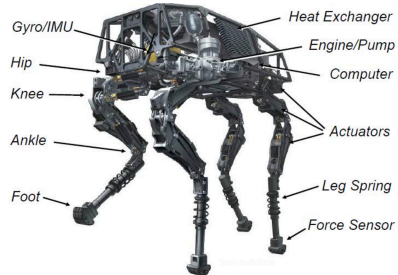


Mobility

Legs and Wheels



Many slides adapted from slides © R. Siegwart, ETH Zürich and Dr. Tim Oates, UMBC

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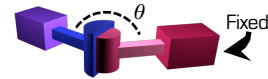
Today's Class

- Degrees of Freedom, revisited
- Slip
- Legged Motion
 - Leg joints
 - Gaits
 - DoFs
 - Static/dynamic gaits
 - Static/dynamic stability

3

Degrees of Freedom (revis.)

- 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?

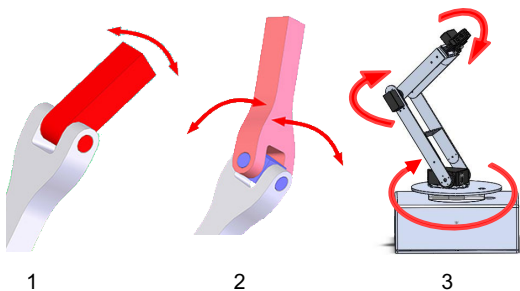


- This arm can be straight, or bent some amount
- To know its state, you need to know **1** thing: θ

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

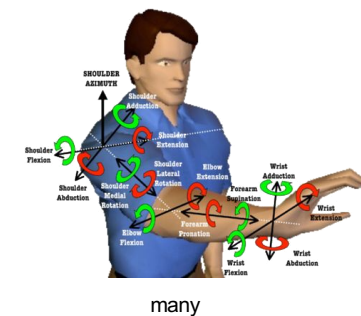
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Degrees of Freedom



6

Degrees of Freedom



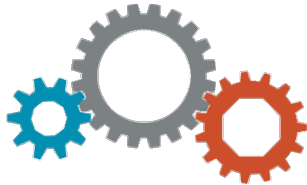
many

https://en.wikipedia.org/wiki/Degrees_of_freedom_%28mechanics%29; Wang et al 2019

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Slip

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



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Legged Motion

- Fewer legs $\rightarrow$ 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!

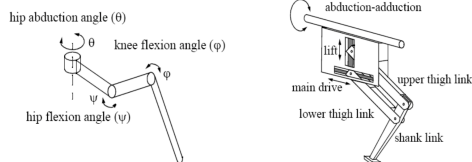


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Leg Joints (DoFs)

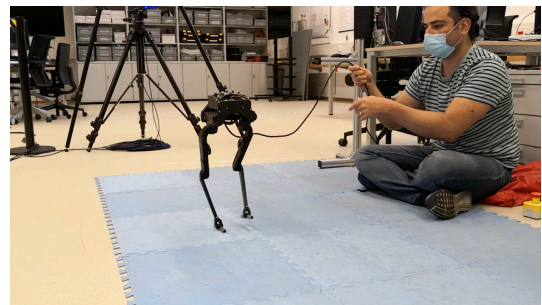
- 2+ DoFs to move a leg forward: **lift** and **swing**
- Three DoFs for each leg in most cases
 - 4th DOF for the ankle joint
 - Might improve walking and stability
 - More joints increase design / control complexity



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Dynamic biped



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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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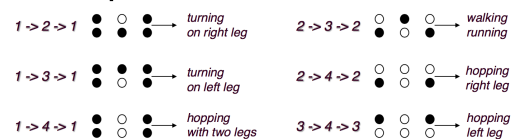
12

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

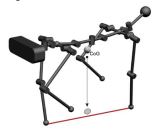


Adapted from © R. Siegwart, ETH Zürich – A13

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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

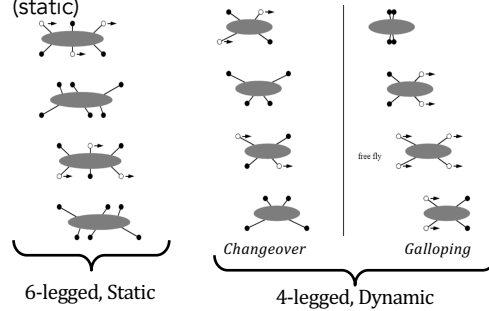


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Static vs. Dynamic Gait

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



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Spot has an Arm!



