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):

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

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

\[
\min_{\mathbf{R} \in SO(3)} f(\mathbf{R})
\]
How would you minimize this?

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

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

$$x^{(t+1)} = x^{(t)} - \gamma \nabla_x f(x^{(t)}) \quad \in \mathbb{R}^n$$

$$\nabla_x f(x) = \left[\frac{\partial f}{\partial x_0}, \frac{\partial f}{\partial x_1}, \ldots, \frac{\partial f}{\partial x_n}\right]$$
Gradient Descent?

$$\min_{R \in SO(3)} f(R)$$
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: $R(t)^T R(t) = I$

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

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

\[ \exp(\phi^\wedge) = I + \frac{\sin(\|\phi\|)}{\|\phi\|} \phi^\wedge + \frac{1-\cos(\|\phi\|)}{\|\phi\|^2} (\phi^\wedge)^2 \]

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

\[ \log(R) = \frac{\varphi \cdot (R - R^T)}{2 \sin(\varphi)} \text{ with } \varphi = \cos^{-1} \left( \frac{\text{tr}(R) - 1}{2} \right) \]
When to Use Lie Algebra?

- Integration
- Smoothing
- Interpolation
- Uncertainty
- Control
- Optimization
- ...

\[
\min_{\mathbf{R} \in SO(3)} f(\mathbf{R})
\]

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?

- Integration
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- ...

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When to Use Lie Algebra?

- Integration
- Smoothing
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- Optimization
- ...

\[ \log(R) \rightarrow \phi + \delta\phi \rightarrow \exp(\phi + \delta\phi) \]
SE(3) Lie Group and se(3) Lie Algebra

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

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

- se(3) Lie algebra:

\[ \xi^\wedge = \begin{bmatrix} \omega \times \nu \\ 0^T \ 0 \end{bmatrix} \in \mathfrak{se}(3) \subset \mathbb{R}^{4 \times 4} \]
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
https://github.com/utiasSTARS/liegroups PyTorch + Numpy
Sensors I

Shenlong Wang
UIUC

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

Gyroscope, Accelerometers, Magnetometers

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

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

\[ \omega_{\text{measured}}(t) = \omega_{\text{true}}(t) + b_g(t) + n_g(t) \]
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:

\[ a_{\text{measured}}(t) = R(I_G q(t))(G a - G g)(t) + b_a(t) + n_a(t) \]
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](https://www.youtube.com/watch?v=eqZgxR6eRjo)
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
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
Why Do We Use LiDAR?

- Captures Geometry of the Scene
How Does a LiDAR Work?

Range = Time * LightSpeed / 2
Laser Range Finder

- Polar to Euclidean:

\[
x = r \cos \varphi \\
y = r \sin \varphi
\]
3D Spinning LiDAR
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).

Disadvantages of LiDAR

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

Image credit: Velodyne
Disadvantages of LiDAR

- Need to handle rolling shutter effect.
Disadvantages of LiDAR

- Need to handle rolling shutter effect.
Disadvantages of LiDAR

- Need to handle rolling shutter effect.
LiDAR

- Transmit a packet of EM waves
- Distance $d = \text{propagation speed of light} \cdot c \cdot \frac{t}{2}$

Pros:
- Accurate Geometry
- Large FOV
- See in the dark

Cons:
- Reflective surface
- Particles
- Rolling shutter
Ultrasonic Sensor (Sonar)

- Transmit a packet of (ultrasonic) pressure waves
- Distance $d = \text{propagation speed of sound } c \times \text{the time-of-flight } t / 2.$

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

Cons:
- Sound absorbing surfaces
- Effective range is smaller
- Resolution
Tactile Sensors

Human uses tactile sensing:

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

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!