Sensing 2
Localization and Mapping

Some slides adapted from Mark Donovan @ ROBO Business, with thanks
Many slides adapted from slides © R. Siegwart, ETH Zürich – Autonomous Systems Laboratory

Last Time

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- Sensor Traits
  - Proprioceptive or exteroceptive
  - Passive or active
  - Absolute or incremental/relative
  - Range
  - Resolution
  - Linearity
  - Bandwidth
  - Sensitivity
  - Cross-sensitivity
- Senses, pt. I
  - Pose
    - Body pose
    - Orientation
  - Location
- Types of Sensors, pt. I
  - Optical joint encoders

Upcoming

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Today

- More encoders
  - Magnetic joint encoders
  - More about optical encoders
- Frames of reference
- Heading sensors
- Location sensors
- Physics of motion
- Movement sensors

Next Class

- Sensor fusion
- Vision
- Distance sensors

Followed By

- Probability
- Sensor error

Some Valid Questions

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- Why do we need to know what sensors there are?
- ➢ To use, understand, and build robots that can adapt and function flexibly in the world.
- Why do we need to know how they work?
- ➢ Largely, to understand what's going on when they don't work.

Odometry and Localization

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- The localization problem: where is the robot?
  - Odometry: figuring it out without environment cues
- Why not just look around?
  - Requires knowledge of the map
  - Often we are discovering it as we go, so that's uninformative
- The mapping problem: building (or using) a map of the environment
- Heading + approximate velocity = position estimate
  - (Eventually we'll get to SLAM: Simultaneous Localization And Mapping)

Pose: Encoders

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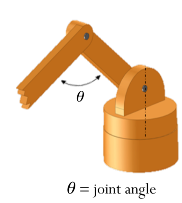
- What does an encoder do?
  - In general, "encodes" motion to an electrical signal
- Almost always encodes rotation.
- In robotics:
  - Joint angles (how "open" is a joint?)
  - Wheel rotations
  - Motor rotations
- Can be absolute or relative
- Can be magnetic, optical, or other



θ = joint angle

http://nptel.ac.in/courses/112103174/module7/lec5/3.html

Magnetic Encoders

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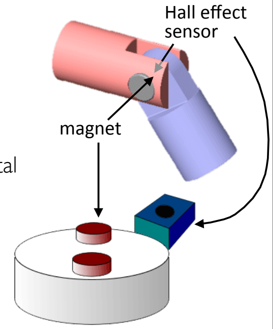
- Cheap, precise, lightweight
- Magnet + Hall effect sensor
  - "Hall effect": moving wire past a magnet induces electric field
- Can be absolute or incremental
- Equivalent to stripes (the marker) and camera (the sensor) in optical encoders



en.wikipedia.org/wiki/Hall_effect_sensor, www.mathworks.com/help/physmod/sm/mech/ref/revolute.html

Optical Encoders

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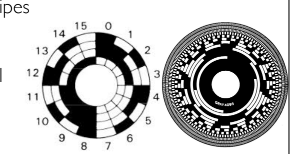
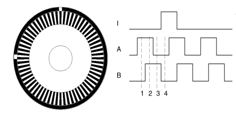
- Use a light source + light sensor
  - Plus disk with gaps or dark stripes
- Absolute encoders
  - Every station has unique signal
  - Requires better sensors
- Quadrature encoders
  - Two off-phase sensors
  - Rotation direction





State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

http://transducersensors.com/absolute-encoders, Danaher Industrial Controls—Dynapar

Heading Sensors

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- Heading: direction robot is facing
  - With respect to some frame of reference
- Estimate of robot's orientation (x,y) + inclination (z)
- Proprioceptive heading sensors
  - Gyroscope, inclinometer
- Exteroceptive heading sensors
  - Compass, sundial

