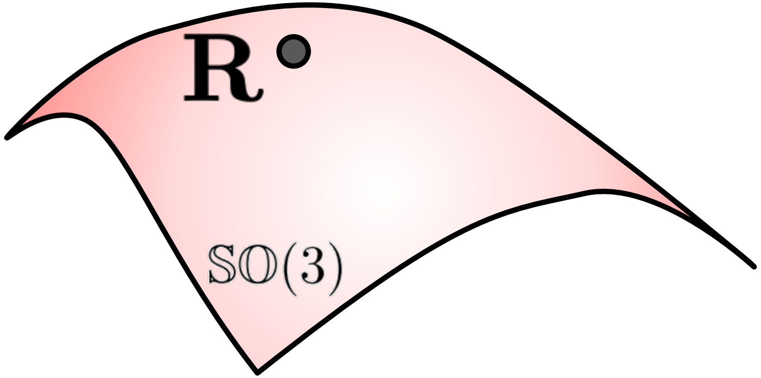
Quick Recap from Last Lecture

- Coordinates and Rigid Transforms
- Coordinate Frame Composition
- 3D Rotation Representations
- **Lie Group and Lie Algebra**

The Space of Rotations

Special Orthogonal Matrix Lie Group SO(3):

$$\mathbb{SO}(3) = \{\mathbf{R} | \mathbf{R} \in \mathbb{R}^{3\times 3}, \mathbf{R}^T\mathbf{R} = \mathbf{R}\mathbf{R}^T = \mathbf{I}, \det \mathbf{R} = 1\}$$



I want to…

- Integration
- Smoothing
- Interpolation
- Uncertainty
- Control
- Optimization
- …

$$\min_{\mathbf{R} \in \mathbb{SO}(3)} f(\mathbf{R})$$

How would you minimize this?

$$\min_{\mathbf{x} \in \mathbb{R}^n} f(\mathbf{x})$$

Gradient Descent?

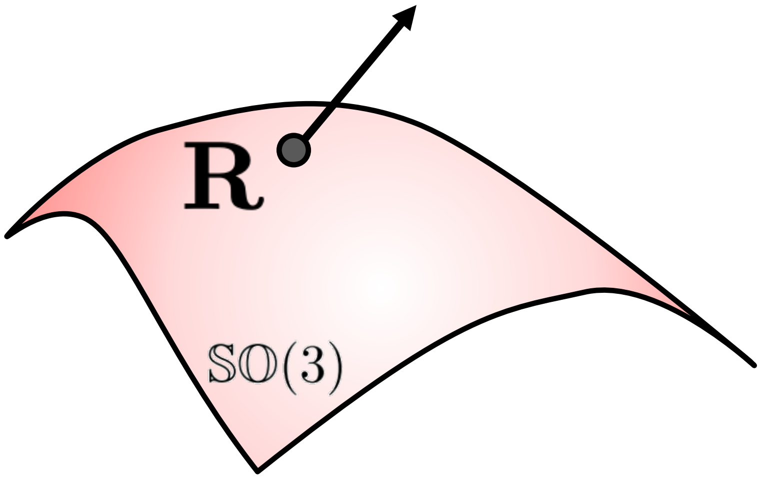
$$\min_{\mathbf{x} \in \mathbb{R}^n} f(\mathbf{x})$$

$$\mathbf{x}^{(t+1)} = \underline{\mathbf{x}^{(t)} - \gamma \nabla_{\mathbf{x}} f(\mathbf{x}^{(t)})} \longrightarrow \in \mathbb{R}^n$$

$$\nabla_{\mathbf{x}} f(\mathbf{x}) = \left[\frac{\partial f}{\partial x_0}, \frac{\partial f}{\partial x_1}, \ldots, \frac{\partial f}{\partial x_n} \right]$$

Gradient Descent?

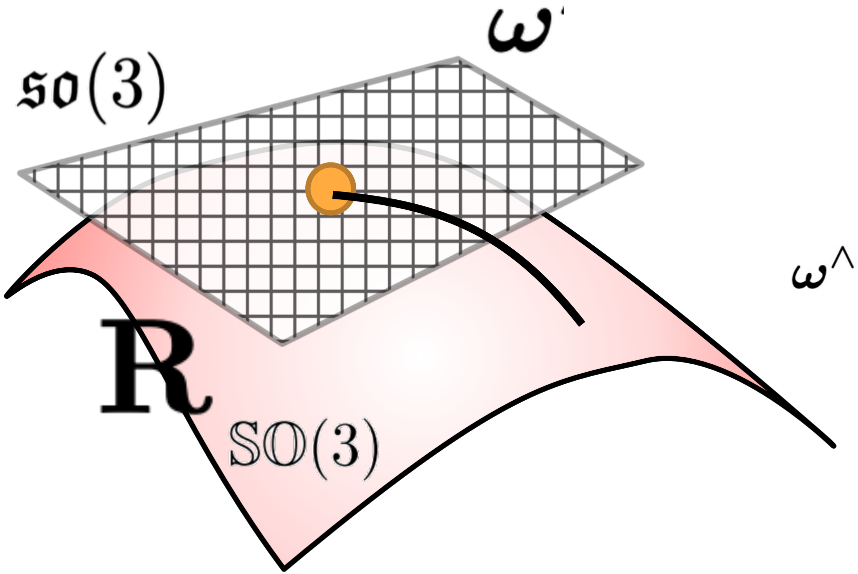
$$\min_{\mathbf{R} \in \mathbb{SO}(3)} f(\mathbf{R})$$



so(3) Lie Algebra

- The tangent space of the SO(3) manifold.
- Coincides with the space of skew-symmetric matrix

Prove it? Hint:
(1). Define a trajectory R(t)
(2). Compute the derivate wrt t on both sides: R(t)^T R(t) = I



$$\boldsymbol{\omega}^{\wedge} = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}^{\wedge} = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix} \in \mathfrak{so}(3).$$

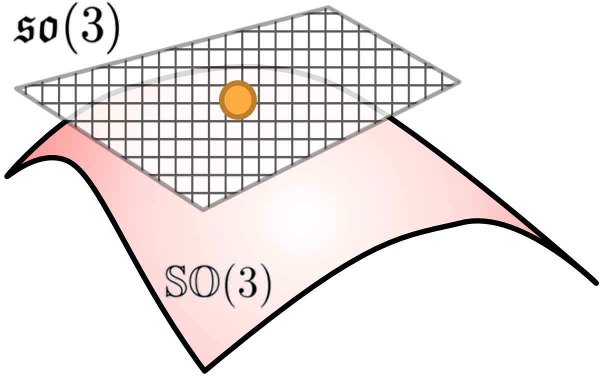
so(3) Lie Algebra

- Mapping from so(3) algebra to SO(3) group:

$$\exp(\boldsymbol{\phi}^\wedge) = \mathbf{I} + \frac{\sin(\|\boldsymbol{\phi}\|)}{\|\boldsymbol{\phi}\|}\boldsymbol{\phi}^\wedge + \frac{1-\cos(\|\boldsymbol{\phi}\|)}{\|\boldsymbol{\phi}\|^2}\left(\boldsymbol{\phi}^\wedge\right)^2$$

- Mapping from SO(3) group to so(3) algebra:

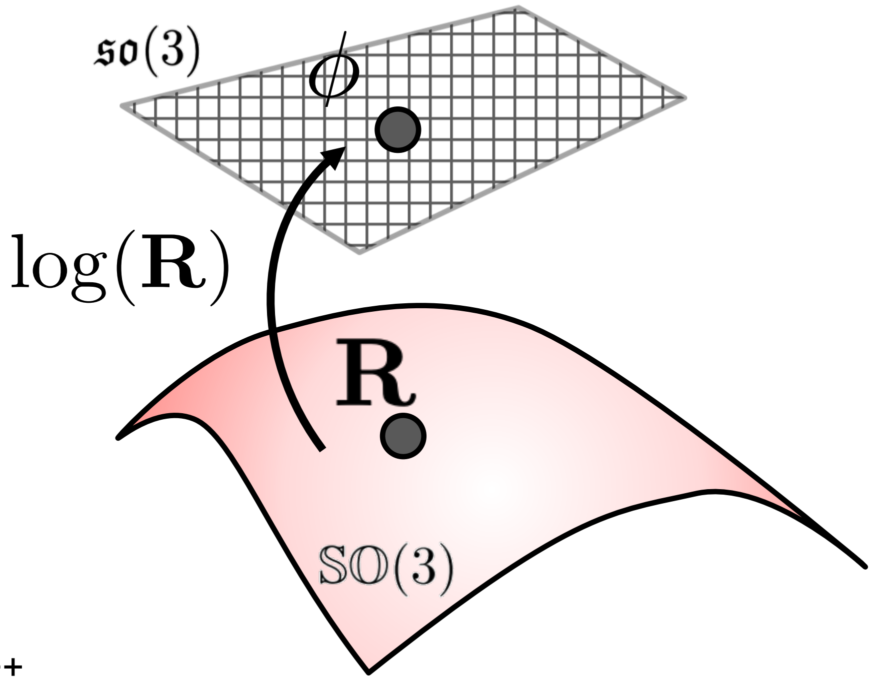
$$\log(\mathtt{R}) = \frac{\varphi \cdot (\mathtt{R} - \mathtt{R}^\mathsf{T})}{2\sin(\varphi)} \text{ with } \varphi = \cos^{-1}\left(\frac{\mathrm{tr}\left(\mathtt{R}\right) - 1}{2}\right)$$



When to Use Lie Algebra?

$$\min_{\mathbf{R} \in \mathbb{SO}(3)} f(\mathbf{R})$$

- Integration
- Smoothing
- Interpolation
- Uncertainty
- Control
- Optimization
- …



https://github.com/artivis/manif C++
https://github.com/princeton-vl/lietorch PyTorch
https://github.com/utiasSTARS/liegroups PyTorch + Numpy

When to Use Lie Algebra?

