Autonomous Mobile Robots

Introduction & History of Mobile Robotics

Introduction

- What is robotics? What is a robot?
- Why use robots?
- Who is involved in robotics?
- Where are robots?

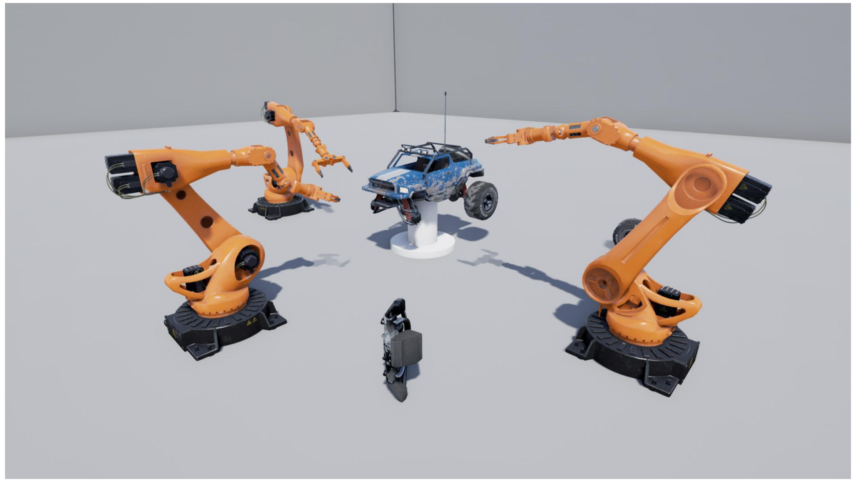
What is a Robot?

- Intuitively, a device that can replicate some human activity
- *Webster:* "an automatic device that performs functions ordinarily ascribed to human beings."
- *Oxford:* "A machine capable of carrying out a complex series of actions automatically, especially one programmable by a computer"
- *International Organization for Standardization (ISO):* "An automatically controlled, reprogrammable, multipurpose manipulator programmable in 3 or more axes, which can be either fixed in place or mobile for use in industrial automation applications
- *Robot Institute of America (1979):* "An industrial robot is a **reprogrammable multifunctional manipulator** designed to move materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks."
- " .... operating in the three-dimensional world as a machine endowed with the capacity to interpret and to reason about a task and about its execution, by intelligently relating perception to action."

Why use robots?

- 4Ds
  - ➢ Dangerous
  - ➢ Dirty
  - ➢ Dull
  - ➢ Difficult
- High precision and speed
- Market factors: driving low cost, efficiency

Industrial Manipulators



http://robots.com   http://ros.org   https://www.unrealengine.com

What are Autonomous Mobile Robots?

- Mobile: Move around in environment, such as manufacturing plant
- Autonomous:
  - ➢Perform tasks with minimum instructions
  - ➢Can make decisions and act independently

What is needed for Autonomy and Mobility

- Goal: to move unsupervised in an environment

Locomotion mechanism
- Wheels
- Track
- Legs
- Propellers (air, underwater)

Perception
- Vision
- Proximity
- Tactile

Localization & Mapping

Planning & Navigation
- Path
- Trajectory
- Tracking
- Obstacle avoidance

History of Mobile Robots

- 1967 – General Electric Co. produce 4 legged vehicle that was remotely operated
- 1968 – Stanford Research Institute makes ***Shakey*** intelligent mobile robot with vision, optical range finder and touch sensors, ability to understand and react to verbal English commands, moved in highly irregular jerky manner
- 1975 - Raibert - one legged hopping machine, first dynamically stable
- 1983 – Mobile robots – Odetics develops experimental

