Locomotion

EE468/CE468: Mobile Robotics

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Image on my room's ceiling from gaps in my curtain

- How do you actually make a robot move?
- Why don't more robots have legs?
- Synchrodrive, Omnidirectional
- Ackermann, Differential Drive
- larger tracks, more traction
- polymorphic skid system
- all terrain vs locomotion choice?

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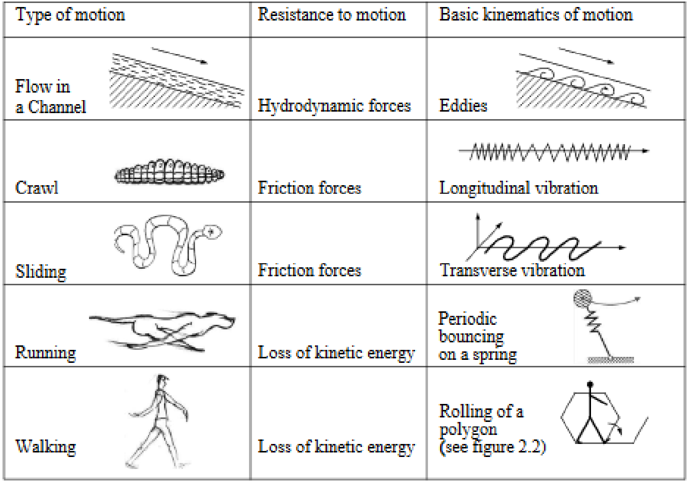
What is locomotion?

- **Locomotion:** It is a robot's ability to move itself.
- **Manipulation:** A robot's ability to move objects in its environment.



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	Periodic bouncing on a spring
Walking	Loss of kinetic energy	Rolling of a polygon (see figure 2.2)

Figure: Locomotion Ideas [2]

A crawling robot
Lateral undulation

Rolling doesn't exist in nature.

- Walking can be approximated as rolling polygon.
- Side of polygon is equal to step size.
- In limit, approximated as a rolling ball.

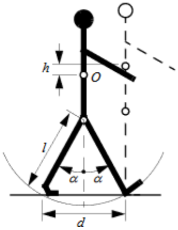


Figure: Walking can be approximated as rolling. [2]

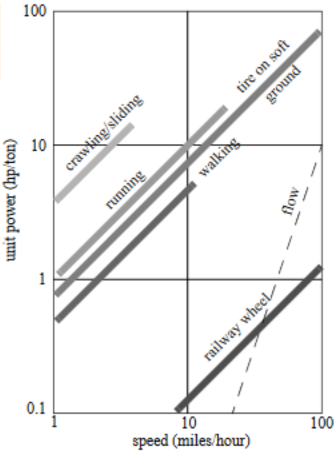


Figure: Power vs attainable speed of locomotion [2]

- Rolling is efficient on flat ground.
  - Losses due to back and forth motion.
  - Energy loss during deceleration is not recovered.

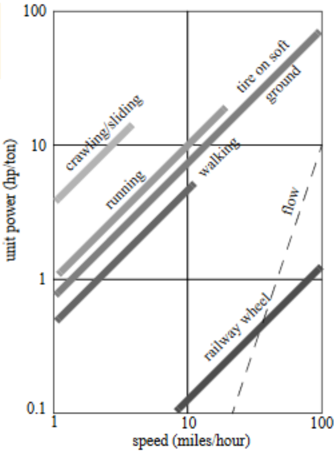


Figure: Power vs attainable speed of locomotion [2]

- Rolling is efficient on flat ground.
  - Losses due to back and forth motion.
  - Energy loss during deceleration is not recovered.
- Biomimetic robots
  - Structural complexity increases.
  - Control expense increases.
  - Up and down movement of the involved masses.

Configuration of robot

Complete specification of position of every point of the robot.

Configuration of a robot

Configuration of robot

Complete specification of position of every point of the robot.

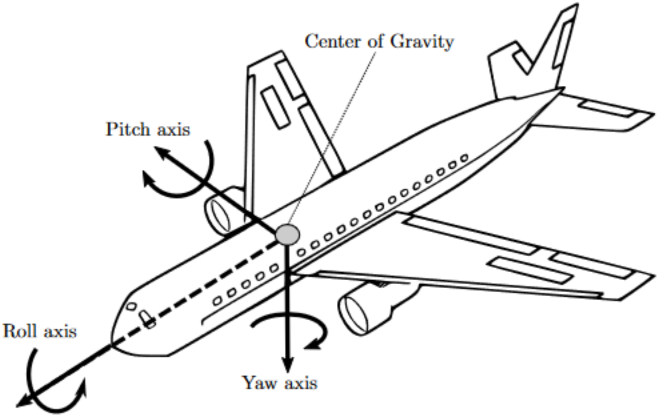
- Rigid bodies with known shapes need few numbers (coordinates) to specifying configuration

How many coordinates are needed?