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- Smoothing
- Interpolation
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- Optimization
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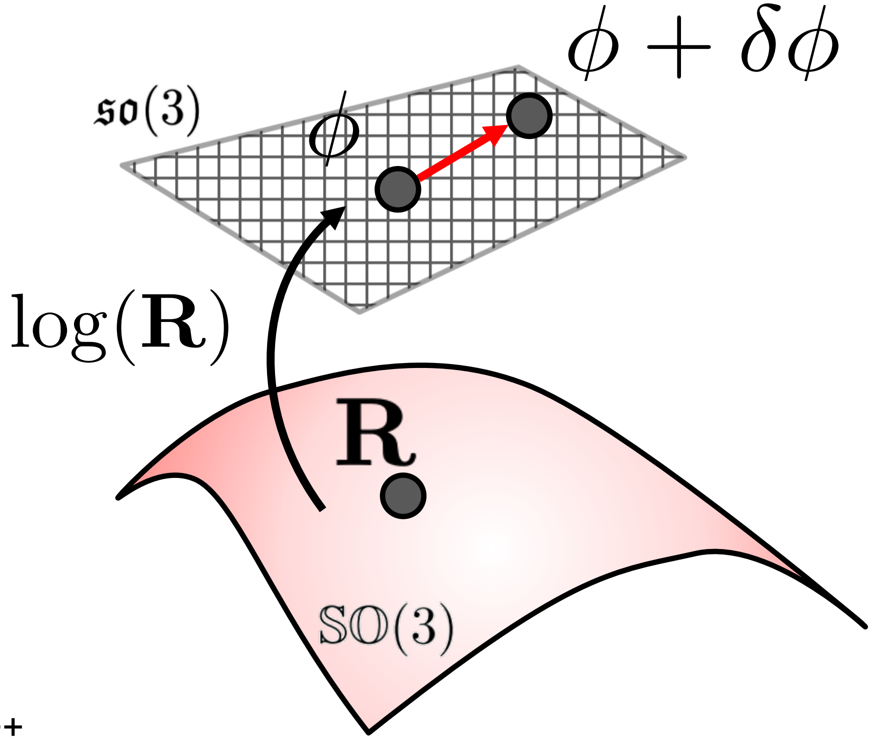

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When to Use Lie Algebra?

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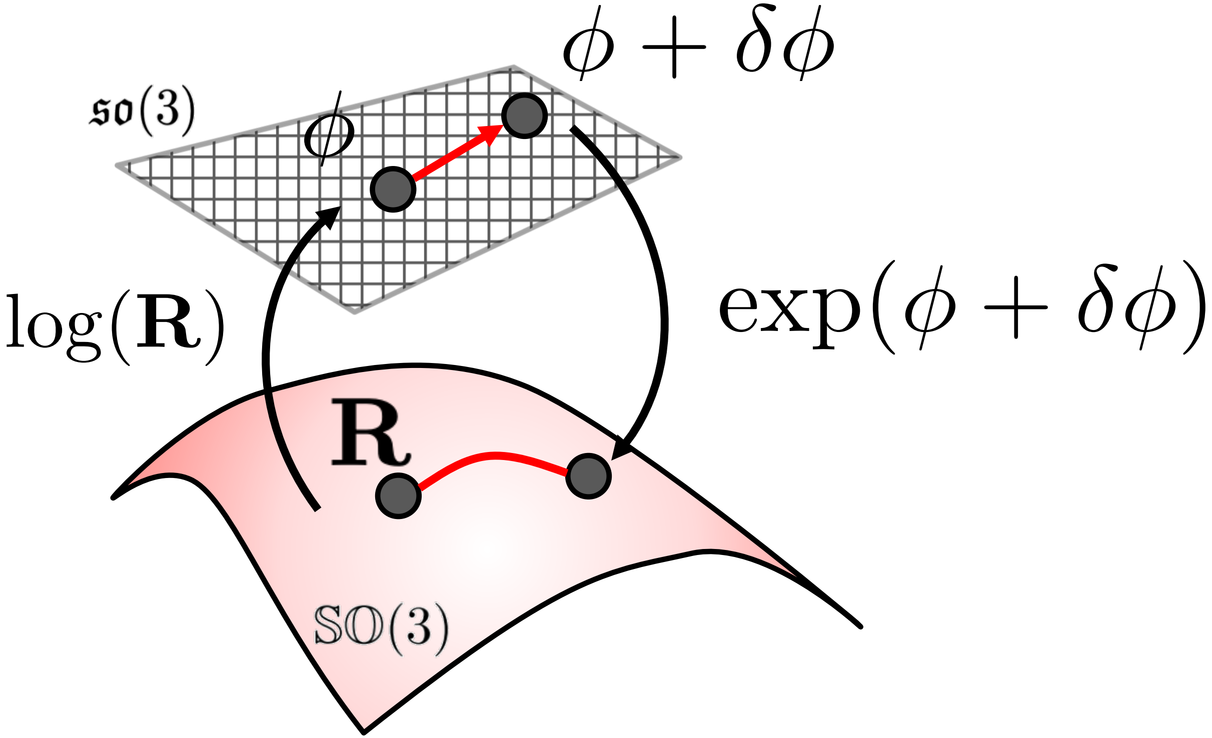

SE(3) Lie Group and se(3) Lie Algebra

- SE(3) Lie Group group: the group of all rigid poses

$$\mathbf{T} = \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0}^T & 1 \end{bmatrix} \in \mathbb{SE}(3) \subset \mathbb{R}^{4\times 4} \quad \text{with} \quad \mathbf{R} \in \mathbb{SO}(3), \mathbf{t} \in \mathbb{R}^3$$

- se(3) Lie algebra:

$$\boldsymbol{\xi}^\wedge = \begin{bmatrix} \boldsymbol{\omega}_\times & \boldsymbol{v} \\ \mathbf{0}^T & 0 \end{bmatrix} \in \mathfrak{se}(3) \subset \mathbb{R}^{4\times 4}$$

References

Reading: Sola et al., A micro Lie theory for state estimation in robotics

https://github.com/strasdat/Sophus C++
https://github.com/artivis/manif C++
https://github.com/princeton-vl/lietorch PyTorch
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Sensors I

Shenlong Wang
UIUC

ILLINOIS

Some materials borrowed from Florian Shkurti, Kris Hauser, Roland Siegwart, Steve Stancliff

Today’s Agenda

- Overview
- Motion Sensors
- Range Sensors
- Touch Sensors

Motivation

Why should a roboticist know about sensors?

- Sensing is the **key technology** for perceiving the environment

Understanding the physical principle behind sensors enables us:

- To **properly select** the sensors for a given application
- To **properly model** the sensor system, e.g. resolution, bandwidth, uncertainties

Sensing in Nature

Humans:

- Vision (See)
- Audition (Listen)
- Gustation (Taste)
- Olfaction (Smell)
- Tactition (Touch)
- Thermoception (Heat)
- Nociception (Pain)
- Equilibrioception (Balance)
- Proprioception (Body-Awareness)

Other Animals:

- Magnetoception (birds)
- Electroception (sharks, etc.)
- Echolocation (bats, etc.)
- Pressure gradient (fish)
- …

What Do We Care?

- What does the sensor measure?
- What is the source of error?
- How frequent does it measure?
- What information do we actually want to know?