6-legged robot with gait based on humans and insects

- Teleoperated – for use in nuclear power plants

Shakey: Photo – SRI International

https://spectrum.ieee.org/sri-shakey-robot-honored-as-ieee-milestone

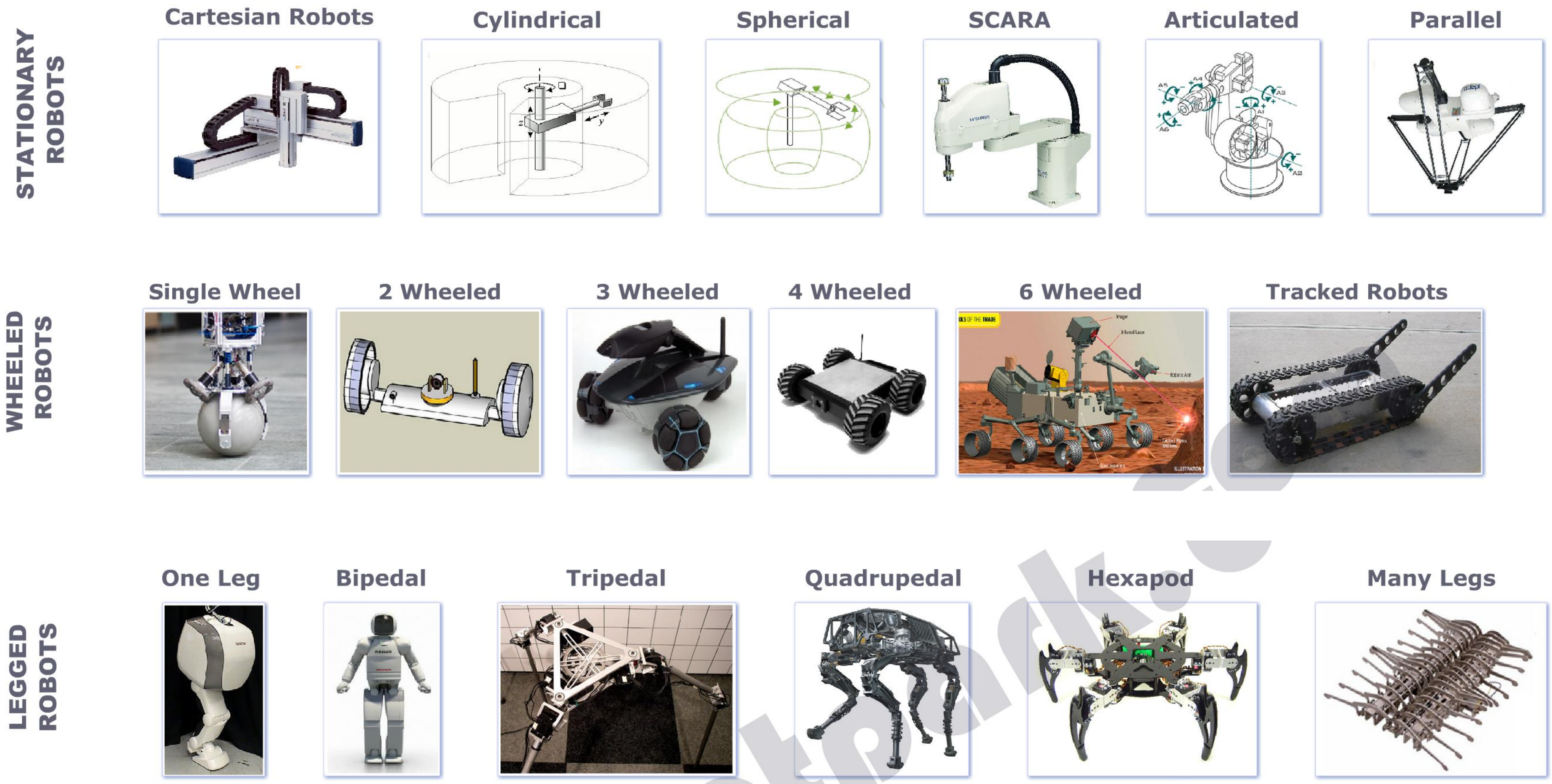
Additional Material

- **Odex-1 Walking robot:** youtube.com/watch?v=EWX9iRw33OE
- **Robots from MIT-Leg Lab:** youtube.com/watch?v=XFXj81mvInc
- **Shakey:** youtube.com/watch?v=GmU7SimFkpU

History of Mobile Robots

- 1984 – French shipbuilding company – tested marine mobile robot for cleaning sides of ship
- 1990s – Diversified into walking robots at MIT, humanoids (Honda), rehabilitation robots, healthcare robots, defense and space applications
- 2000s – Development of micro and nano robots using smart materials, Unmanned aerial vehicles and Unmanned Underwater vehicles – Tesla, Roomba, Drones, ASIMO …

Classification of Robots – Based on Locomotion



http://www.robotpark.com/All-Types-Of-Robots

Locomotion

- Locomotion mechanisms are needed to move through environment

Biologically-insipired locomotion mechanisms

- ➢ Walk
- ➢ Jump
- ➢ Run
- ➢ Slide
- ➢ Swim
- ➢ Fly
- ➢ Roll

Biological systems are very intricate and complex to replicate

Wheeled locomotion

Course will only focus on wheeled and legged systems

Legged locomotion v/s Wheeled locomotion

Legged Locomotion

- Consider human legs
- High number of degrees of freedom
- Mass associated with leg and body
- Can adopt to variations in terrain

Wheeled Locomotion

- Wheels most suited for flat terrains and ground
- Requires ground to be flat and hard
- Cannot handle uneven terrains easily

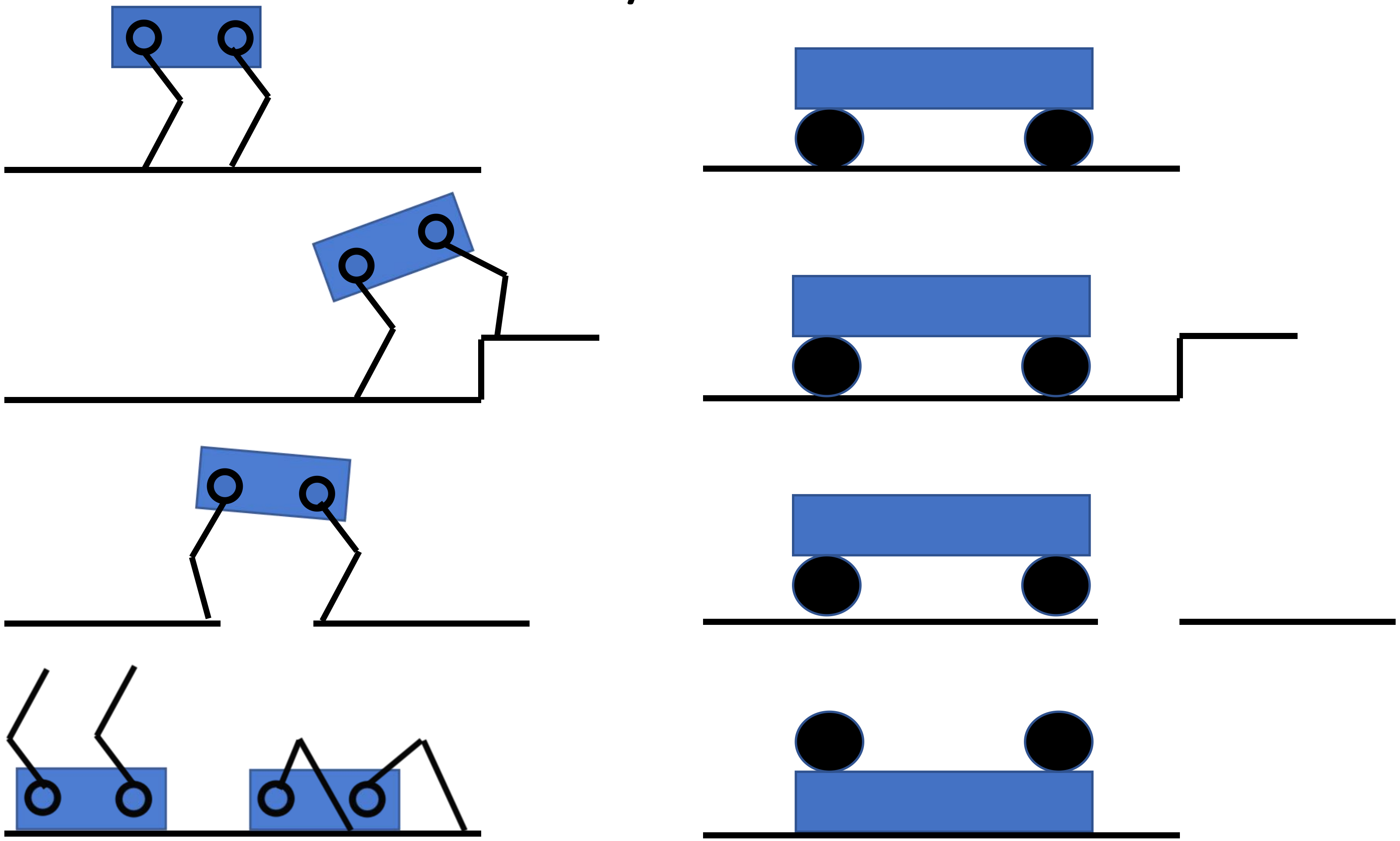
Legged locomotion v/s Wheeled locomotion