Degrees of Freedom

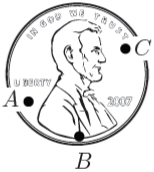
The minimum number of real-valued coordinates, n, needed to represent the configuration is number of degrees of freedom of robot.

Rigid bodies in free space have 6 DOF.

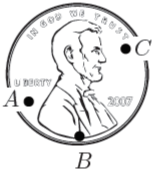


What is the number of degrees of freedom for this?

How many DoF does a planar rigid body have?

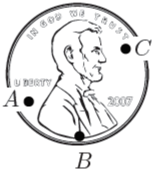


How many DoF does a planar rigid body have?



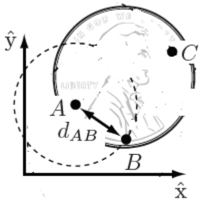
- A planar rigid body has 3 DOF.

How many DoF does a planar rigid body have?

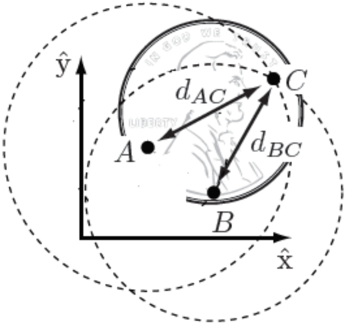


- A planar rigid body has 3 DOF.
- Possible coordinates are (x, y, θ). For a robot, this is called its **pose**.

All points on rigid body are at a fixed distance from each other



- Start with A. How many coordinates do we need?
  - (x_A, y_A). 2 coordinates
- Pick another point: B. How many additional coordinates do we need?
- B on circle with center A and radius d_{AB}. We only need to specify location on circle.
  - Requires only 1 coordinate.



(b)

- Let's consider C now.
  - Distance from A and B is fixed. So, C is at intersection of two circles.
  - Out of two solutions, only one corresponds to heads.
- What about more points?
  - Every point brings two independent constraints.

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Legged robots perform better on rough terrains.

Figure: Require minimal contact. Terrain between ground contact points is irrelevant.

Figure: Legs can be used as manipulators.

But, coordinating legs for locomotion is a complex problem.

- Locomotion is a sequence of 'lift and release events' of individual legs.

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- Locomotion is a sequence of 'lift and release events' of individual legs.

- For two legs, distinct events:
  1. DD $\rightarrow$ UD $\rightarrow$ DD
  2. DD $\rightarrow$ DU $\rightarrow$ DD
  3. DD $\rightarrow$ UU $\rightarrow$ DD
  4. DU $\rightarrow$ UD $\rightarrow$ DU
  5. DU $\rightarrow$ UU $\rightarrow$ DU
  6. UD $\rightarrow$ UU $\rightarrow$ UD

  where *UD* means left leg up and right leg down.

But, coordinating legs for locomotion is a complex problem.

- Locomotion is a sequence of 'lift and release events' of individual legs.
- Number of distinct 'lift and release events' for robot with k legs is N:

$$N = (2k - 1)!$$

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$$N = (2k - 1)!$$

- For $k = 6$, $N = 39,916,800$.

- For two legs, distinct events:
  1. DD $\rightarrow$ UD $\rightarrow$ DD
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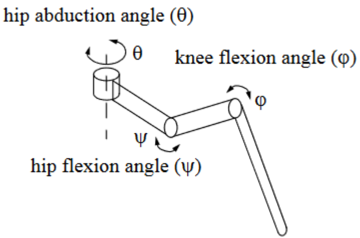
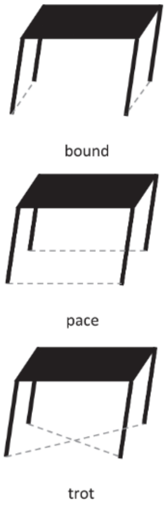
  where *UD* means left leg up and right leg down.

Control of leg event is also challenging.