Inertial Sensors

Gyroscopes, Accelerometers, Magnetometers

- Inertial Measurement Unit (IMU)
- Perhaps the most important sensor for 3D navigation, along with the GPS

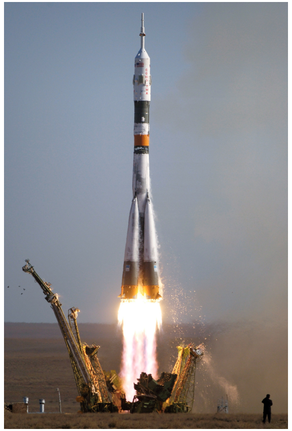

Image credit: Tesla, Uber, Oculus, Apple

Inertial Sensors

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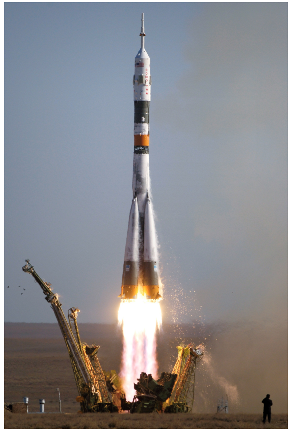


Could anyone name a use case of this motion sensors in your cellphone?

Image credit: Tesla, Uber, Oculus, Apple

Magnetometers

Pros:

- A compass for absolute heading

Cons:

- Needs careful calibration
- Needs to be placed away from moving metal parts, motors

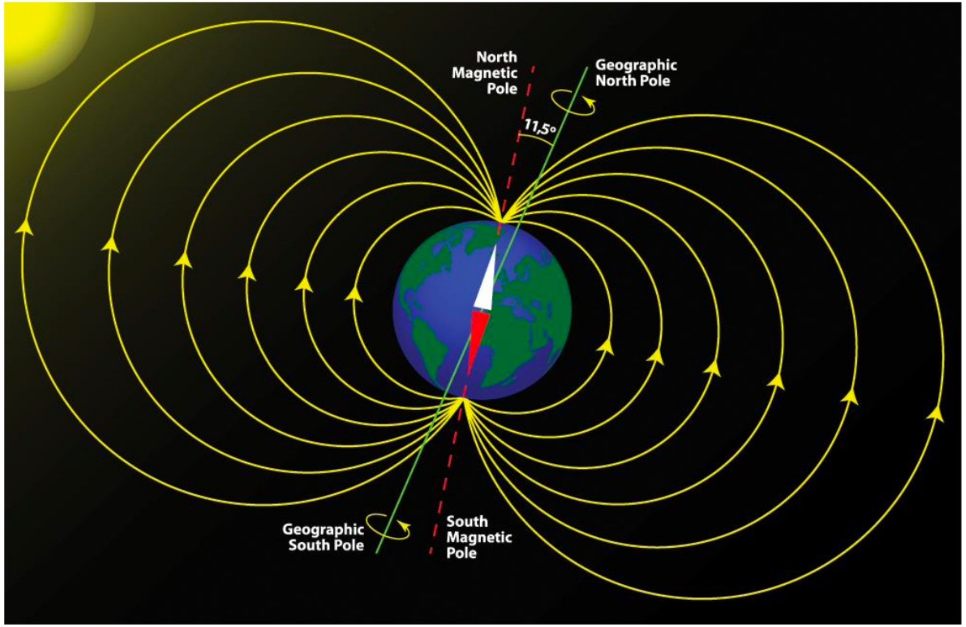


Image credit: Florian Shkurti

Gyroscope

Pros:

- Measure angular velocity in the body frame

Cons:

- Needs noise and bias modeling

$$\omega_{\text{measured}}(t) = \omega_{\text{true}}(t) + b_g(t) + n_g(t)$$

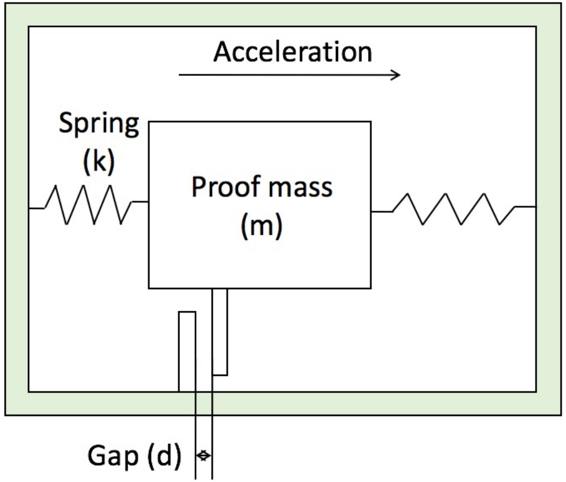
Image credit: Wikipedia

Accelerometer

Pros:

- Modeling linear acceleration
- Integration gives velocity
- Double integration gives poses

Accelerometer reading placing on surface on Earth?



Cons:

- Need to handle bias and noise:

$$a_{\text{measured}}(t) = R({}^{I}_{G}q(t))({}^{G}a - {}^{G}g)(t) + b_a(t) + n_a(t)$$

Image credit: Wikipedia

Inertial Measurement Unit

Combines measurements from accelerometer, gyroscope, and magnetometer to output an estimate of orientation with reduced drift.

Pros:

- Runs at 100-1000Hz
- Low-cost
- Modern MEMS IMUs are small

How MEMS IMU work: https://www.youtube.com/watch?v=eqZgxR6eRjo

Image credit: Sparkfun

Inertial Measurement Unit

Combines measurements from accelerometer, gyroscope, and magnetometer to output an estimate of orientation with reduced drift.

Cons:

- Does not typically provide a position estimate, due to double integration.
- Expect significant yaw drift of 5-10 deg/hour on most modern low-end IMUs

Learning to conduct low-drift IMU integration is an interesting and practical topic

See more on: https://cathias.github.io/TLIO/

Global Positioning System (GPS)

Location of any GPS receiver is determined through a time of flight measurement

- Satellites send orbital location (*ephemeris*) plus time
- Full message length is 12.5min
- The receiver computes its location through **trilateration** and **time correction**)
- Update rate: 1-10Hz

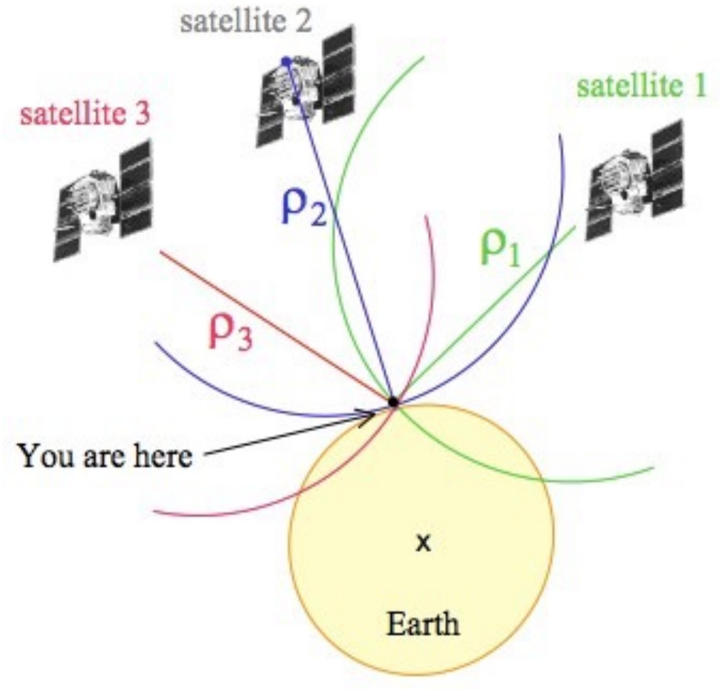


Image credit: nationalgeographic

Global Positioning System (GPS)

Pros:

- Measures absolute position
- Global coverage
- Cheap

Cons:

- Outdoor only
- GPS denied environment (tunnel, urban canyon)
- Meter-level errors

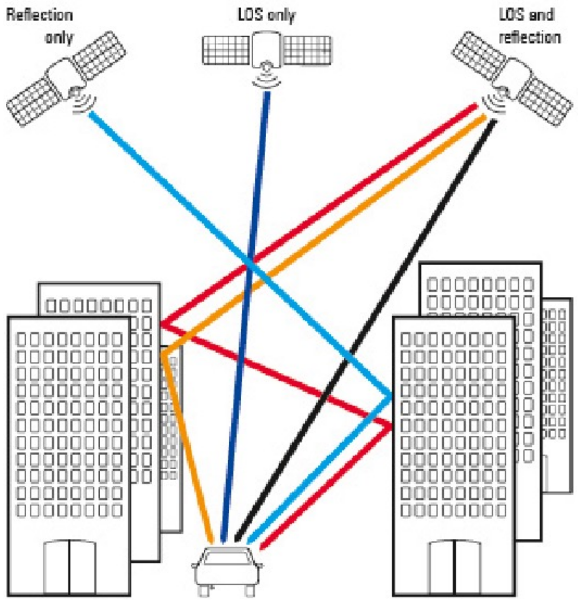


Image credit: Andrei Barsan

Real-time-kinematic (RTK)

Augment GPS with inertial measurements and base stations to achieve centimeter-level accuracy.

