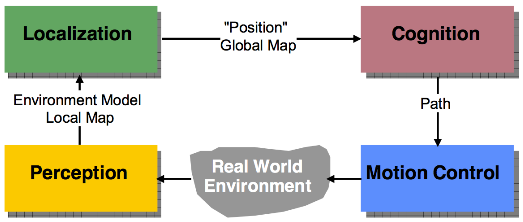
Mobility

Legs and Wheels



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1

Today's Class

- Useful terminology
  - Degrees of Freedom
  - Compliance and back-drive
  - Actuator saturation
  - Slip
- Mechanics: 3 most common mobility actuators
  - Legs, wheels (we leave wings for future)
- If we have time:
  - Other mobile actuators
  - Wings, walking wheels, passive flight, swimming, …

 2

2

Locomotion in Nature

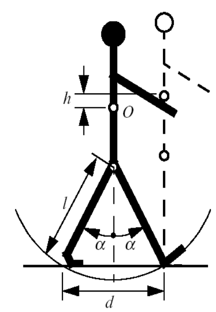
Type of motion	Resistance to motion	Basic kinematics of motion
Flow in a Channel	Hydrodynamic forces	Eddies
Crawl	Friction forces	Longitudinal vibration
Sliding	Friction forces	Transverse vibration
Running	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum
Jumping	Loss of kinetic energy	Oscillatory movement of a multi-link pendulum
Walking	Gravitational forces	Rolling of a polygon (see figure 2.2)

 3

3

Locomotion in Nature

- Concepts found in nature
  - Difficult to imitate technically
  - Why?
- Most technical systems use wheels or caterpillars
  - Rolling is most efficient, but not found in nature
  - Nature never invented the wheel!
- However, a walking biped is close to rolling



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4

Walking or Rolling?

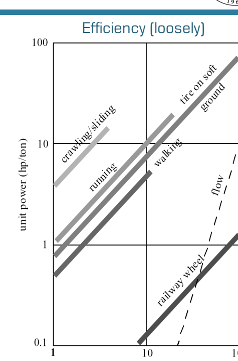
	Walking	Rolling
Number of Actuators	More	Fewer
Structural Complexity	Higher	Lower
Control Expense	Higher (*walking = complicated*)	Lower (*wheels = simple*)
Energy Efficiency (depends on terrain)	Worse (*depends*)	Better (*depends*)
Movement of masses (walking adds up-down)	More movement	Less movement

 5

5

Walking or Rolling? (II)

1. Number of actuators
2. Structural complexity
3. Control expense
4. Energy efficient
   - Terrain (flat ground, soft ground, climbing, rubble, stairs…)
5. Movement of physical masses
   - Walking / running includes up and down movement
   - Some extra losses



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6

Passive Dynamic Walking

- Gravity-powered walking with bipedal gait

We saw this last time – now we're looking at similarity to rolling

 https://www.youtube.com/watch?v=CK8IFEGmikY 7

7

Characterizing Locomotion

- Locomotion is:
  - Physical interaction between robot and environment
  - Concerned with ***interaction forces*** and the ***mechanisms and actuators*** that generate them
- The most important issues in locomotion are:
  - ***Stability***
    - Center of gravity
    - Static/dynamic stabilization
    - Inclination of terrain
  - ***Type of environment***
    - Water, air, soft or hard ground
  - ***Characteristics of contact***
    - Contact point(s)
    - Contact area
    - Angle of Contact
    - Friction

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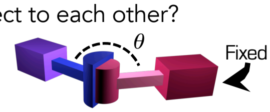
8

Degrees of Freedom

- DoFs: Number of independent parameters that define the **state** (not location) of a physical system
- How many numbers define how parts can move with respect to each other?



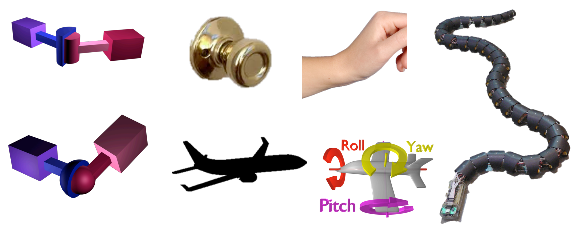
- This arm can be straight, or bent some amount
- To know its state, you need to know **1** thing: θ

 en.wikipedia.org/wiki/Degrees_of_freedom_%28mechanics%29 9

9

Degrees of Freedom

- DoFs
  - Number of independent parameters that define the **state** (not location!) of a physical system.