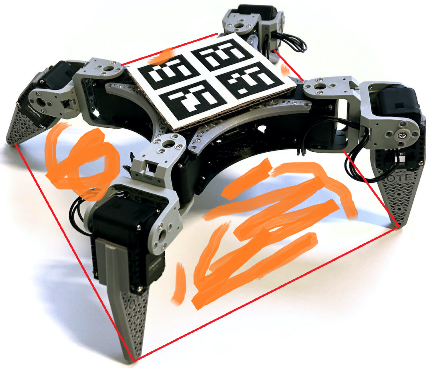
- At least 2 dof are required for each leg, but most have at least 3.
- Human leg has 7 DOF.
- For each leg event, 7 control commands need to be generated.

Solution: Group legs and create gaits



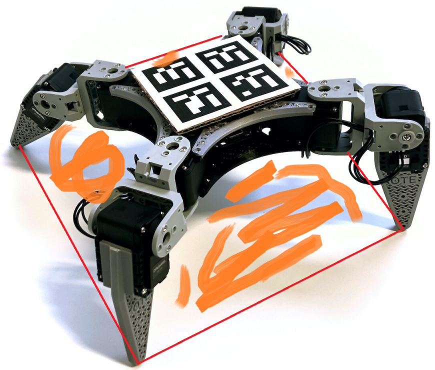
- Legs are grouped into two sets, A and B.
- All legs in group follow the same event.
- Patterns of leg events are created in terms of A and B, called gaits.

Another challenge for legged robots is balancing.



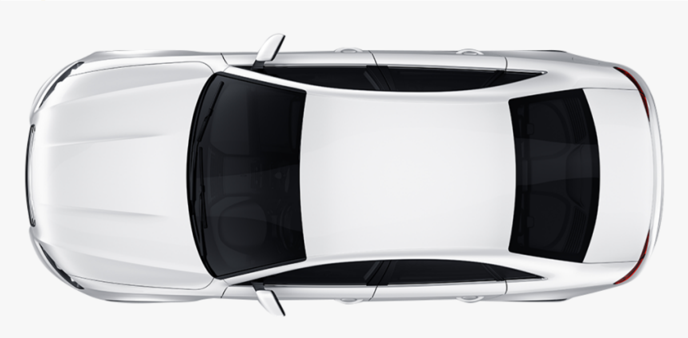
- **Statically balanced:** If the COG of robot is in the support polygon.
- **Support Polygon:** Convex hull of the contact points with the ground.

Another challenge for legged robots is balancing.

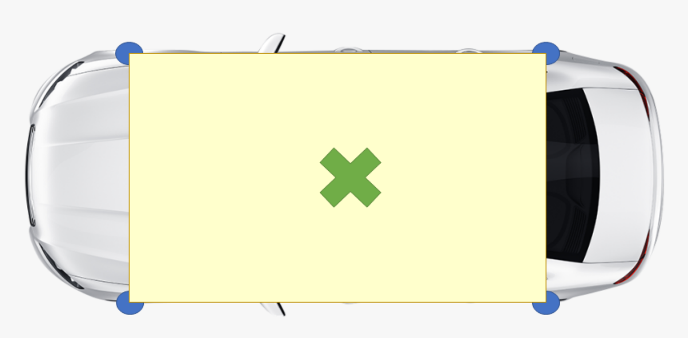


- **Statically balanced:** If the COG of robot is in the support polygon.
- **Support Polygon:** Convex hull of the contact points with the ground.
- **Statically Stable:** The robot is statically balanced at every moment in time [1]. No control effort is required for stability.

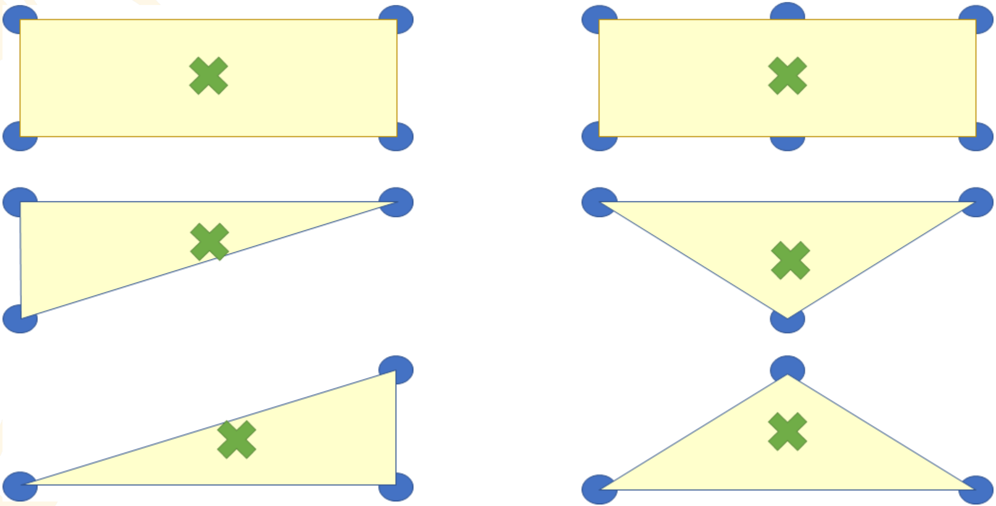
Is a car statically stable?