Pros:

- Centi-meter level accuracy
- Costly

Cons:

- Still needs GPS
- Requires base station, hard to scale

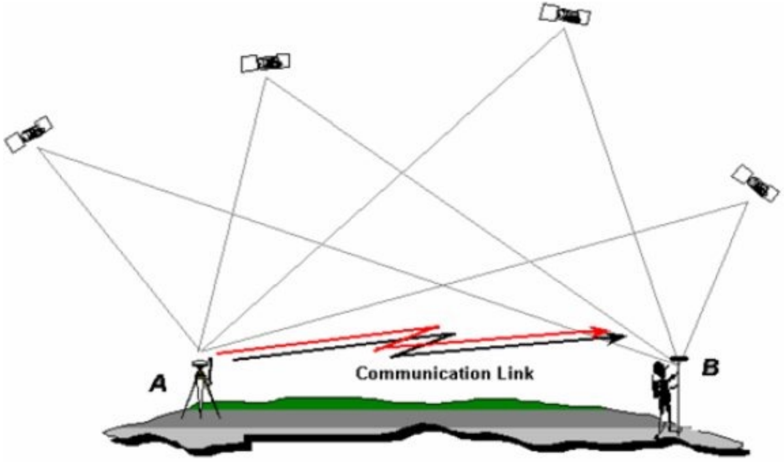


Image credit: Andrei Barsan

Today’s Agenda

- Overview
- Motion Sensors
- **Range Sensors**
- Touch Sensors
- Cameras .. (next slide)

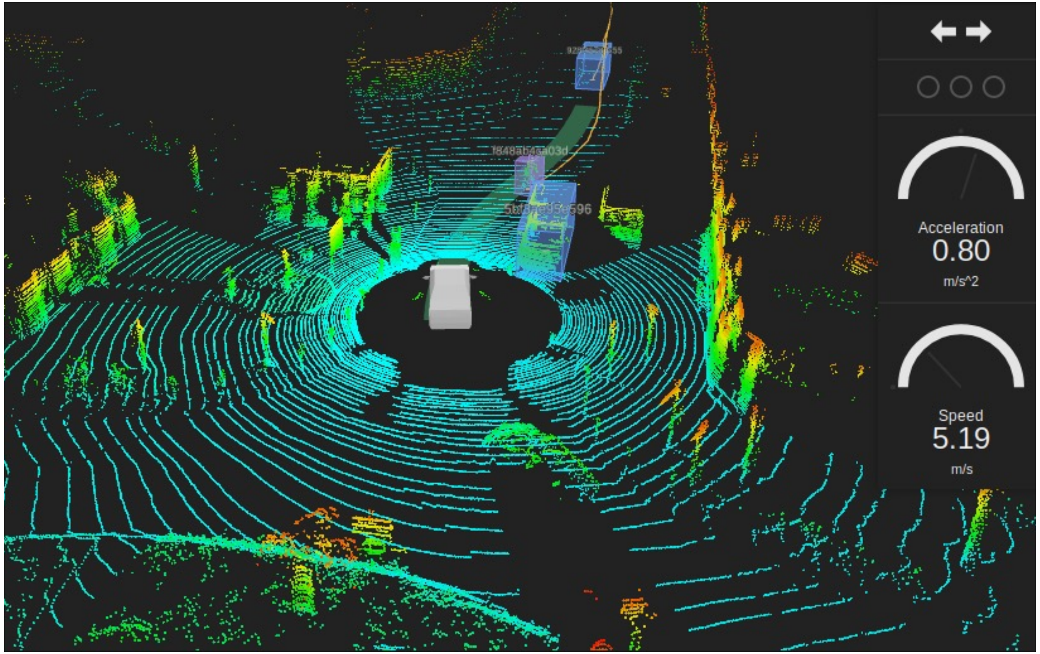
What is LiDAR?

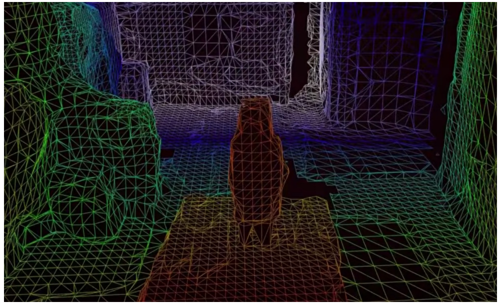
- Light Detection and Ranging

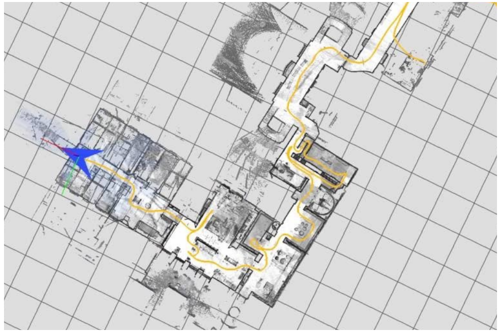
Image credit: Uber, Apple, Xiaomi, DJI

Why Do We Use LiDAR?

- Captures Geometry of the Scene







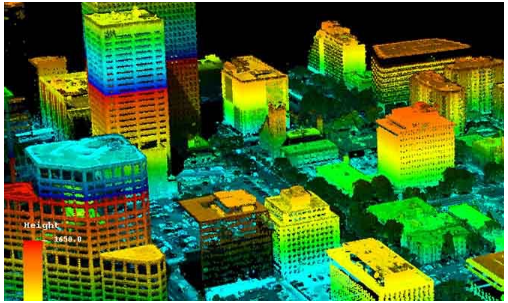
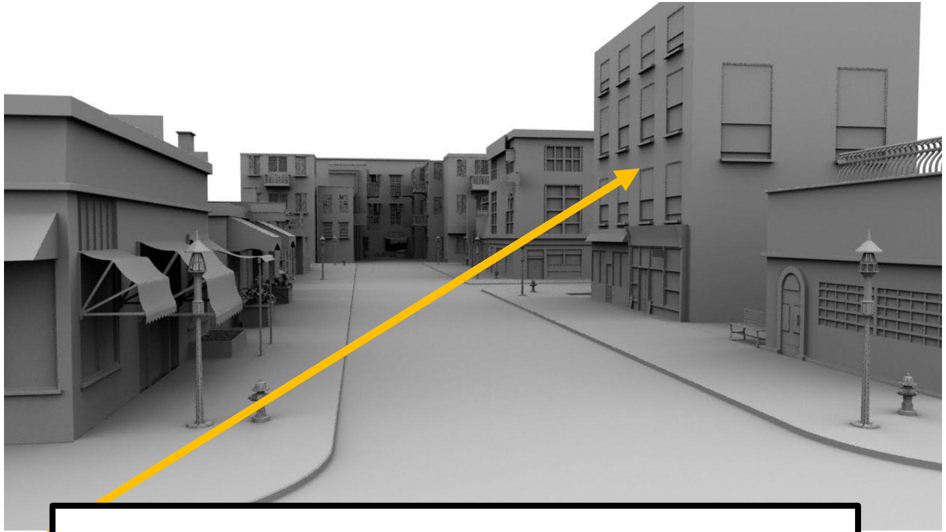
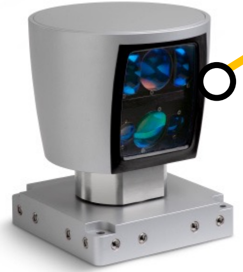


Image credit: KITTI, Apple, Cartographer, NASA

How Does a LiDAR Work?





