COMP417
Introduction to Robotics and Intelligent Systems

Sensors and Actuators
Today: Sensors and Actuators

• Our last introductory/background material lecture before we start talking about algorithms – the main topic of the course.

• Sensors:
  • Characteristics and types
  • Measurement noise
  • Required bandwidth

• Actuators:
  • Types of motors
  • Pulse-Width Modulation
Types of sensors

• General classification:
  • contact vs. non-contact
  • active vs. passive
  • sampling rate: fast vs. slow
  • local vs. non-local

• General examples:
  • vision
  • laser
  • radar
  • sonar
  • compass, gyroscope, accelerometer
  • touch (tactile)
  • infrared
Active v. Passive

- Sensors can be broadly classified as either active (energy emitting) or passive (using energy that's "already out there").
- Active is more "costly", but usually entails a simpler inverse problem and entails fewer assumptions about the environment.
  - **active**
    - radiating some form of energy into the environment
    - e.g.
      - radar (radio direction and ranging)
      - sonar (sound navigation and ranging)
      - lidar (light direction and ranging)
  - **passive**
    - relying on energy emitted by various objects in environment
Sensors

- Devices that can sense and measure physical properties of the environment.

- Key phenomenon is **transduction** (conversion of energy from one form to another). E.g.:
  - Imaging sensors: light to pixel voltages
  - Depth sensors: mechanical pressure to voltage

- Measurements are **noisy**, and difficult to interpret
Sensors: general characteristics

• Sensitivity: (change of output) ÷ (change of input)
• Linearity: constancy of (output ÷ input)
• Measurement range: [min, max] or {min, max}
• Response time: time required for input change to cause output change
• Accuracy: difference between measurement and actual
• Repeatability/Drift: difference between repeated measures
• Resolution: smallest observable increment
• Bandwidth: required rate of data transfer
• SNR: signal-to-noise ratio
Sensors: vision

TODAY: In the case of high volume consumer area and line scan imagers, based on almost imaginable, CMOS imagers outperform CCDs.

**CCD (charge-coupled device) imaging sensors:**
- Capacitor array accumulates electric charge proportional to light intensity.
- Each capacitor’s charge is transferred to its neighbor.
- Last capacitor’s charge gets amplified and output as voltage.
- (+) High-quality, low-noise images
- (-) Higher power consumption
- (-) Slow readout
- (-) Specialized fabrication

**CMOS (complementary metal-oxide semi-conductor) imaging sensors:**
- One amplifier per pixel
- (+) Low power
- (+) Fast readout
- (+) Easier to fabricate
- (-) Poor low-light sensitivity
- (-) Higher noise
Assignment 1: new due date Oct 17 10am
Why pendulums?

• Humans are a bit like an inverted pendulum!
Passive walk schematic
Passive "Walking" Idea

Cornell University
Human Power Lab
Passive Walking

- 4 ideas to try to lift kneed 2D passive-dynamic walking to 3 dimensions.
  - Wide feet that guide the motion (1912 Bechstein patent).
  - Soft heels that kill the instability from indeterminacy at the collision of a line of contact.
  - Counter-swing the arms to reduce angular momentum effects about the vertical axis (1888 Fallis patent).
  - Swing the arms side to side at appropriate times to reduce side-to-side rocking.
Bi-Pedal: Zero Moment Point
ZMP walk

HRP-2 robot
AIST, Shuuji KAJITA
+ Four universities in Japan + LAAS France
Honda

Sony
Open problems

• Dynamical smooth walking
• Energy efficiency
• Robustness
Dynamically Stable Gaits

• Robot is not always statically stable
• Must consider energy in limbs and body
• Much more complex to analyze
• E.G. Running:
  – Energy exchange:
    • Potential (ballistic)
    • Mechanical (compliance of springs/muscle)
    • Kinetic (impact)
• Humans use ankle, hip & foot control.
• Foot placement strategies in bipedal locomotion often based on linear inverted pendulum model (LIPM) – Kajita, Tani, and Kobayashi, IROS 1990.
• Body can be represented as a point mass on a massless rod. 2D motion: foot moves along horizontal axis.
Basic pendulum

- 2D ideal pendulum
- \( F = ma \), tangential component:

\[
F = -mg \sin \theta
\]

Angular acceleration & tangential motion:

\[
\frac{d^2 \theta}{dt^2} + \frac{g}{\ell} \sin \theta = 0
\]