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10

Compliance / Back-drive

- Motion of a DoF in response to external force
  - High compliance: moves a lot when stressed (pushed)
  - Low compliance: stiff when stressed
- Active compliance: software recognizes motion
- Passive compliance: mechanical structure
- Back-driveable means that you can physically move it (without breaking it) – passive compliance
  - If you grab my arm and bend it, the elbow joint moves
    - When I'm asleep, anyway…
  - Mostly a product of motor and gear type

 11

11

Saturation

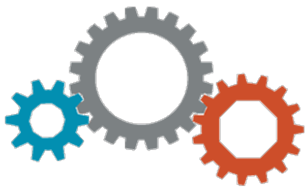
- Actuator saturation: physical performance limit
  - Saturation is (generally) a nonlinear response
  - Example: The more power you push into a motor, the less extra motion you get per unit
  - Eventually you get none – it's ***saturated***
- Example: electric motor
  - Driving circuit has amp limit
  - Result: torque or speed limit
  - When limit is exceeded, parts start to burn out
  - It's a hard, nonlinear limit

 12

12

Slip

- Slip: some interface fails to catch
  - Gears, wheels, belts…
  - Examples: tires on snow; overdriven motor
- More power in ≠ more movement out



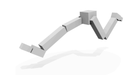
 13

13

Legged Motion

- Fewer legs → more complicated mechanically
  - Static stability
    - With point contact – at least three legs for static stability
    - With surface contact – at least one leg required
- During walking some legs are lifted
  - Usually half
  - Losing stability?

- For static walking 4+ legs are required
  - Animals usually move two legs at a time
  - Humans require more than a year to learn to do this!



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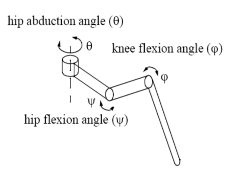
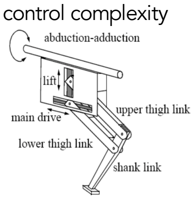
14

Leg Joints (DoFs)

- 2+ DoFs to move a leg forward: **lift** and **swing**
- Three DoFs for each leg in most cases
  - 4th DOF for the ankle joint
  - Might improve walking and stability
  - More joints increase design / control complexity





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15

Gait Options

- Gait: the number of distinct event sequences
  - **Distinct sequence of lift and release events of individual legs**
  - Depends on number of legs
- Number of possible events N with k legs: $N = (2k - 1)!$
- For a biped (k=2), number of possible events N: $N = (2k-1)! = 3! = 3 \cdot 2 \cdot 1 = 6$
- For a robot with 6 legs (hexapod): $N = 11! = 39{,}916{,}800$

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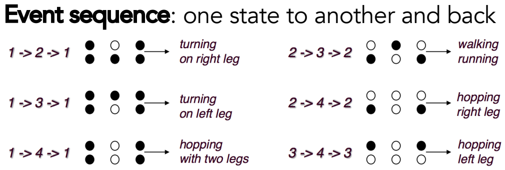
16

Gait Options

- Two legs (biped) can have four different states:
  - Both legs down
  - Right leg down, left leg up
  - Right leg up, left leg down
  - Both legs up

● *Leg down*
○ *Leg up*

- **Event sequence**: one state to another and back



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17

Static vs. Dynamic Walking

- Statically stable

  - Bodyweight supported by at least three legs
  - Even if all joints freeze, the robot will not fall
  - Safe ➔ slow and inefficient

- Dynamic walking

  - Robot will fall if not continuously moving
  - Fewer than three legs in ground contact
  - Fast, efficient ➔ harder actuation and control

 18

18

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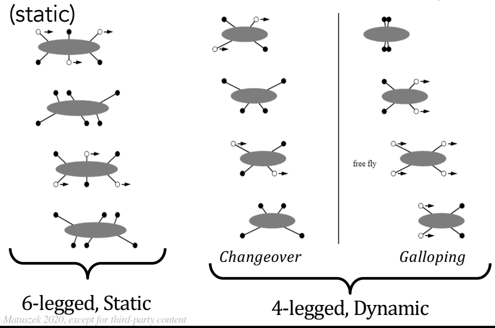
Static vs. Dynamic Gait

- Whether robot is stable at all times during walking (static)