Range = Time * LightSpeed / 2

Laser Range Finder

- Polar to Euclidean:

$$x = r\cos\varphi$$
$$y = r\sin\varphi$$

Range

Yaw angle

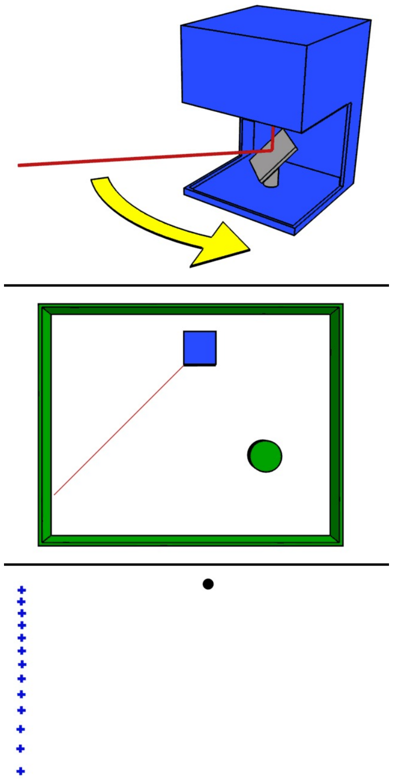


Image credit: Wikipedia

3D Spinning LiDAR

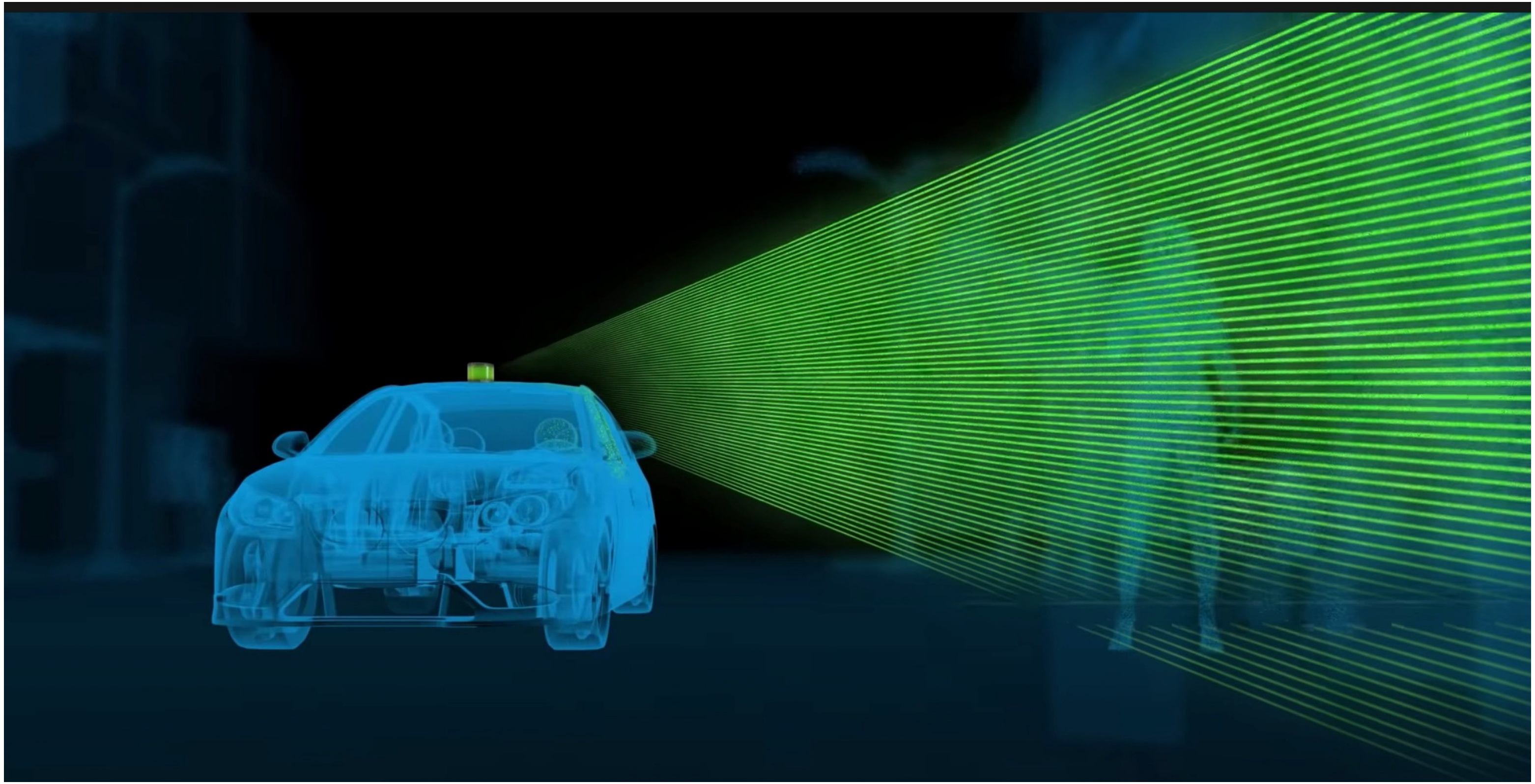
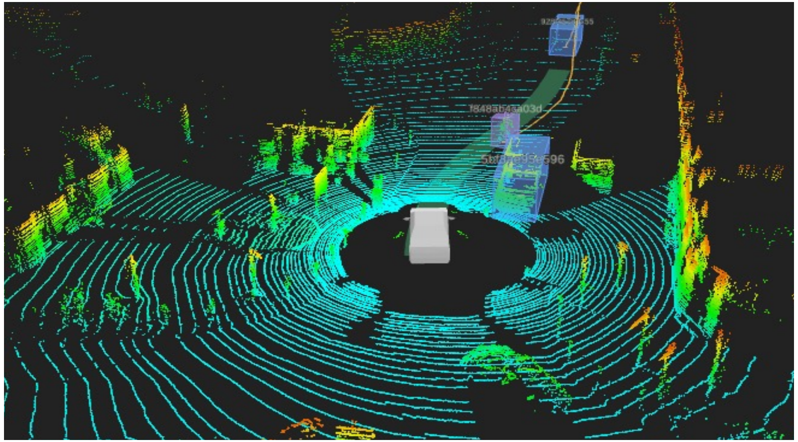


Image credit: Velodyne

Advantages of LIDAR

- Capturing highly accurate geometry

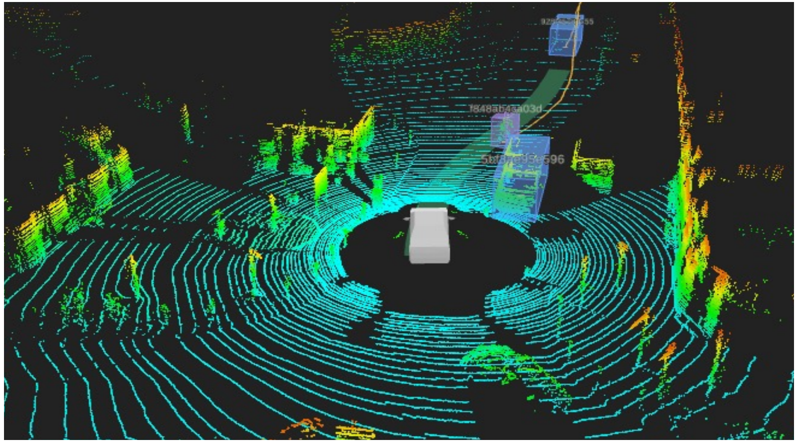


All observations are in 3D metric space

Observations on 2D image plane; Depth Ambiguity

Advantages of LIDAR

- Large horizontal field-of-view

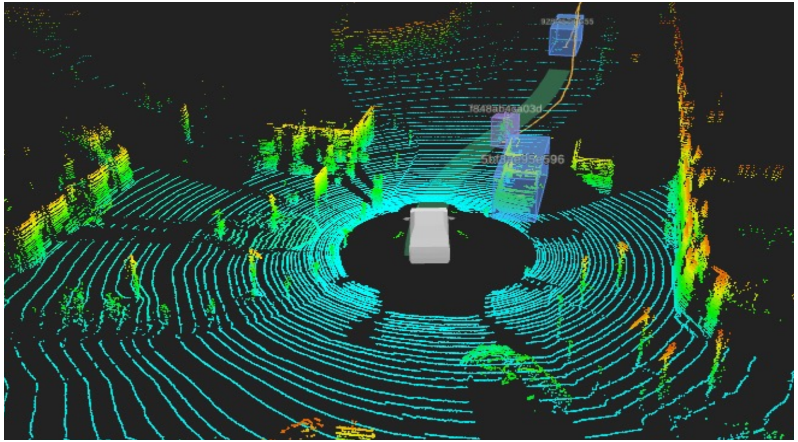


360 deg horizontal FOV

76 deg horizontal FOV

Advantages of LIDAR

- Works perfectly at night



No degradation at night

Performance drop at night due to weak lighting.