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Do You Love Me


<https://www.youtube.com/watch?v=fu3KWA11xdu>

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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

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Wheels



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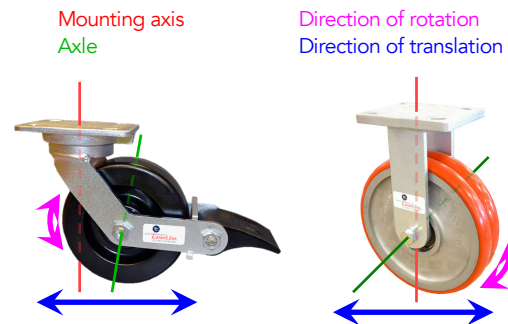
All About Wheels

- 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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Mountings and Axles



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4 Basic Wheel Types

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



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4 Basic Wheel Types

- Standard wheel
 - Two degrees of freedom: Rotation around wheel axle, **contact point**
- Castor wheel
 - Three degrees of freedom
 - Rotation around wheel axle, **contact point**, castor axle



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Basic Wheel Types

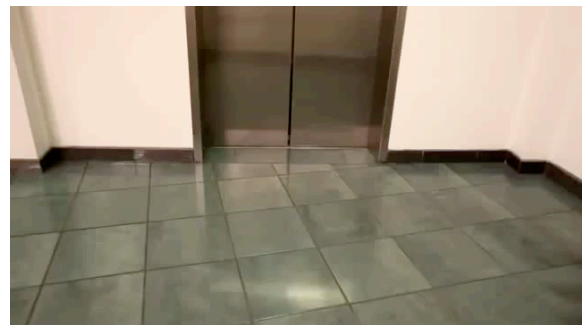
- Swedish (Mecanum, Ilon) wheel
 - Three degrees of freedom
 - Rotation around the (motorized) wheel axle, rollers, contact point



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Omni Wheels

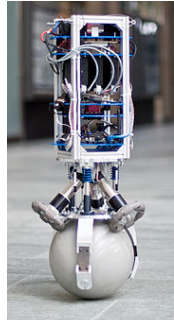
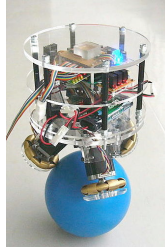


<https://www.youtube.com/watch?v=8sH1a511> 26

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Basic Wheel Types

- Ball or spherical wheel
 - Suspension not solved

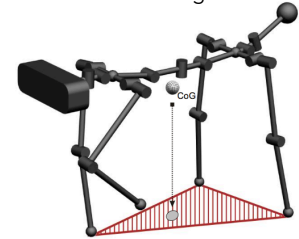


<https://en.wikipedia.org/wiki/Ballbot>

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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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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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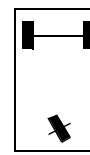
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Wheel Arrangements

- Of 2 wheels



- Of 3 wheels



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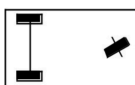
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Three Wheels



- Differential drive plus castor or omnidirectional wheel



- Connected drive wheels at rear, steered wheel at front



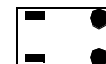
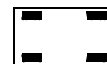
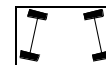
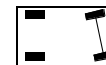
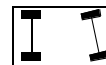
- Two free wheels in rear, steered drive wheel in front

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Arrangements

- Of 4 wheels:



- Of 6 wheels:



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Treads, slip and skid

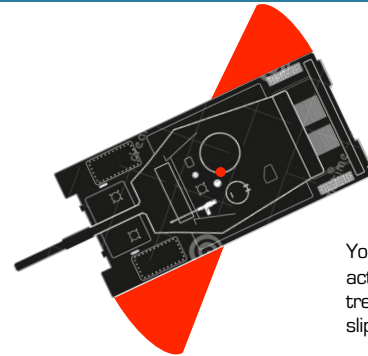
- Great at moving heavy things
 - Lots of support
 - Even over bad terrain
- Treads are "wheels" with large surface contact
 - Violate the "point contact" assumption
- Q: How do you turn a tank?
 - What's the difficulty?
- A: Rotate treads opposite directions
 - How can this work?