Small angle approximation:

\[
\frac{d^2 \theta}{dt^2} + \frac{g}{\ell} \theta = 0.
\]
Inverted pendulum

- The inverted pendulum uses the same equation, but with a minus sign in front of $g$ relative to the above.
- Move base to maintain balance.
- Same idea to balance walking!
Zero momentum point walk

- Force over foot modeled by reaction force at single point (ZMP): center of pressure.
- Point can be found by analysis or measurement.
- 1. Leg motion precomputed
- 2. Upper body motion chosen to keep ZMP within foot

Fig. 1. Zero-moment point (ZMP).
Vukobratovic and Stepanenco, 1972
Wagon (Kingpin) steering

- "Wagon steering": like the old covered wagons of yore.
- Two front wheels on common axle.
- Simple, but inefficient.
  - Small bumps effect steering angle
Ackerman Steering

• Car-like steering
  – "Double pivot"

• Original design: each wheel turns by same amount.
  – Different centers of curvature: leads to slip
    • Energy inefficient, hard to control (physically)
  – Jeantaud modification: slightly different steering angles.

• Front wheels turn by different amounts
• Back wheels do not turn
• ICC
\[ \cot \theta_i - \cot \theta_o = \frac{d}{l} \]

where:

- \( \theta_i \) = relative steering angle of inner wheel
- \( \theta_o \) = relative steering angle of outer wheel
- \( l \) = longitudinal wheel separation
- \( d \) = lateral wheel separation.
Geometric constraints

\[ \cot \theta_{SA} = \frac{d}{2l} + \cot \theta_i \quad \text{or alternatively:} \quad \cot \theta_{SA} = \cot \theta_o - \frac{d}{2l}. \]
Ackerman (Used in Cars)
Legged Locomotion

• Started to resolve a bet between Governor of California *Leland Stanford* and a friend, in 1872.

• Muybridge took the challenge

Eadweard Muybridge
(April 9, 1830 – May 8, 1904)
Legged Locomotion
Legged Locomotion
Hildebrand Gait Diagrams

Trot

Front Left
Front Right
Back Left
Back Right

Ballistic Phase

Trot
Hildebrand Gait Diagrams
Stability Analysis

• Stability (in the sense of balance). Under what condition can we assure an object (vehicle, animal) will not fall over?

• Two classes of analysis (and behavior).
  – Static stability
  – Dynamic stability.
Support Polygon
Support Polygon
Support Polygon
Support Polygon
Support Polygon
Support Polygon
Support Polygon

And so on...
Hexapod RHex
Aqua: Tripod Gait
RHex legs: varied terrains
Sensors: what for?

• To measure stuff, of course, but why?

• In robotics, big motivators:
  • How far to the next obstacle (defining $C_{\text{free}}$)
  • What's (specifically) is out there?
  • Where am I? (e.g. GPS)
Sensors: general characteristics

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A gyroscope is a spinning wheel with most of its mass concentrated in the outer periphery
- e.g. a bicycle wheel

Due to the law of *conservation of momentum*
- the spinning wheel will stay in its original orientation
- a force is required to rotate the gyroscope

A gyro. can thus be used to maintain orientation or to measure the rate and direction of rotation

In fact there are different types of mechanical gyro.
- and even optical gyro’s with no moving parts!
  - these can be used in e.g. space probes to maintain orientation
Gyrosopes

- Measure angular velocity in the body frame
- Often affected by noise and bias

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

- We integrate it to get 3D orientation (Euler angles, quaternions rotation matrices), but there is drift due to noise and bias
Cameras: Global vs. Rolling Shutter

Shutter = mechanism that allows light to hit the imaging sensor

Shutter “speed” = Exposure time = time duration in which the sensor is exposed to light
Reading RGB images from a camera

Each pixel contains an intensity value from 0...255
Reading images from a camera

Each pixel contains an intensity value from 0…255

A matrix of $600 \times 1000 \times 3 = \approx 1.8$ million numbers

600 x 1000 pixels

600 x 1000 pixels

600 x 1000 pixels
Computer/robot vision

1. I’m seeing a parrot
2. I’m seeing a toy bicycle
3. The parrot is riding the bicycle
4. The bicycle is on top of a desk
5. Is this physically plausible?
6. Where is the parrot in 3D w.r.t. the camera?
7. Where will the parrot go next?
8. What is the speed of the parrot?