Flat Terrain

Steps

Gaps

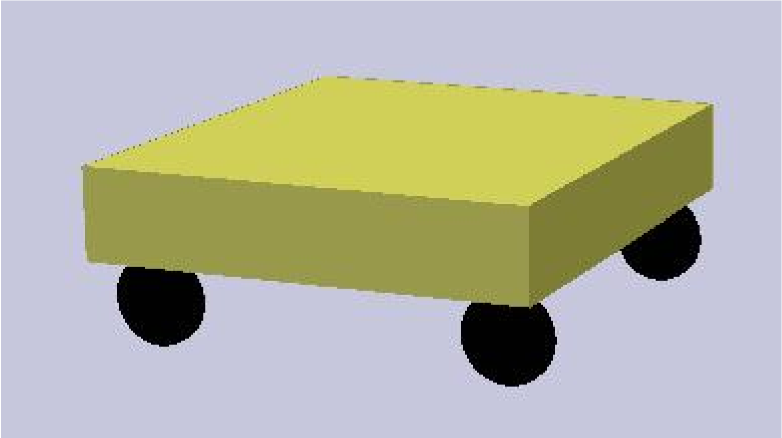
Flipped/Fallen

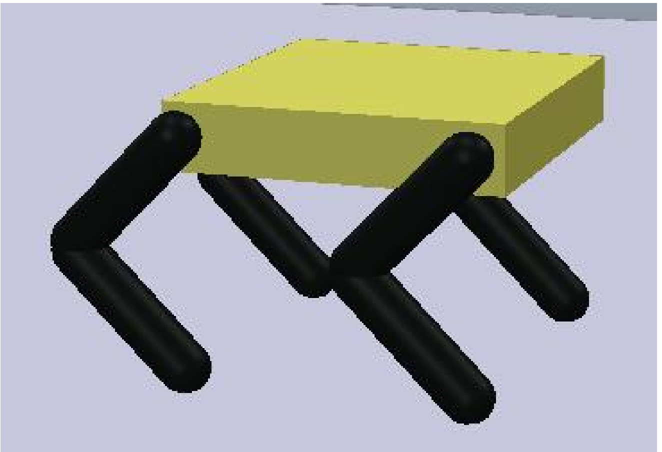


Legged locomotion can help overcome usual challenges in wheeled locomotion, but at cost of complexity

Locomotion – key issues

- Basic principle of locomotion: use actuators to generate interaction forces through contact



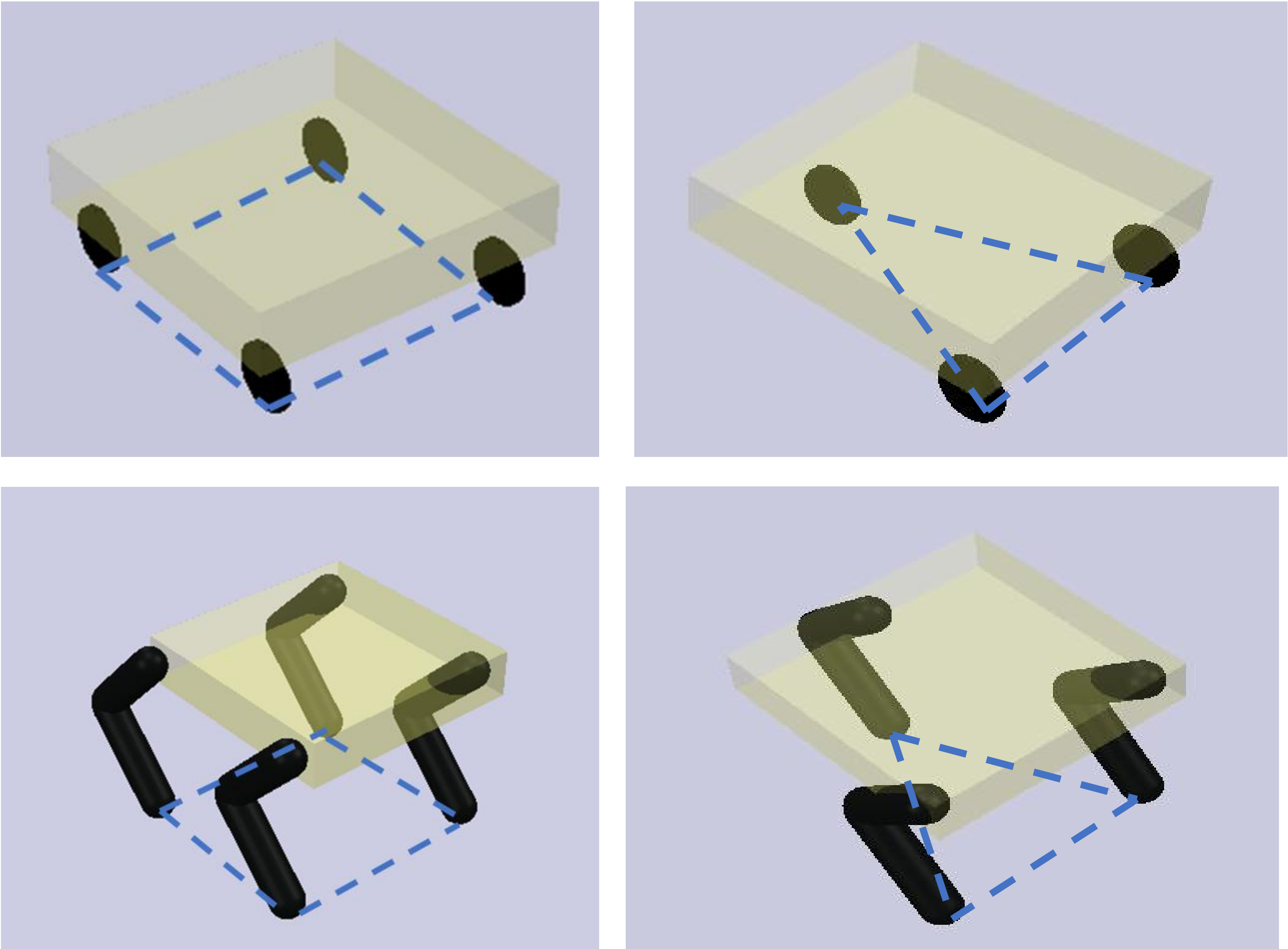


- Issues of **stability**, **contact characteristics** and **type of environment** need to be looked into

