Mobility 2
DoFs, Wheels, and Wings

Many slides adapted from slides © R. Siegwart, ETH Zürich – Autonomous Systems Laboratory
Bookkeeping

- By now
  - Have read SNS ch. 2, SNS 4.1
  - Have met with your group outside class
  - Group is ready to go over ideas with me

- By next time
  - Finish 4.1 if you haven’t!
  - Sign up for meeting:

- Announcements
  - Assignment 1 out next week
  - Quiz 1 next Tuesday
For Next Time...

- Finish SNS 4.1 if you haven’t
- Schedule meeting with Dr M
- Prep for quiz
  - Overview
  - Concepts
  - Mobility
- Class or readings are fair game
  - Slides should be a good (but not complete) resource
  - This one: trying to get to ideas, not nits
Today’s Class

- More mobility terminology
- A bit more about wheels
- Wings/propellers
- Other mobile actuators
  - Walking wheels, passive flight, swimming, …
- Sensing round 1 🙄
Degrees of Freedom

- Formally this time.

- DoFs: the number of independent parameters that define the state of a physical system.
  - Fine, but it underdefines “state”

- DoFs in robotics can be (and formally are) all of:
  - The number of independently controlled actuators.
  - Possible changes of orientation of some set of parts:
    - Now includes “the whole robot”.
    - Max: pitch, yaw and roll.
  - Possible directions a robot can move in:
    - Max: translation in x, y, z.
Pitch, Yaw, Roll

Pitch, Yaw, Roll

https://www.youtube.com/watch?v=rlVw-SNU8cM
Odometry (Dead Reckoning)

- Use proprioceptive sensors to estimate location
  - Motion sensors to estimate change in position over time
  - Sensitive to errors due to:
    - Sensor inaccuracies
    - Integration of velocity measurements over time
    - Equipment calibration
  - Motion sensors or known commands
Wheels

- Most appropriate solution for most applications
- Three wheels guarantee stability
- With more than three wheels an appropriate suspension is required
  - Why?
- Selection of wheels depends on the application

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Mountings and Axles

Mounting axis
Axle

Direction of rotation
Direction of translation
4 Basic Wheel Types

- **Standard wheel**
  - Two degrees of freedom
  - Rotation around the (motorized) wheel axle and the contact point

- **Castor wheel**
  - Three degrees of freedom
  - Rotation around the wheel axle, the contact point and the castor axle

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Basic Wheel Types: Omni

- Swedish (Mecanum, Ilon, Omni) wheel
  - Three degrees of freedom
  - Rotation around the (motorized) wheel axle, (sometimes motorized) rollers, contact point

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Basic Wheel Types

- Alternating left and right-handed rollers
  - Wheel applies force at right angles to the wheelbase diagonal
  - Can move in any direction by varying speed, direction of rotation of each wheel

- Types of motion
  - All four wheels in same direction: forward or backward
  - Wheels on one side opposite to other side: rotation
  - Wheels on one diagonal opposite direction to wheels on other diagonal: sideways movement

https://en.wikipedia.org/wiki/Mecanum_wheel
Basic Wheel Types

https://www.youtube.com/watch?v=8sH1a511_q4
Basic Wheel Types

- Ball or spherical wheel
  - Suspension not solved

https://en.wikipedia.org/wiki/Ballbot
Characterization: Stability

◆ Stability of a vehicle is guaranteed with 3 wheels
  ◆ If center of gravity is within the triangle which formed by the ground contact point of the wheels

◆ Stability is improved by 4+ wheels
  ◆ However, arrangements require a flexible suspension
  ◆ Why?

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Characterization: Geometry

- Bigger wheels overcome higher obstacles
  - But require higher torque or reductions in the gear box

- Most wheel arrangements require high control effort
  - Non-holonomic – we’ll get into that in Ch. 3

- Combining actuation and steering on a single wheel
  - Makes the design complex
  - Adds errors for odometry
    - Data from motion sensors used to estimate position
    - “Dead reckoning”
Maneuvering and Control

- Two more axes of characterization

- Maneuverability
  - How many different maneuvers a robot can do
    - “An act or instance of changing direction”
    - “To change the position of by a maneuver”
    - “To steer in various directions as required”
  - Most maneuverable?