Conclusions/Inference/Deduction/Estimation
1. I’m seeing a parrot
2. I’m seeing a toy bicycle
3. The parrot is riding the bicycle
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Conclusions/Inference/Deduction/Estimation
Camera lenses

• Lens determines:
  • image distortion
  • focus
  • sharpness or blur

• Lens characteristics:
  • focal length
  • aperture
  • depth-of-field
Pinhole Camera Model

We know approximately how a 3D point \((X,Y,Z)\) projects to pixel \((x,y)\)
We call this the **pinhole projection model**
Pinhole Camera: Image inversion

We push the image plane forward along the positive z-axis
Pinhole Camera: From 3D points to pixels

1. \([x, y] = \pi(X, Y, Z)\)  
   perspective projection
2. \([x^*, y^*] = D(x, y)\)  
   lens distortion
3. \([u, v, 1] = K[x^*, y^*, 1]'\)  
   pixel coordinates
(1) Perspective projection

\[ [x, y] = \pi(X, Y, Z) \]

By similar triangles: \( x/f = X/Z \)

So, \( x = f \times X/Z \) and similarly \( y = f \times Y/Z \)

Problem: we just lost depth (Z)
information by doing this projection, i.e.
depth is now unknown.

Going from 3D -> image: forward problem
Going from image -> 3D: inverse problem
(2) Lens distortion

\[[x^*, y^*] = D(x, y)\]
(2) Estimating parameters of lens distortion:
\[ [x^*, y^*] = D(x,y) \]

Illustrative example: you don't need to remember the details.

\[ x^* = x \frac{1 + k_1r^2 + k_2r^4 + k_3r^6}{1 + k_4r^2 + k_5r^4 + k_6r^6} \]

where \( r = x^2 + y^2 \)
Non-pinhole cameras: thin lens model

Unlike the pinhole camera, this is able to model blur.

http://www.cim.mcgill.ca/%7Elanger/558.html
Beyond the visible spectrum: infrared cameras
Beyond the visible spectrum: infrared cameras

Drawback:
Doesn’t work underwater
Beyond the visible spectrum: infrared cameras
Beyond the visible spectrum: RGBD cameras

Main ideas:
- Active sensing
- Projector emits infrared light in the scene
- Infrared sensor reads the infrared light
- Deformation of the expected pattern allows computation of the depth
Beyond the visible spectrum: RGBD cameras

Drawbacks:
- Does not work outdoors, sunlight saturates its measurements
- Maximum range is [0.5, 8] meters

Advantages:
- Real-time depth estimation at 30Hz
- Cheap
Beyond the visible spectrum: RGBD cameras

Enabled a wave of research, applications, and video games, based on real-time skeleton tracking
Beyond the visible spectrum: RGBD cameras

Despite their drawbacks RGBD sensors have been extensively used in robotics.
2D LIDAR (Light detection and ranging)

Produces a scan of 2D points and intensities
• (x,y) in the laser’s frame of reference
• Intensity is related to the material of the object that reflects the light

Certain surfaces are problematic for LIDAR: e.g. glass
2D LIDAR (Light detection and ranging)

- Produces a scan of 2D points and intensities
  - \((x,y)\) in the laser’s frame of reference
  - Intensity is related to the material of the object that reflects the light

Certain surfaces are problematic for LIDAR: e.g. glass

Lots of moving parts: motors quickly rotate the laser beam and once complete (angle bound reached) a scan is returned. I.e. points are not strictly speaking time-synchronized, even though we usually treat them as such.

Usually around 1024 points in a single scan.
3D LIDAR (Light detection and ranging)

Produces a pointcloud of 3D points and intensities
- $(x,y,z)$ in the laser’s frame of reference
- Intensity is related to the material of the object that reflects the light

Works based on time-of-flight for each beam to return back to the scanner

Not very robust to adverse weather conditions: rain, snow, smoke, fog etc.

Used in most self-driving cars today for obstacle detection. Range < 100m.

Usually around 1 million points in a single pointcloud
Did you come late?