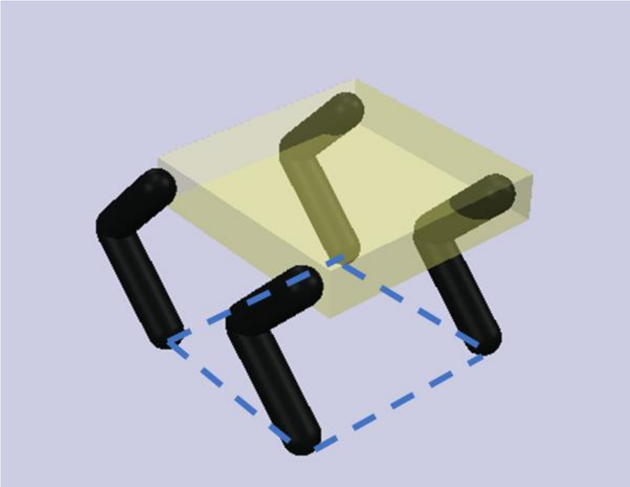
Key Issues in Locomotion - Stability

Stability

- Number of contact points
- Geometry of contact points
- Static/dynamic stability
- Inclination of terrain
- Centre of gravity



Key Issues in Locomotion – Contact Characteristics & Type of Environment



- Contact characteristics
  - Contact point size & shape
  - Angle of contact
  - Friction

- Type of Environment
  - Medium (ground, air, water, hard, soft)

Autonomous Mobile Robots

Module 5: Legged Locomotion

Characteristics

- Legged locomotion is characterized by a series of point contacts between robot and ground
- Advantage of this type of locomotion is adaptability and maneuvrability in rough terrain
- Quality of ground between points does not matter
- Capable of crossing gaps, holes if reach exceeds width of hole
- Legs can also be used to manipulate objects in certain cases

Characteristics (contd.)

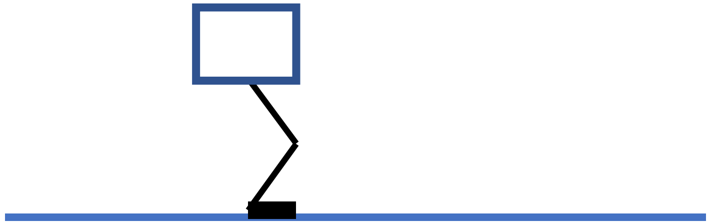
- Disadvantages :
  - Mechanical complexity is more
  - Power required is more
  - Each leg requires multiple degrees of freedom and therefore more motors and control
  - This also adds more mass to the system
  - Legs also need to be able to lift and lower the robot
  - High maneuvrability is possible only if sufficient degrees of freedom exist to impart forces in a number of different directions

Leg configuration

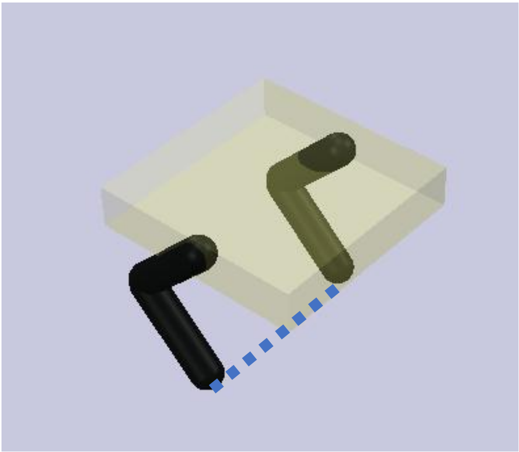
- In biological organisms:
  - 2 legs - humans
  - 4 legs - animals
  - 6 legs – insects
- In robots:
  - 1 leg
  - 2 legs - biped
  - 4 legs - quadruped
  - 6 legs - hexapod

Stability

- Stability of single-legged system:
  - Ankle and feet help increase contact area and improve stability



- Stability of a two-legged system



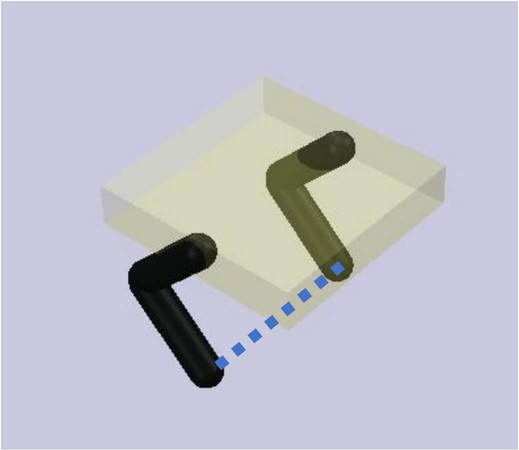
Static Stability

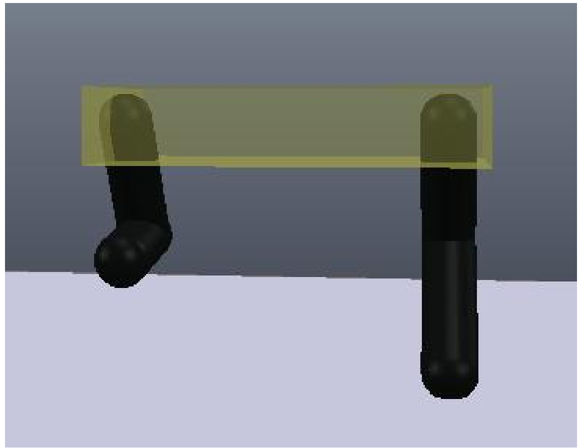
- When balance is maintained without need for motion, system is said to have static stability
- Think of two-, three- and four-wheeled vehicles
- Three points of contact on the ground ensure that an area is available for CG projection to fall within

Stability

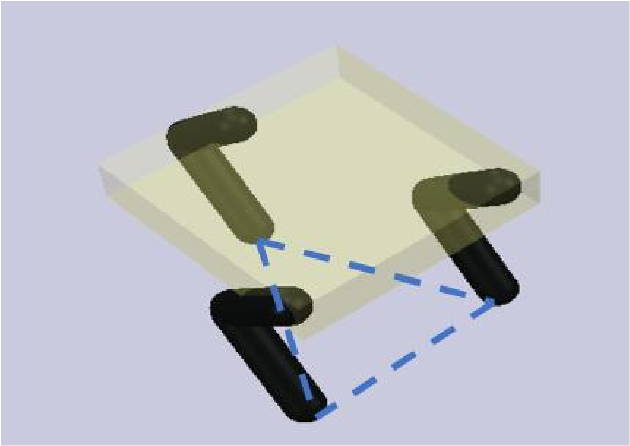
- Moving requires lifting of legs
- Stability is affected when leg is lifted