LiDAR

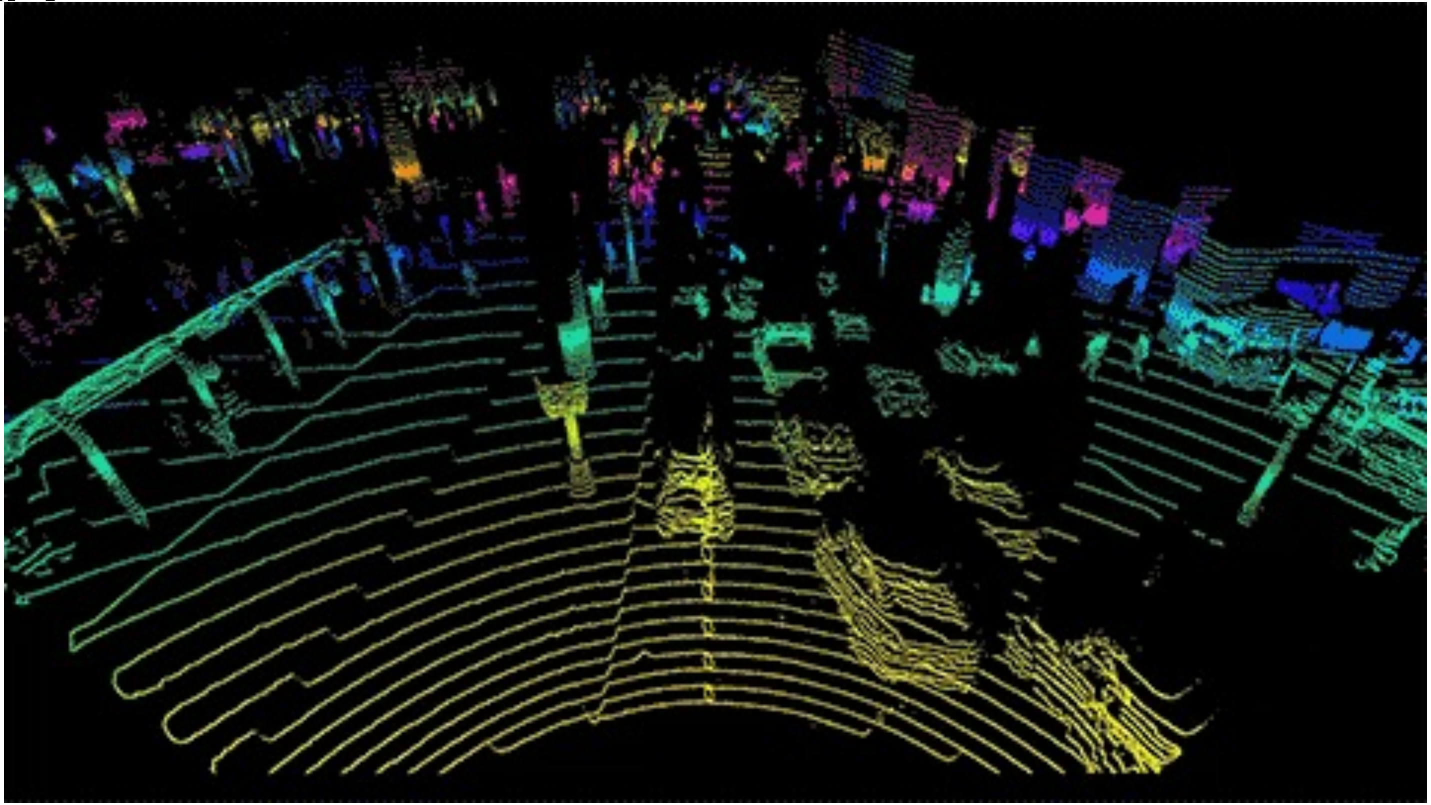


Image credit: Luminar

Disadvantages of LiDAR

- Cannot detect reflective or transparent surfaces (e.g. metal surface and glass).

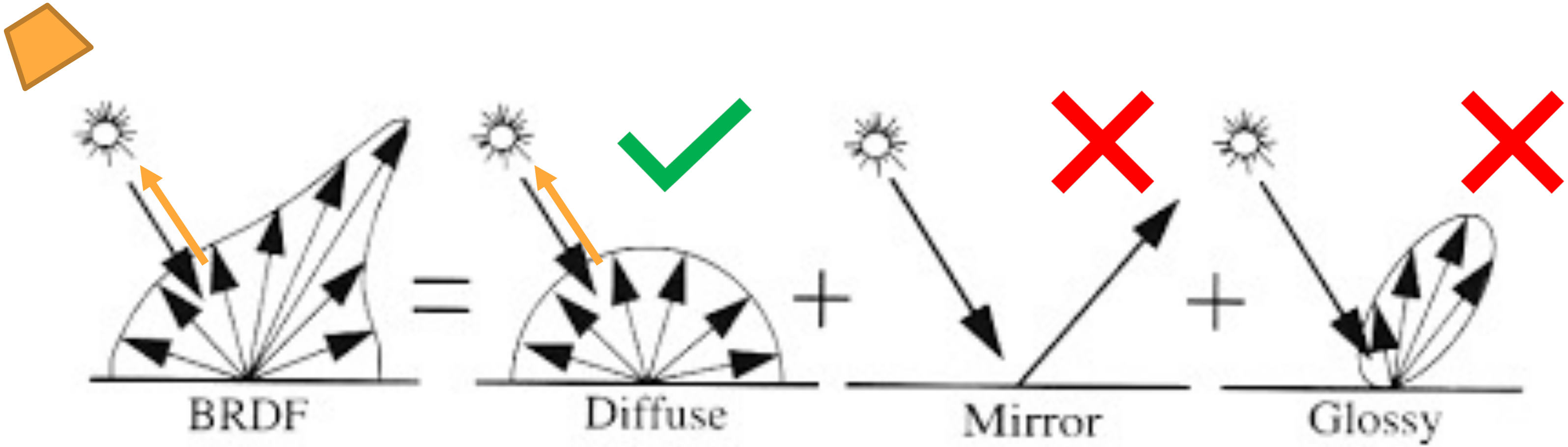


Image credit: Wikipedia

Disadvantages of LiDAR

- Not robust to adverse weather: rain, snow, smoke, fog etc.
- Wavelength ~ 1000nm.

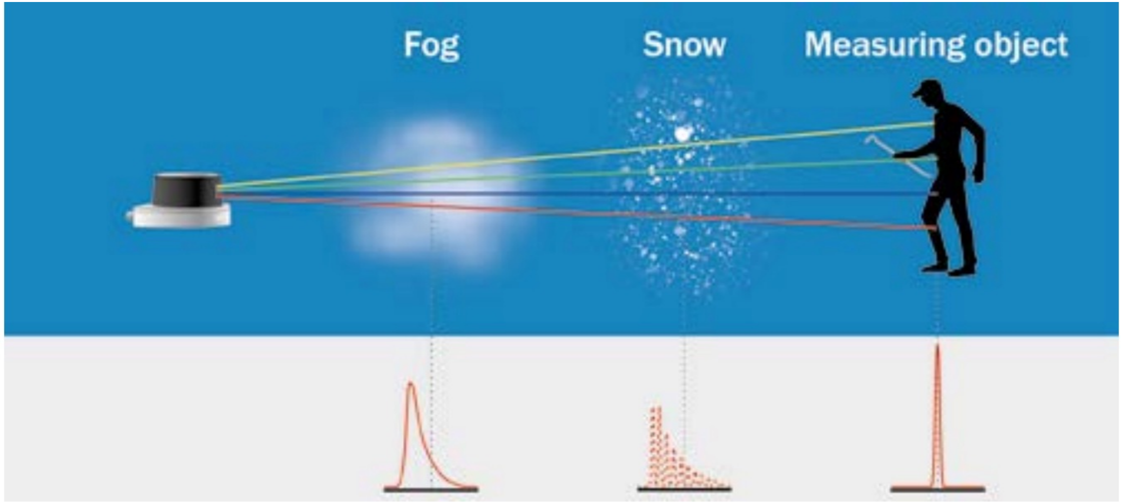


Image credit: Velodyne

Disadvantages of LiDAR

- Need to handle rolling shutter effect.