For static stability, it requires suspension on uneven terrain.

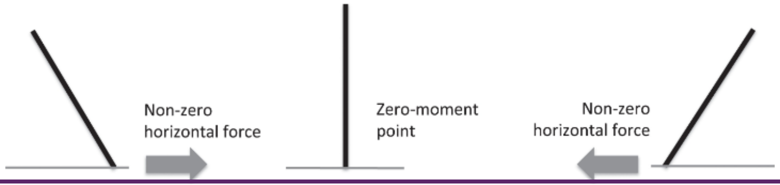


There are more statically stable gaits with six legs than four legs.



Bipedal robots are not statically stable.

- Stability is constantly evaluated and maintained.
- Foot placement is to be planned so that leg does not slip out from under. Planned using zero moment point (ZMP).
- ZMP is the angle where horizontal forces of momentum and friction are balanced.
- Dynamic Balancing for one-legged robot



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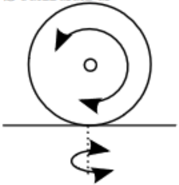
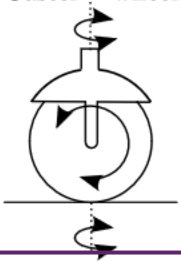
What are the available wheel design options?

Wheel type	Example	Degrees of Freedom
Standard 	Front-wheel of a wheelbarrow	Two: • Rotation around the wheel axle • Rotation around its contact point with the ground
Caster wheel 	Office chair	Three: • Rotation around the wheel axle • Rotation around its contact point with the ground • Rotation around the caster axis

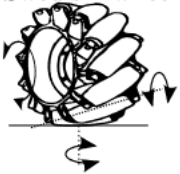
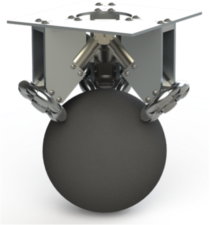
Swedish wheel	Standard wheel with non-actuated rollers around its circumference	Three:
		• Rotation around the wheel axle • Rotation around its contact point with the ground • Rotation around the roller axles

Figure: Adopted from [2]

What are the available wheel design options?



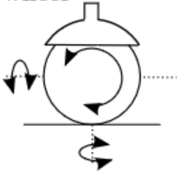
Spherical wheel 	Ball Bearing	Three: • Rotation in any direction • Rotation around its contact point

Figure: Adopted from [2]

Combine wheels in a configuration to have a functional vehicle.

Design Space

- Any number of wheels.
- Active or Passive.
- Steered or Fixed.

Considerations

- Static Stability
- Vehicle should be able to achieve any pose.

Combine wheels in a configuration to have a functional vehicle.

Design Space

- Any number of wheels.
- Active or Passive.
- Steered or Fixed.

Icons for the each wheel type are as follows:	
	unpowered omnidirectional wheel (spherical, castor, Swedish)
	motorized Swedish wheel (Stanford wheel)
	unpowered standard wheel
	motorized standard wheel
	motorized and steered castor wheel
	steered standard wheel
	connected wheels

Two-wheel Configurations

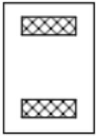
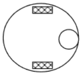
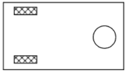
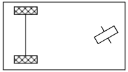
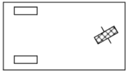
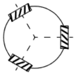
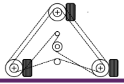
Arrangement	Description	Typical examples
	One steering wheel in the front, one traction wheel in the rear	Bicycle, motorcycle
	Two-wheel differential drive with the center of mass (COM) below the axle	Cye personal robot

Figure: Adopted from [2]