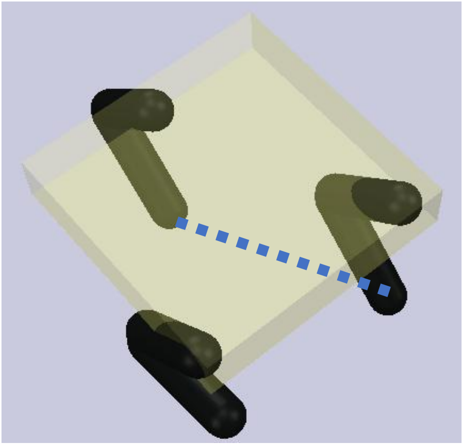
- Two-legged system





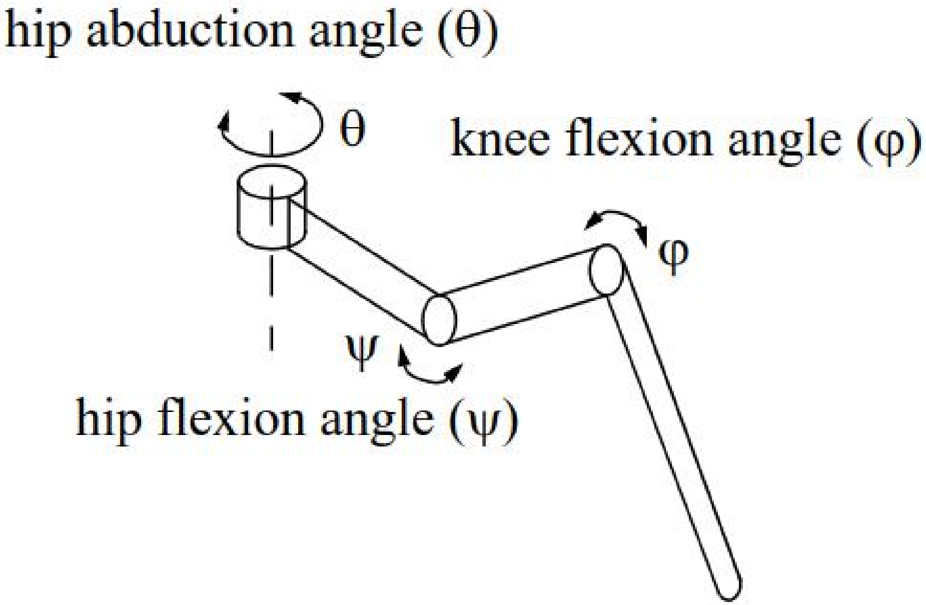
Three-legged system





Legged locomotion

- Each leg can have multiple degrees of freedom
- Typically, legs for robots each have 3 degrees of freedom: hip abduction, hip-flexion and knee-flexion



Siegwart, Roland, Illah Reza Nourbakhsh, and Davide Scaramuzza. Introduction to autonomous mobile robots. MIT press, 2011.

Legged locomotion

- 3 degrees of freedom: hip abduction, hip-flexion and knee-flexion

Simulation in CoppeliaSim – Educational Version

Adding more DoFs

- Advantages:
  - Increases maneuvrability
  - Increases range of terrains on which robot can travel
  - Can generate more variety of gaits

- Disadvantages
  - Need additional actuators
  - Need more power and control
  - Becomes heavier

Gait

- Pattern of limb movement during locomotion
- Walk, amble, pace, trot, canter, gallop
- The number of possible gaits depends on number of legs
- For robot with ***k*** legs, the total number of distinct event sequences (N) is given as

$$\mathbf{N = (2k-1)!}$$

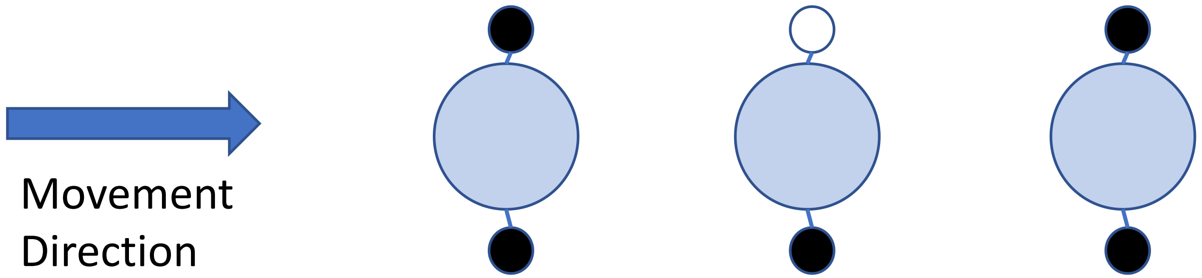
Gait

- For 2 legs, 6 distinct event sequences are possible

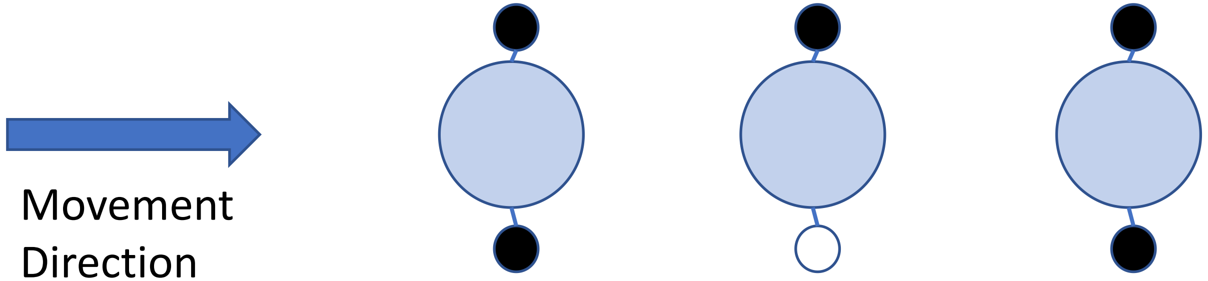
1) **Both legs down – right down/left up – both legs down**
2) **Both legs down – right up/left down – both legs down**
3) **Both legs down – both legs up – both legs down**
4) **Right down/left up – right up/left down – right down/left up**
5) **Right down/left up – both legs up – right down/left up**
6) **Right up/left down – both legs up – Right up/left down**