Frames of Reference

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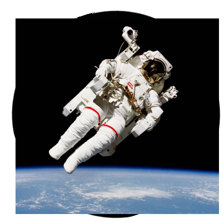
- A FoR is a coordinate system, plus anchor points
- So what does that mean?
  - Imagine someone floating in an infinite, featureless space.
  - Which way is she facing?
  - Is she moving?
- What about now?
  - The Earth gives us a frame of reference
- The frame is the space in which she is oriented



https://www.nasa.gov/mission_pages/shuttle/multimedia/mmu_eva.html

More Formally

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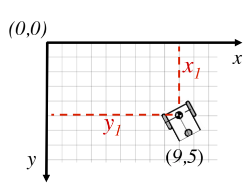
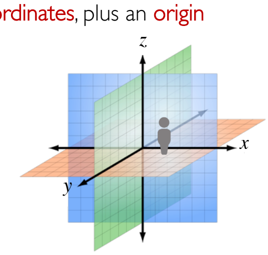
- A frame of reference is a coordinate system plus one or more points that locate and orient it
- x, y, and sometimes z coordinates, plus an origin





en.wikipedia.org/wiki/Frame_of_reference, study.com/academy/lesson/coordinate-system-in-geometry-definition-types.html

Comparing Frames of Reference

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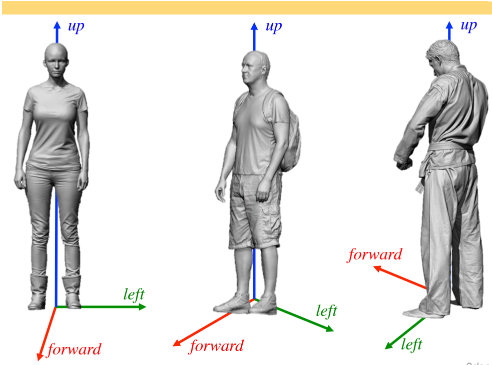

3dscanstore.com

Heading: Compasses

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Han dynasty "South pointer"

- Used since at least 2000 B.C.
  - Absolute measure for orientation
- Many ways to measure Earth's magnetic field
  - Mechanical magnetic compass
  - Direct measure of magnetic field (Hall effect sensor, magnetoresistive sensors)
  - Hang piece of magnetite from thread
- Major drawbacks:
  - Weakness of the field
  - Easily disturbed by magnetic objects or other sources
    - Not typically feasible for indoor environments

Heading: Gyroscope

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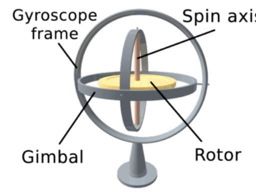
- Heading sensors that keep *orientation* wrt. a fixed frame
  - Absolute measure of heading of a mobile system
- Mechanical or optical



Mechanical Gyros

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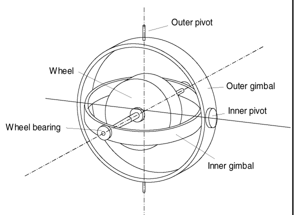
- Concept: inertial properties of a fast spinning rotor
  - "Gyroscopic precession"
  - Angular momentum of spinning wheel keeps axis of gyroscope stable
- Quality: 0.1° in 6 hours (!)
- If spinning axis is aligned north-south, earth's rotation doesn't affect horizontal axis
- If it points east-west, horizontal axis reads the earth rotation



Optical Gyroscopes

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- First commercial use: 1980's on airplanes
- Optical gyroscopes
  - Angular speed (heading) sensors using two laser beams from same source
- One is traveling in a fiber clockwise, the other counterclockwise around a cylinder
- Laser beam traveling in direction of rotation
  - Slightly shorter path → shows a higher frequency
  - Difference in frequency Δf of the two beams is proportional to the angular velocity Ω of the cylinder
- There are solid-state variants!

Need precise measurement of time!

Location: Beacons

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- Guiding devices with precisely known position
- Used since humans started to travel
- Natural beacons (landmarks): stars, sun, mountains, "that one weird tree"
- Artificial beacons: lighthouses

Sextant
(AKA: "Why sailors are depicted with eyepatches")

Ground-Based Beacons

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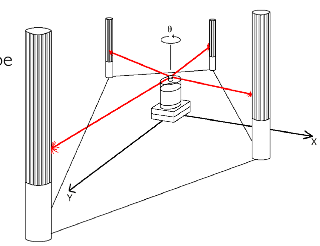
- Active or passive?
  - Beacon has reflective tape and robot has a camera?
  - Infrared beacons?
- Major drawback: Requires instrumenting environment!
  - Limits flexibility and adaptability to novel or dynamic environments
  - Costly and sometimes infeasible