Assignment 1: new due date Oct 17 10am
Radar usually uses electromagnetic energy in the 1 - 12.5 GHz frequency range
  - this corresponds to wavelengths of 30 cm - 2 cm
    - microwave energy
    - unaffected by fog, rain, dust, haze and smoke
It may use a pulsed time-of-flight methodology of sonar and lidar, but may also use other methods
  - continuous-wave phase detection
  - continuous-wave frequency modulation
Continuous-wave systems make use of Doppler effect to measure relative velocity of the target
Inertial Sensors

- Gyroscopes, Accelerometers, Magnetometers
- Inertial Measurement Unit (IMU)

- Perhaps the most important sensor for 3D navigation, along with the GPS

- Without IMUs, plane autopilots would be much harder, if not impossible, to build
Magnetometers

Drawbacks:
• Needs careful calibration
• Needs to be placed away from moving metal parts, motors

Advantages:
• Can be used as a compass for absolute heading
Gyroscopes

- Measure angular velocity in the body frame
- Often affected by noise and bias

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

- We integrate it to get 3D orientation (Euler angles, quaternions rotation matrices), but there is drift due to noise and bias
Accelerometers

- Measure linear acceleration relative to freefall (measured in g)
- A free-falling accelerometer in a vacuum would measure zero g
- An accelerometer resting on the surface of the earth would measure 1g
- Also affected by bias and noise. Usually modelled as:

\[ a_{\text{measured}}(t) = R(I_G q(t))(G a - G g)(t) + b_a(t) + n_a(t) \]

Where \( g \) is the gravity vector, \( I \) is the IMU body frame and \( G \) is the fixed world frame

- Double integration to get position is very noisy. Errors grow quadratically with time.
Inertial Measurement Unit

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

- Does not typically provide a position estimate, due to double integration.

- Runs at 100-1000Hz

- Expect yaw drift of 5-10 deg/hour on most modern low-end IMUs
IMU's

- Gyro, accelerometer combination.
- Typical designs (e.g. 3DM-GX1™) use triaxial gyros to track dynamic orientation and triaxial DC accelerometers along with the triaxial magnetometers to track static orientation.
- The embedded microprocessors contains a programmable filter algorithms, which blends these static and dynamic responses in real-time.
Global Positioning System: Satellites

- Each GPS satellite periodically transmits:
  - **[Coarse/Acquisition code]** A 1023-bit pseudorandom binary sequence (PRN code), which repeats every 1 ms, unique for each satellite (no correlation with other satellites).
  - **[Navigation frame]** A 1500-bit packet that contains
    - GPS date, time, satellite health
    - Detailed orbital data for the satellite, accurate for the next ~4hrs
    - PRN codes and status of all satellites in the network
    - Takes 12.5mins to transmit
  - **[Precision code]** A 6.2-terabit code for military use.

- Carrier frequencies are 1575.42 MHz (L1) and 1227.60 MHz (L2)
Global Positioning System: Receivers

- Each (civilian) GPS receiver:
  - Knows the PRN codes for each satellite in advance
  - Correlates received PRN signal with database PRN signal $\rightarrow$ time shift $\rightarrow$ noisy distance to satellite
  - If 4 or more satellite PRN codes are received, it does **trilateration** to compute latitude and longitude
Global Positioning System: Receivers and Dilution of Precision
Hall Effect Sensor

• Varies its voltage in response to a magnetic field

• Used as a proximity switch, to measure a full rotation of a wheel for example

• Used to measure rate of rotation of wheels
Sensors

• **Proprioceptive Sensors**
  (monitor state of robot)
  – IMU (accels & gyros)
  – Wheel encoders

• **Exteroceptive Sensors**
  (monitor environment)
  – Cameras (single, stereo, omni, FLIR ...)
  – Laser scanner
  – MW radar
  – Sonar
  – Tactile...
Rotary Encoder

- Contains an analog to digital converter for encoding the angle of a shaft/motor/axle

- Usually outputs the discretized absolute angle of the shaft/motor/axle

- Useful in order to know where different shafts are relative to each other.
Example: flippers on the Aqua robot
**Actuators**

**DC (direct current) motor**
They turn continuously at high RPM (revolutions per minute) when voltage is applied. Used in quadrotors and planes, model cars etc.

**Servo motor**
Usually includes: DC motor, gears, control circuit, position feedback Precise control without free rotation (e.g. robot arms, boat rudders)
Limited turning range: 180 degrees

**Stepper motor**
Positioning feedback and no positioning errors. Rotates by a predefined step angle. Requires external control circuit. Precise control without free rotation. Constant holding torque without powering the motor (good for robot arms or weight-carrying systems).
Pulse Width Modulation

- 50% duty cycle
- 75% duty cycle
- 25% duty cycle

Used for creating analog/continuous behavior when voltage applied is discrete. Main idea: turn on and off the motor fast enough so average voltage is the desired target. Used in dimming LEDs, controlling the speed of DC motors, controlling the position of servo motors.