Gait: movement from left to right

1) **Both legs down – right down/left up – both legs down**

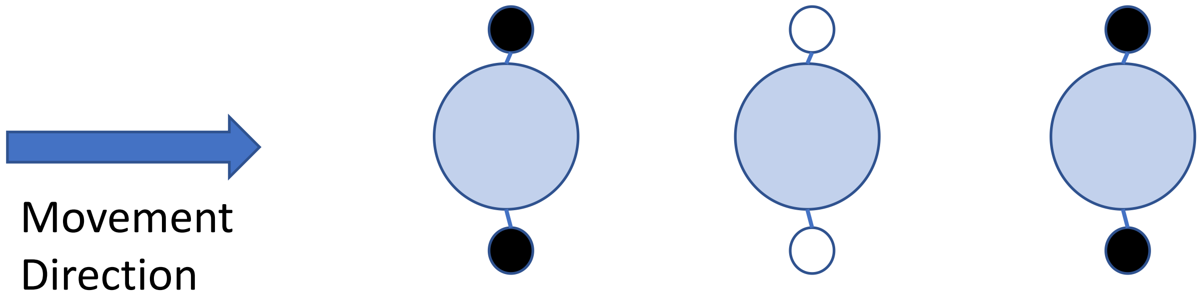


2) **Both legs down – right up/left down – both legs down**

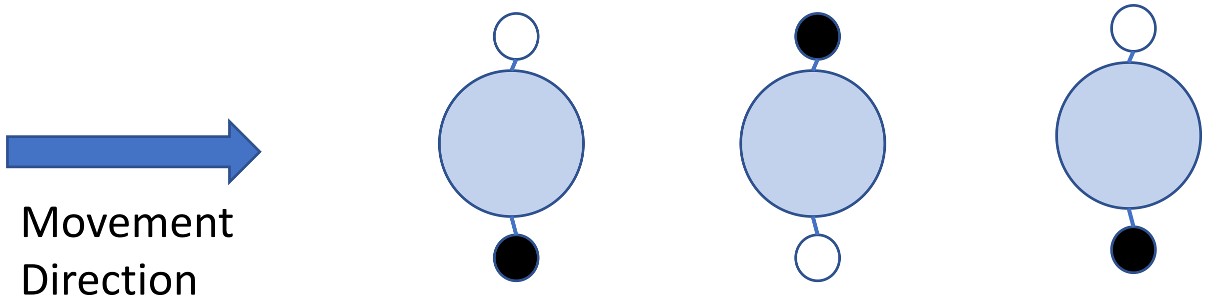


Gait: movement from left to right

3) Both legs down – both legs up – both legs down

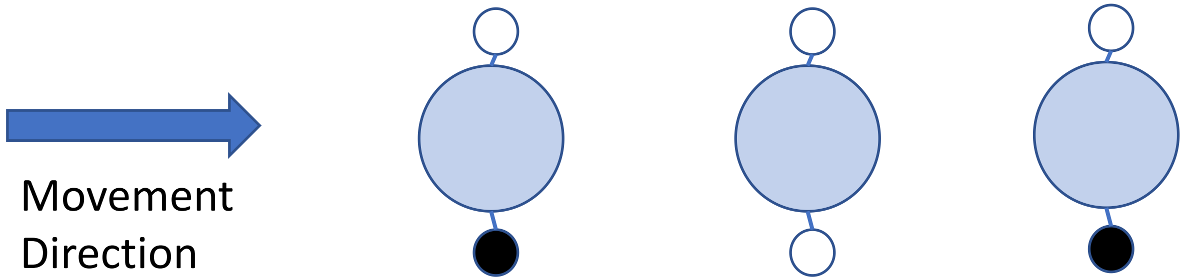


4) Right down/left up – right up/left down – right down/left up

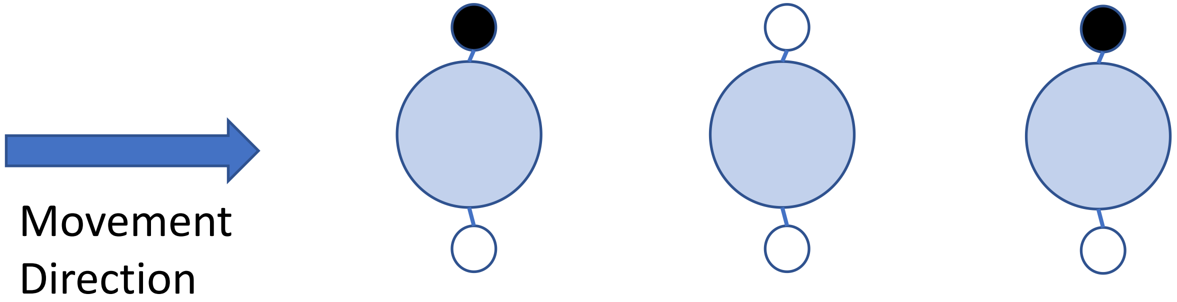


Gait: movement from left to right

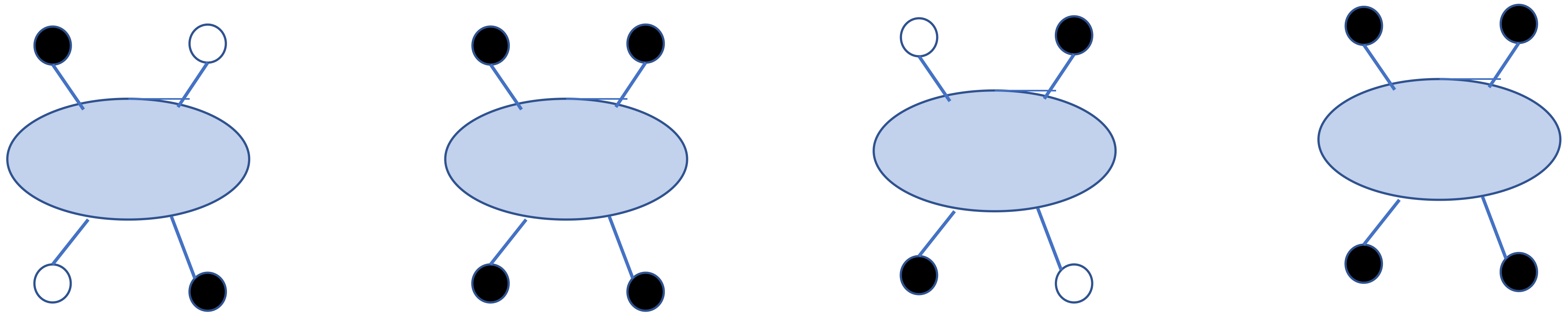
5) Right down/left up – both legs up – right down/left up