Global Positioning System

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- 24 satellites (including three spares)
  - Orbit earth every 12 hours at a height of 20.190 km
  - Four in each of six planes inclined 55° wrt. earth's equator
  - Location of any GPS receiver is determined through a time of flight measurement
- Technical challenges:
  - Time synchronization between individual satellites and GPS receiver
  - Real time update of the exact location of the satellites
  - Precise measurement of the time of flight
  - Interferences with other signals

GPS

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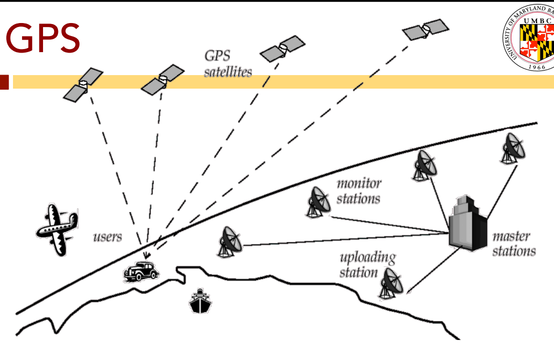

- Commercial GPS → accurate position down to ~2 meters
  - < 15 meters used to be encrypted, military-only signal

GPS

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- Time synchronization:
  - Atomic clocks on each satellite
  - Monitored from different ground stations
- Real time update of exact location of satellites:
  - Master station analyses all measurements, transmits actual position to each satellite
- Ultra-precise time synch extremely important
  - Electromagnetic radiation propagates at light speed
    - Roughly 0.3 m per nanosecond
  - Accuracy proportional to precision of time measurement

Physics of Localization

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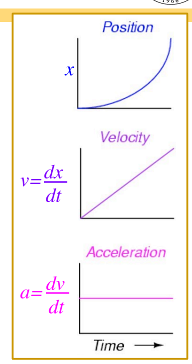
- Derivative of **position** x with respect to time is **velocity**, v
- Second derivative is **acceleration**, a
  - Third is **jerk**, j, as in "jerking to a stop"
    - After that it gets silly
- So, given time + acceleration or velocity, we integrate to get position

$$x = \int v(t)dt = \iint a(t)dt$$



https://www.youtube.com/watch?v=PDhLLURJSPs

Physics of Localization

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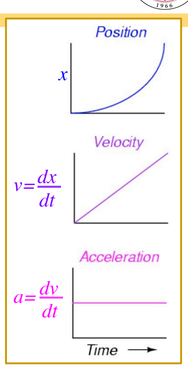
- Derivative of **position** x with respect to time is **velocity**, v
- Se
- So, given time + acceleration or velocity, we integrate to get position

You *do* need to understand this conceptually.
You *don't* need to do integrals or derivations on exams.

$$x = \int v(t)dt = \iint a(t)dt$$



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Accelerometers

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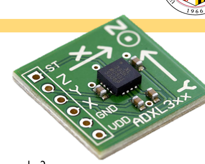

- Measure acceleration forces
  - Could just track encoder information …if you have wheels!
  - So how does your phone know whether it's in landscape or portrait mode?
- Piezoelectric accelerometer
  - Microscopic crystal structures are stressed by acceleration
  - This creates a voltage that can be measured
- Capacitive accelerometer
  - Crystal stress can also create a measurable change in capacitance

IMUs

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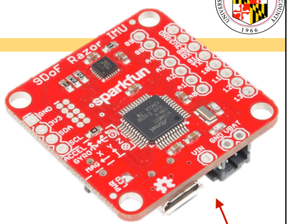

- Inertial Measurement Units: report **motion**
  - Linear motion (direction, velocity/acceleration)
  - Angular motion (rotational direction/speed)
- Simple implementation: three gyroscopes plus three accelerometers
  - Gives you all of x, y, and z
- Even easier implementation: buy from Sparkfun

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Followed By

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- Sensor error

Exercise

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- You are building a mail delivery robot for the CSEE department
  - One floor, cubbyhole mailboxes
  - All doors are open
- Assume a manipulator arm
- No limits on battery/etc
- 2-4 people
  - Write down each others' names!
- Sketch out a design!
- The structure of the robot
  - How does it move?
    - Wheels? Legs? How big? How many?
  - What's attached where?
  - Size, speed, ..?
- All sensors
  - Include encoders etc.
  - Where are they on the robot?
  - (You will need at least 5, probably more like 15+)