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Turning treads



You can't actually turn on treads without slip!

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Treads, slip and skid

- Tradeoffs?
 - High friction on flat surfaces (= inefficiency)
 - High torque requirements
 - Tread wear
 - Terrain damage
 - A lot
 - Odometry



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More about omni wheels

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

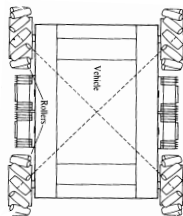


Kinetically identical to spherical castors

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Omni movement

- 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 direction to wheels on other diagonal: sideways movement**

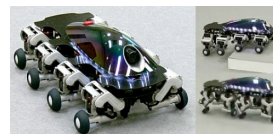


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Walking Wheels

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



Halluc II, Chiba Inst. Of Tech.



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Passive: the Shrimp

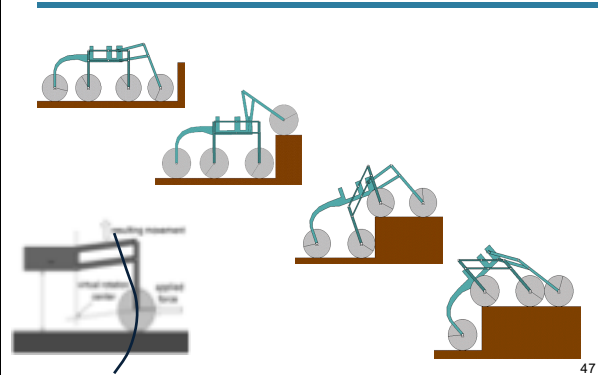
- Passive locomotion on rough terrain
- 6 wheels
 - One fixed wheel in back
 - Two bogies on each side
 - Front wheel, spring suspension
- ≈ 60 cm long, 20 cm tall
- Highly stable in rough terrain
- Climbs obstacles up to 2x wheel diameter



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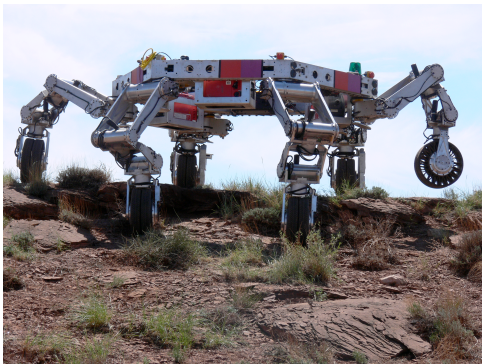
Shrimp "Walking"



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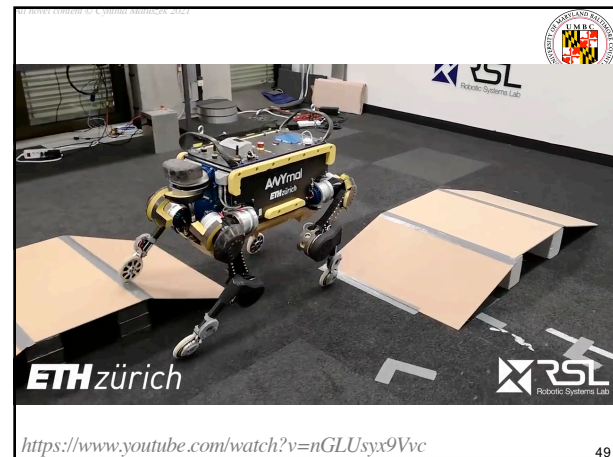
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Active



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<https://www.youtube.com/watch?v=nGLUsyx9Vvc>

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