6) Right up/left down – both legs up – Right up/left down

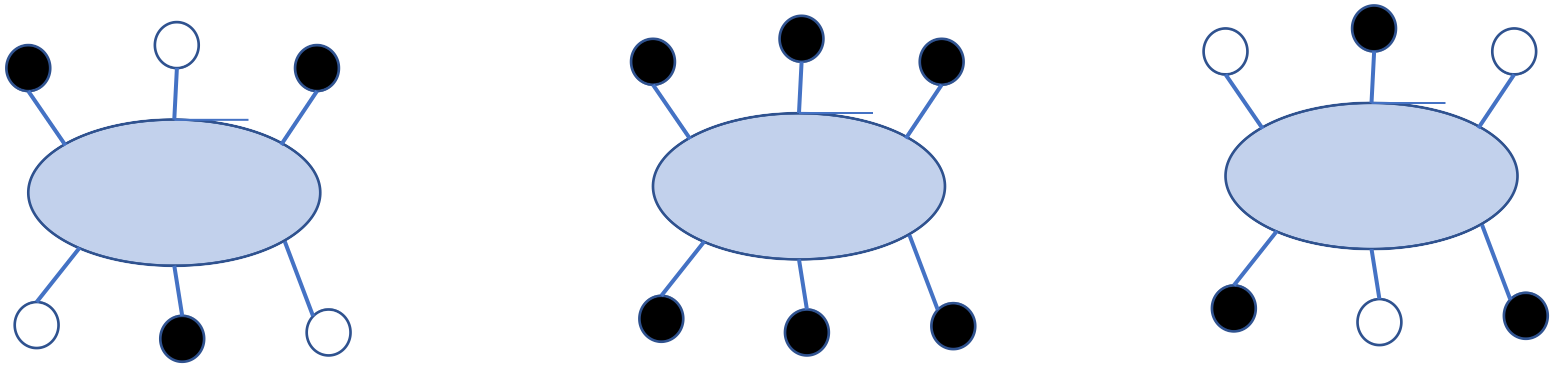


Trot Gait: movement from left to right



Static Walking: movement from left to right

3 points of contact must be maintained at all times



Additional Material

- **Animal Gaits for Animators:** youtube.com/watch?v=AZGNjKolAiQ
- **Robots from MIT-Leg Lab:** youtube.com/watch?v=XFXj81mvInc

Autonomous Mobile Robots

Module 6: Wheeled Locomotion

Characteristics

- Characterized by rotational motion of wheels in contact with the ground
- Very highly efficient mode of transport for flat terrains
- Balance is usually not a problem in flat terrains
- Wheels are usually in contact with ground at all times
- 3 wheels guarantee stable balance

Characteristics (contd.)

- Suspension system required to allow wheels to maintain ground contact in uneven terrains
- Need to study traction, stability, maneuvrability, control

Characteristics (contd.)

- Advantages:
  - Optimized for movement on flat surfaces
  - Mechanically very simple
- Disadvantages:
  - Cannot address uneven terrains
  - Cannot address gaps in floor if size exceeds a threshold

Design Space for Wheeled Locomotion

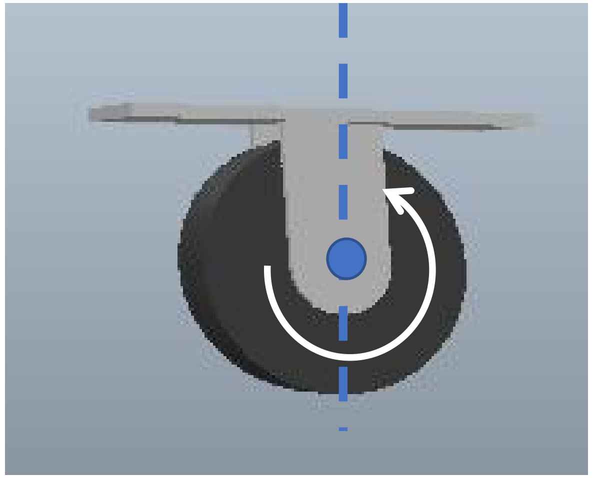
- Wheel Design
- Wheel Geometry
- Stability
- Maneuverability
- Controllability

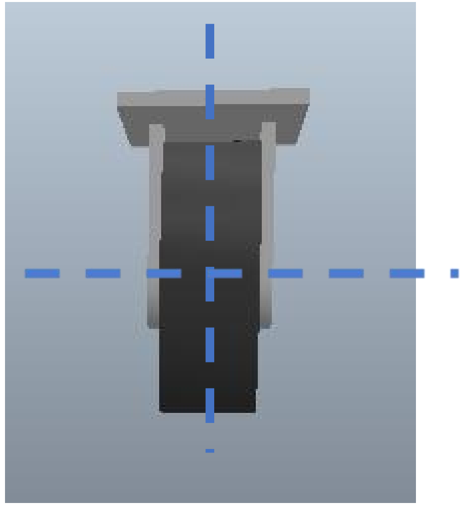
Design Space – Wheel Design

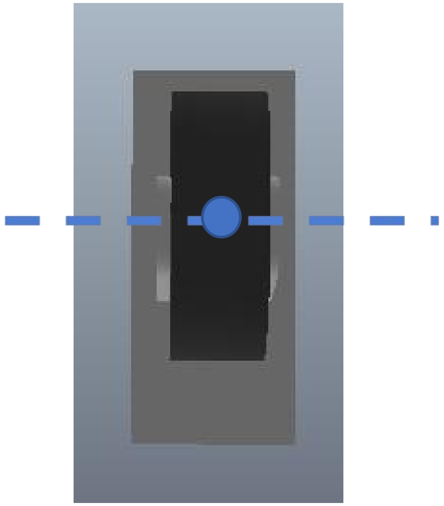
- 4 major classes of wheels
  - Standard wheel
  - Caster wheel
  - Swedish wheel
  - Spherical wheel
- Standard wheels and Caster wheels are highly directional in nature
- Swedish wheels and Spherical wheels are less directional in nature

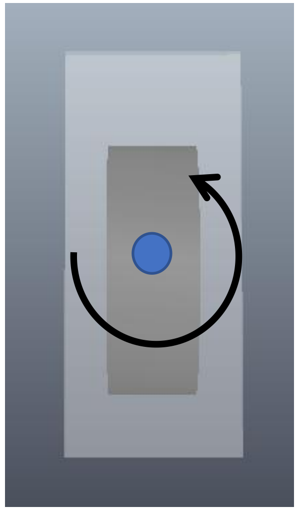
Wheel Design – Standard wheel

- Standard wheel is highly directional
- To change the direction, we need to steer about a vertical axis passing through the wheel
- This axis passes through the point of contact with ground
- Primary axis controls speed of motion
- Secondary axis controls steering
- 2-degrees of freedom