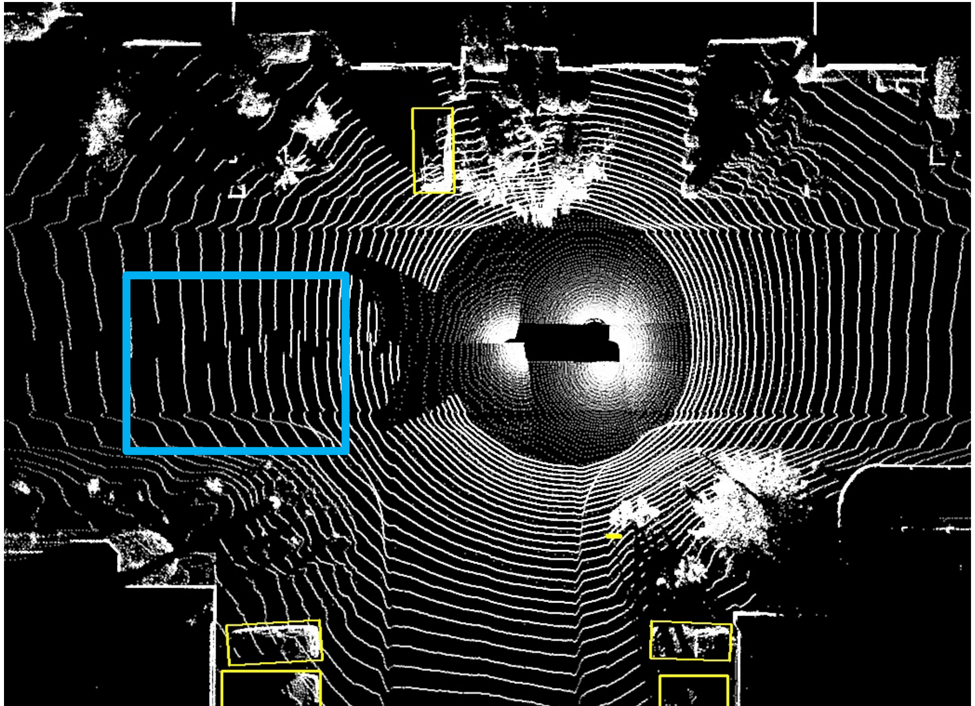


Image credit: Waymo

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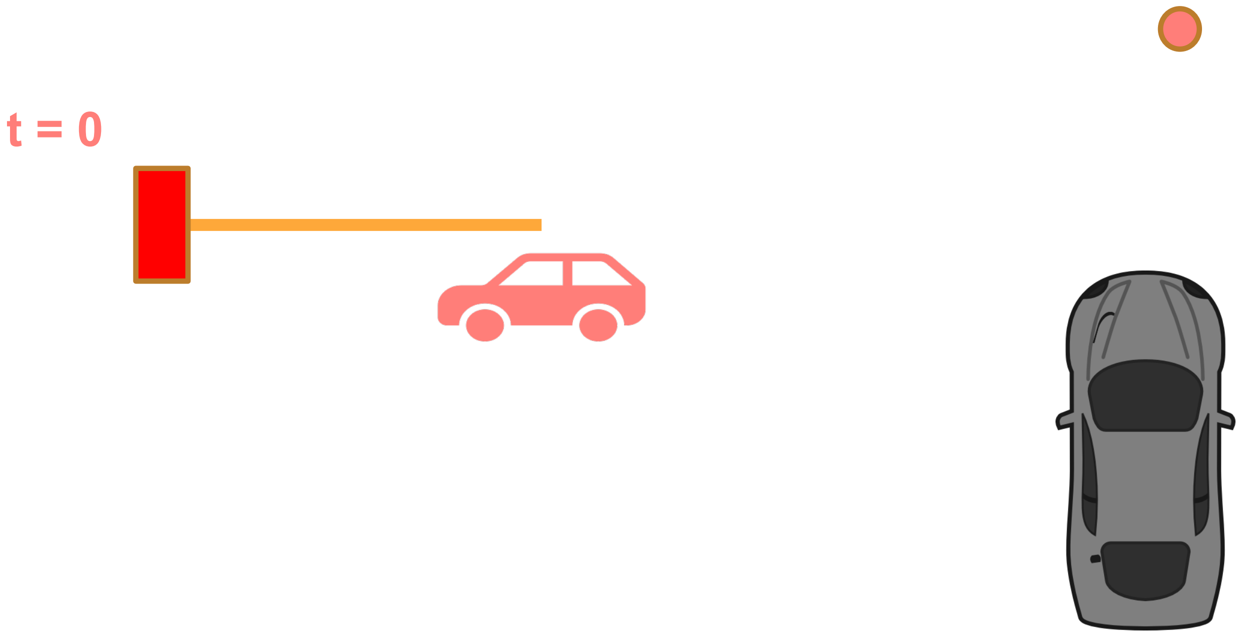

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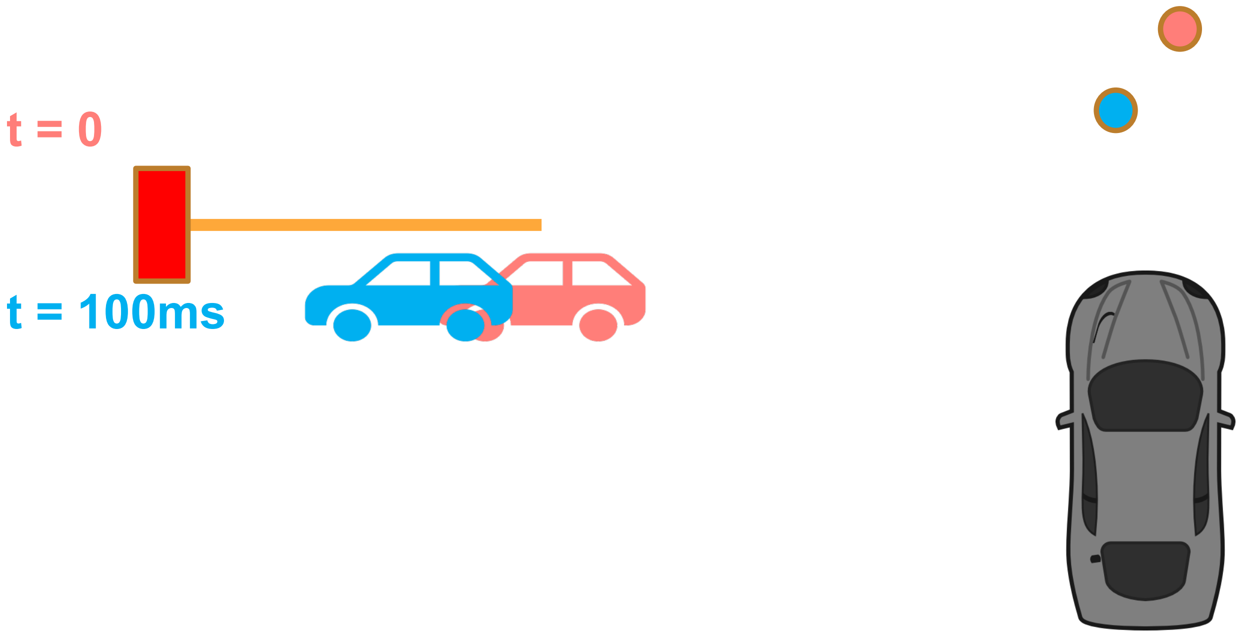


LiDAR

- Transmit a packet of EM waves
- Distance d = propagation speed of light c * the time-of-flight t / 2

Pros:

- Accurate Geometry
- Large FOV
- See in the dark

Cons:

- Reflective surface
- Particles
- Rolling shutter

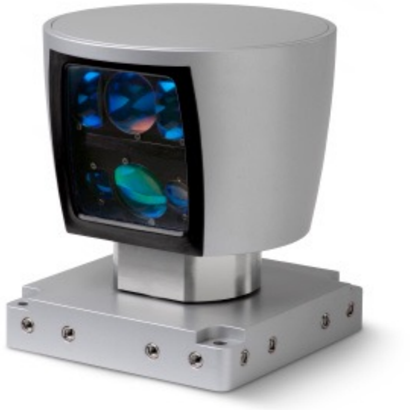


Image credit: Velodyne

Ultrasonic Sensor (Sonar)

- Transmit a packet of (ultrasonic) pressure waves
- Distance d = propagation speed of sound c * the time-of-flight t / 2.

Pros:

- Wavelength is longer (Frequency: 40 - 180 kHz) can pass small object.
- Cheap

Cons:

- Sound absorbing surfaces
- Effective range is smaller
- Resolution

Tactile Sensors

Cutting

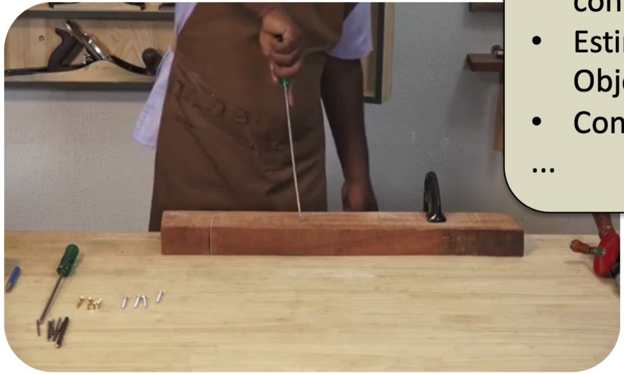
Folding

Human uses tactile sensing:

- Detect contact
- Detect & control contact state
- Estimate & control Object pose
- Control contact force

...