- Controllability
  - How easy it is to get the robot to do what you intend
    - Mechanically: e.g., slippage
    - Programmatically: e.g., 4 independently controlled wheels moving in unison

- Maneuverability and controllability ≈ inverse correlation
Slip/Skid

Q: How do you turn a tank?
- Treads are “wheels” with large surface contact
- Violate the “point contact” assumption
- What’s the difficulty?

A: Rotate treads opposite directions
- How can this work?

What are the tradeoffs?
- Friction on flat surfaces
- High torque requirements
- Tread wear / Terrain damage
- Odometry
Arrangements

- Of 2 wheels
- Of 3 wheels

Omnidirectional Drive
Synchro Drive

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Arrangements

- Of 4 wheels

- Of 6 wheels

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Synchro Drive

- All wheels are actuated synchronously by one motor
  - Defines the speed of the vehicle

- All wheels steered synchronously by a second motor
  - Sets the heading of the vehicle

- Orientation in space of robot frame will always remain the same

- So, not possible to control orientation of robot frame

Adapted from © R. Siegwart, ETH Zürich – ASL
Caterpillar

The NANOKHOD II, European Space Agency (ESA)

May eventually go to Mars

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Walking Wheels

- Active or passive
- Roll and lift/release
- Roll and rollover

Halluc II, Chiba Inst. Of Tech.
Passive: the Shrimp

- Passive locomotion on rough terrain
- 6 wheels
  - One fixed wheel in the rear
  - Two bogies on each side
  - Front wheel, spring suspension
- ≈ 60 cm long, 20 cm tall
- Highly stable in rough terrain
- Climbs obstacles up to 2x wheel diameter

Adapted from © R. Siegwart, ETH Zürich – ASL
Shrimp “Walking”
Active
Use Case

- What could walking wheels be really good for?

www.youtube.com/watch?v=O7otewMk9pc
Advantages
- Rough terrain
- Ground-inaccessible areas
- Z-axis maneuverability
- Perspective for mapping & sensing
- Flying is cool

Disadvantages
- Control problems
- Z-axis controllability
- Weight & scaling laws
- Flying is dangerous
Types of Flyers

- Fixed wing (sometimes with flaps)
- Flapping wing
- Rotors/props
  - Axial (single)
  - Coaxial (reversed)
  - Tandem (two non-coaxial)
  - Quadcopters (+)
- Lighter-than-air

https://robotics.eecs.berkeley.edu/~ronf/Ornithopter/index.html
Disadvantages

- Fixed wing (sometimes with flaps)
  - Aerodynamics change drastically when miniaturized
  - Forward-only flight

- Flapping wing
  - Complex movements not perfectly understood
  - Scaling laws, wingspan, flapping speed
  - Hovering possible (but not guaranteed)

- Lighter-than-air
  - Slow, subject to wind and air conditions, temperature sensitive

- Rotors/props
  - Dangerous and/or fragile if contacted
Quadcopters

- Most popular by far

- Advantages
  - Hovering
  - VTOL
  - Maneuverability
  - Simple construction
    - No tilt-rotors

- Disadvantages
  - Stabilization & control
    - But, largely automated now
  - Fragility (rotors)
Scaling
Scaling

- **Cube-square law**
  - Relationship between volume and area as function of size
    - Example: cubes
    - Area = $6a^2$
    - Volume = $a^3$
  - The bigger you go, the more “inside” there is

- **Implications**
  - For miniaturization
  - For power
  - For heat dissipation
  - For structural strength

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Wings and Scaling

What we care about: **lift**
- Upward-acting force on an aircraft wing or airfoil
- Directly opposes gravity’s pull on mass (holds robot up)
  - As well as various friction forces

Interrelating factors producing lift
- Wing area: directly related
- Flap speed: indirectly correlated

Scaling
- Wingspan/speed scale logarithmically with mass
Other Choices
Mobile Efficiency

- **Cost of transportation** – how much energy to move?
- Depends heavily on terrain and task
  - On flat terrain: tires
  - On uneven or soft terrain: legs
  - Hovering in still air: blimps
  - For fast flight: wings
  - For material efficiency: fixed wings
  - In water: swimming or propulsion
  - Other (lots)

- Where is efficiency lost?

- Leg lift and carry
- Deceleration
- Contact friction
- Internal friction
- Damping

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