 19

19

Dynamic Quadruped

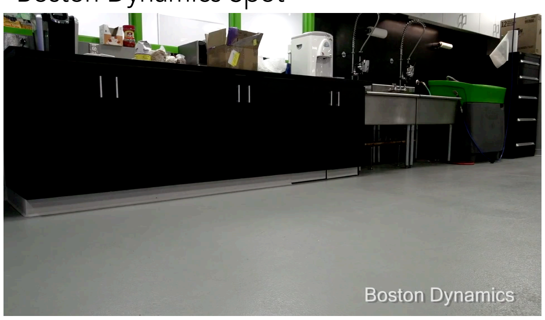
- Boston Dynamics Spot

 https://www.youtube.com/watch?v=kgaO45SyaO4 20

20

Dynamic Quadruped (II)

- Boston Dynamics Spot



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21

Dynamic Quadruped (III)

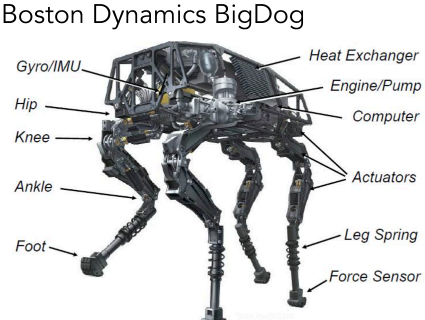
- Boston Dynamics BigDog

 https://www.youtube.com/watch?v=cNZPRsrwumQ 22

22

Dynamic Quadruped

- Boston Dynamics BigDog



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23

All About Wheels

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

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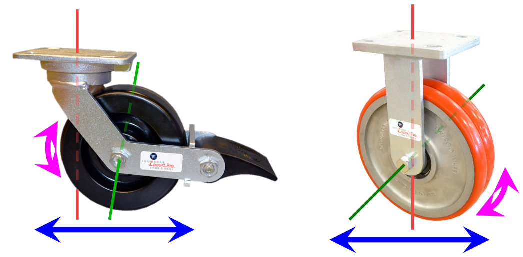
24

Mountings and Axles

Mounting axis
Axle

Direction of rotation
Direction of translation

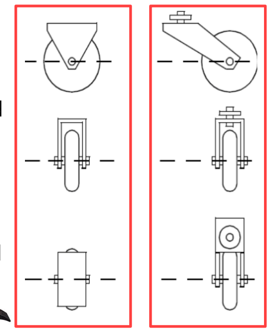


 25

25

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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26

Basic Wheel Types

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

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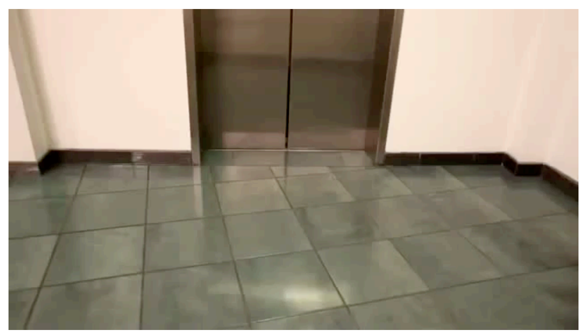
27

Omni Wheels

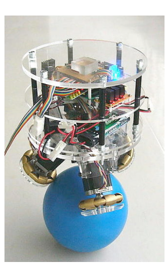


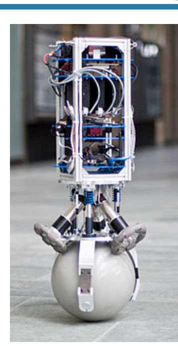
 https://www.youtube.com/watch?v=8sH1a511 28

28

Basic Wheel Types

- Ball or spherical wheel
  - Suspension not solved



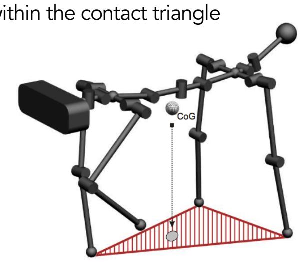


 https://en.wikipedia.org/wiki/Ballbot 29

29

Characterization: Stability

- Stability of a vehicle is guaranteed with 3 wheels
  - If center of gravity is within the contact triangle
- Stability is improved by 4+ wheels
  - However, requires a flexible suspension
  - It's hyperstatic (see later)



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30

Characterization: Stability (II)

- **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

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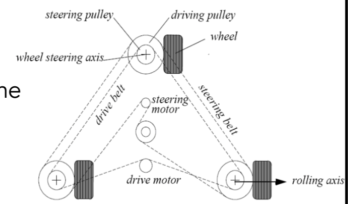
31

Synchro Drive

- All wheels are actuated by one motor
  - Defines the speed of the vehicle
- All wheels steered synchronously by second motor
  - Sets the heading of the vehicle
- Orientation in space of robot frame always the same
- Not possible to control orientation of robot frame



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32