Screwing



Placing / inserting

Image credit: Shuran Song

Tactile Sensors

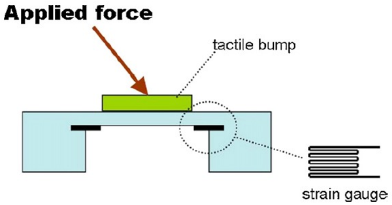
Made of materials whose resistance changes when a force, pressure or mechanical stress is applied

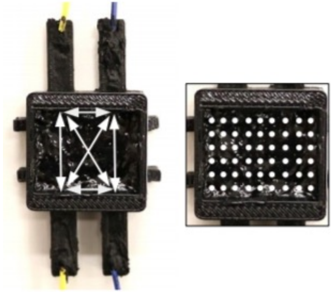
Pros:

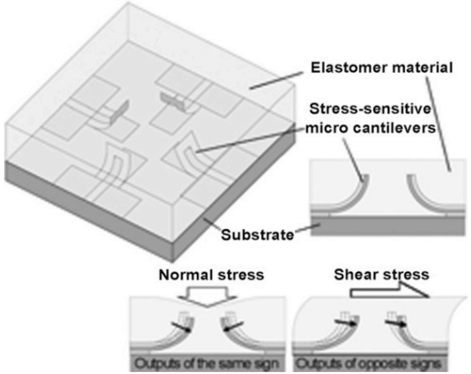
- generally sensitive and economic,
- can be thin and flexible

Cons

- nonlinear response
- low spatial resolution







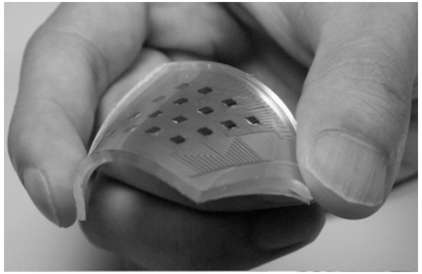
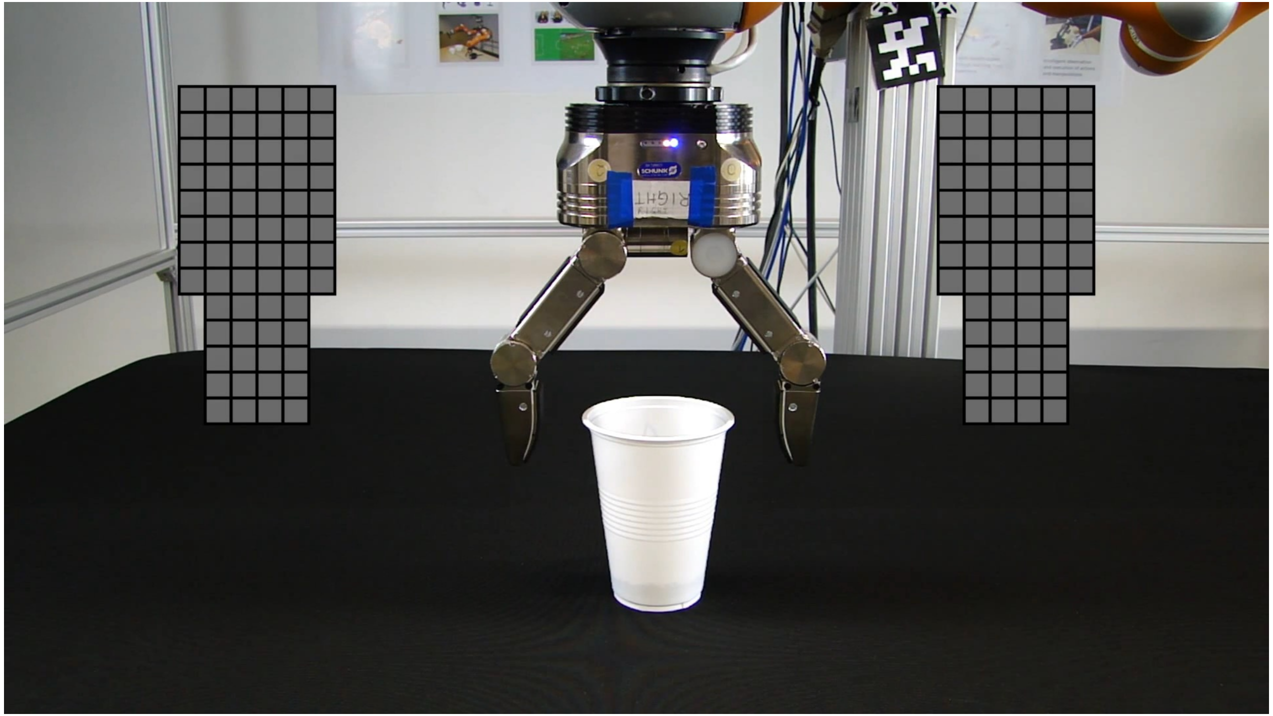


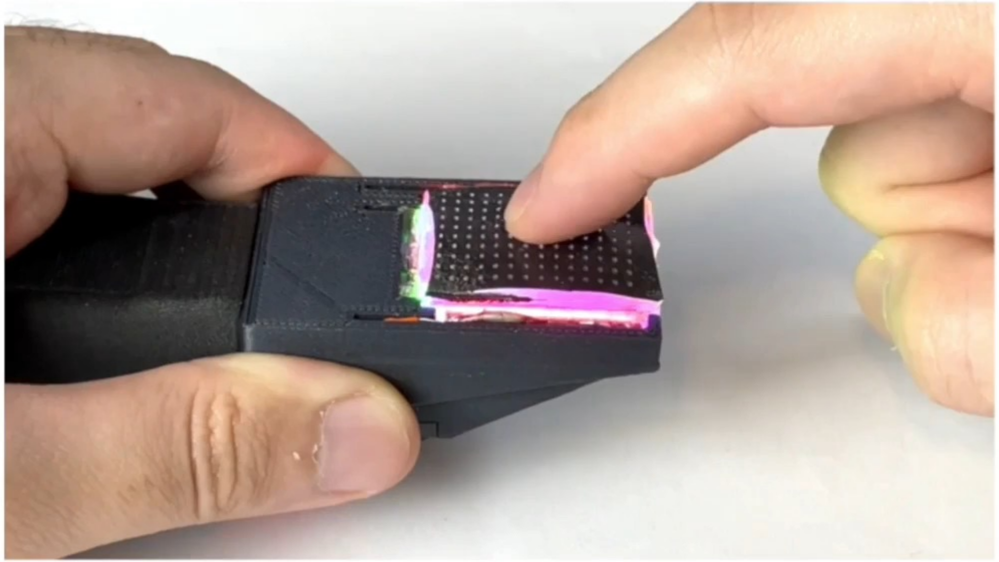
Image credit: Shuran Song

Touching is rich signal



https://www.ati-ia.com/products/ft/ft_models.aspx?id=Nano25

GelSight Tactile Sensor



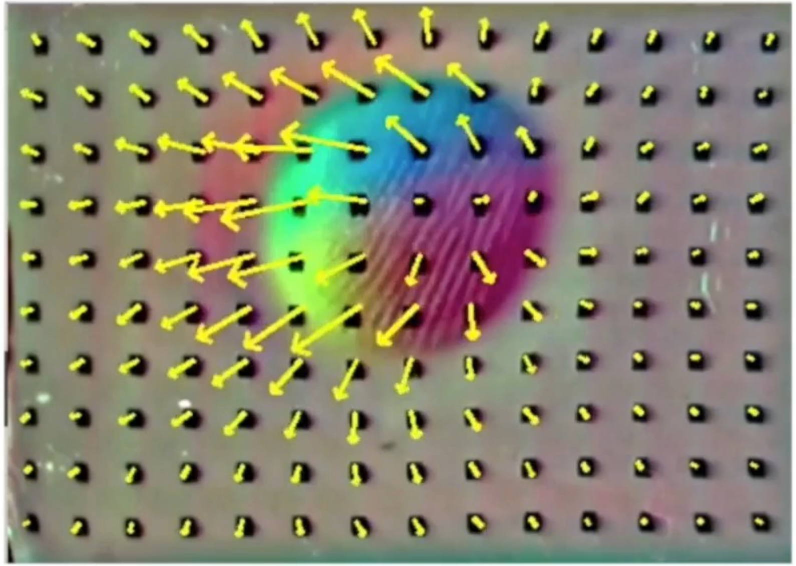


Image credit: Shuran Song

Tactile Perception

- Contact force
- Contact state
- Contact Pose
- Contact Friction
- Center of mass
- Moment of inertia
- ….

Categorization

Proprioceptive sensors *(internal):*

- measure values internally to the system (robot),
- e.g. motor speed, wheel load, heading of the robot, battery status

Exteroceptive sensors *(external):*

- Information from the robots environment
- e.g. distances to objects, intensity of the ambient light

Categorization

Passive sensors:

- Measure energy coming from the environment
- e.g. GPS, camera, Gyroscope

Active sensors:

- Emit their proper energy and measure the reaction.
- Better performance, but some influence on environment
- E.g. LiDAR, structured light

What Do We Care?

- What does the sensor measure?
- What is the source of error?
- How frequent does it measure?
- What information do we actually want to know?

Next Lecture

Cameras!