Three-wheel Configurations

	Two-wheel centered differential drive with a third point of contact	Nomad Scout, smartRob EPFL
	Two independently driven wheels in the rear/front, one unpowered omnidirectional wheel in the front/rear	Many indoor robots, including the EPFL robots Pygmalion and Alice
	Two connected traction wheels (differential) in rear, one steered free wheel in front	Piaggio minitrucks
	Two free wheels in rear, one steered traction wheel in front	Neptune (Carnegie Mellon University), Hero-1
	Three motorized Swedish or spherical wheels arranged in a triangle; omnidirectional movement is possible	Stanford wheel Tribolo EPFL, Palm Pilot Robot Kit (CMU)
	Three synchronously motorized and steered wheels; the orientation is not controllable	"Synchro drive" Denning MRV-2, Georgia Institute of Technology, I-Robot B24, Nomad 200

Four-wheel Configurations

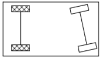
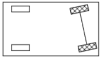
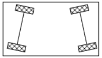
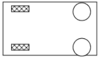
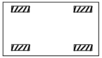
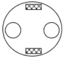
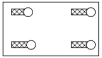
	Two motorized wheels in the rear, two steered wheels in the front; steering has to be different for the two wheels to avoid slipping/skidding.	Car with rear-wheel drive
	Two motorized and steered wheels in the front, two free wheels in the rear; steering has to be different for the two wheels to avoid slipping/skidding.	Car with front-wheel drive
	Four steered and motorized wheels	Four-wheel drive, four-wheel steering Hyperion (CMU)
	Two traction wheels (differential) in rear/front, two omnidirectional wheels in the front/rear	Charlie (DMT-EPFL)
	Four omnidirectional wheels	Carnegie Mellon Uranus
	Two-wheel differential drive with two additional points of contact	EPFL Khepera, Hyperbot Chip
	Four motorized and steered castor wheels	Nomad XR4000

Figure: Adopted from [2]

Six-wheel Configurations

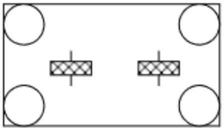
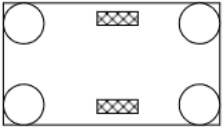
	Two motorized and steered wheels aligned in center, one omnidirectional wheel at each corner	First
	Two traction wheels (differential) in center, one omnidirectional wheel at each corner	Terregator (Carnegie Mellon University)

Figure: Adopted from [2]

Categorization of all drive configurations

- **Differential Drive:** Wheels on two sides are controlled independently. If the left wheel moves faster than the right wheel, then the robot turns right.

Categorization of all drive configurations

- **Differential Drive:** Wheels on two sides are controlled independently. If the left wheel moves faster than the right wheel, then the robot turns right.
- **Decoupled steering and driving:** We can independently control the steering angle of the robot and the speed of the robot.

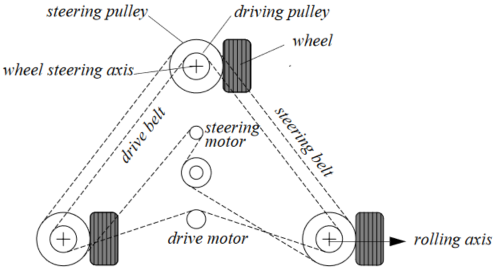


Figure: [2]

- **Synchro-Drive:** Three wheels, each of which can be driven and steered, are synchronized and controlled by two motors only. All wheels turn and drive in unison.
- It can move in any direction, i.e. it is omnidirectional.
- Orientation of chassis cannot be controlled.

Categorization of all drive configurations

Direction of Movement	Wheel Actuation
Forward	All wheels forward same speed
Reverse	All wheels backward same speed
Right Shift	Wheels 1, 4 forward; 2, 3 backward
Left Shift	Wheels 2, 3 forward; 1, 4 backward
CW Turn	Wheels 1, 3 forward; 2, 4 backward
CCW Turn	Wheels 2, 4 forward; 1, 3 backward

Figure: Why does it work?: Force vector diagrams of omnidirectional robot

- **Omnidirectional:** By adjusting the relative speeds of Swedish wheels, the robot can move in any direction, including laterally. Each wheel is independently controlled.
- Three-wheel Omnidirectional Robot
- Four-wheel Omnidirectional Robot

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[1] **Robert B McGhee and Andrew A Frank.**
On the stability properties of quadruped creeping gaits.
Mathematical Biosciences, 3:331–351, 1968.

[2] **Roland Siegwart, Illah R Nourbakhsh, and Davide Scaramuzza.**
Autonomous mobile robots.
A Bradford Book, 15, 2011.