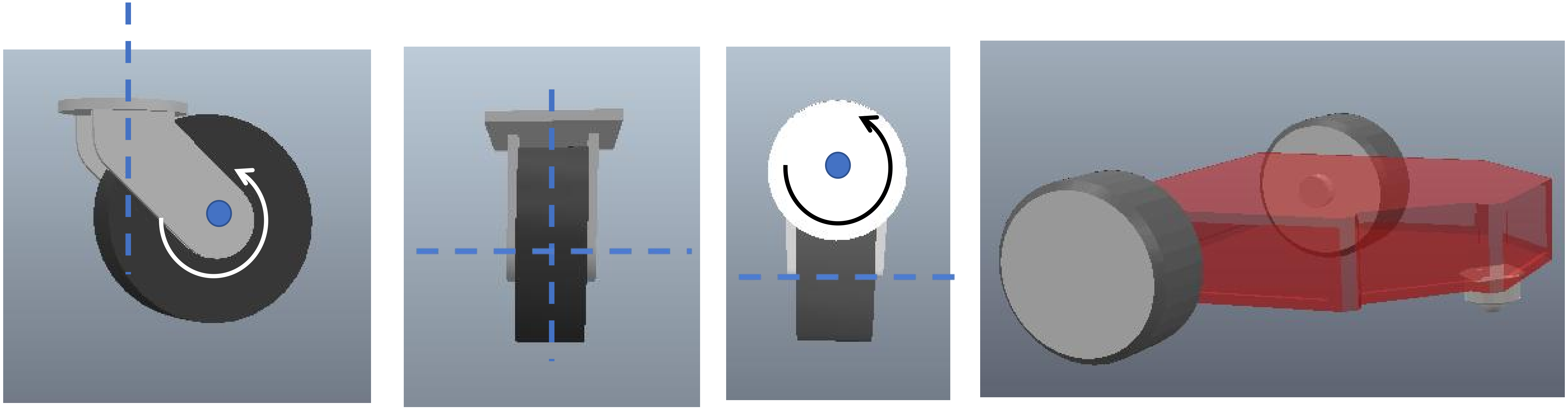






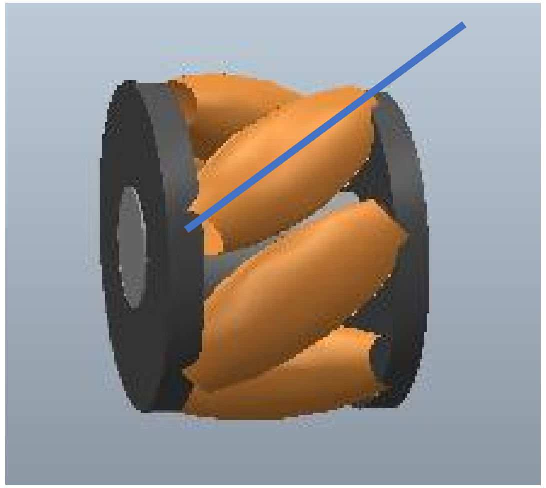
Wheel Design – Caster wheel

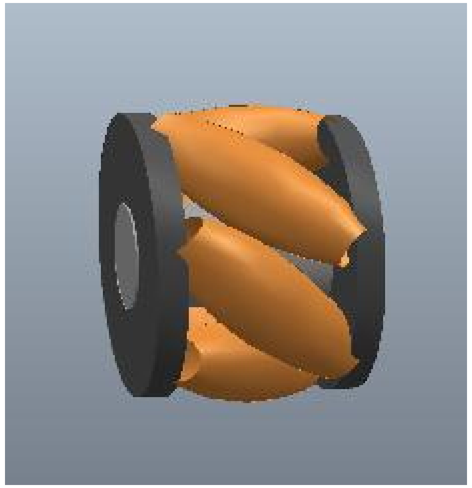
- Caster wheel is also highly directional
- Steering Axis is offset from the wheel contact point
- 2 degrees of freedom
- Spherical casters have a spherical ball instead of a cylindrical wheel

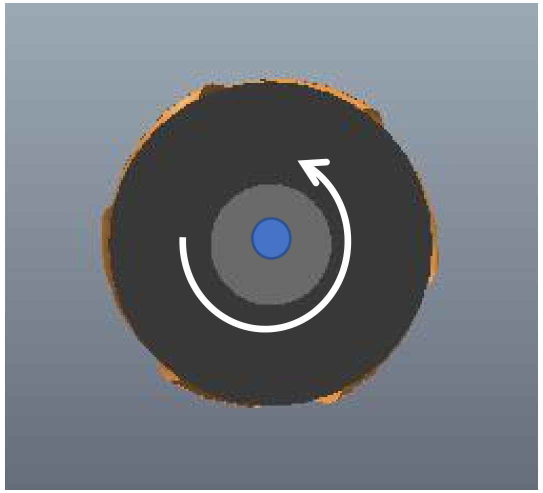


Wheel Design – Swedish wheel

- Swedish wheel consists of rollers which are distributed around the circumference of a cylinder
- The rollers can be at different angles, such as 45° or 90°
- Power is provided only to the wheel's primary axis
- The Swedish wheel functions as a normal wheel, but it has a low resistance in one another direction as well
- The rollers are not actuated, they are passive

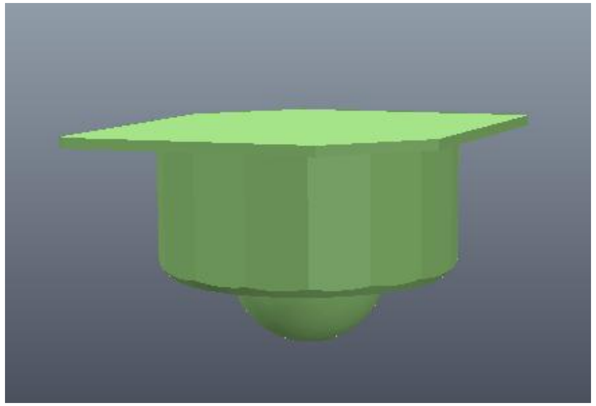






Wheel Design – Spherical wheel

- Spherical wheel consists of a spherical ball for a wheel
- A standard wheel has less resistance in only one direction of movement
- A Swedish wheel has less resistance in one additional direction
- A spherical wheel is truly omnidirectional with same low resistance in all directions and can spin in any direction
- Actuating a spherical wheel is more complex that operating a standard or Swedish wheel



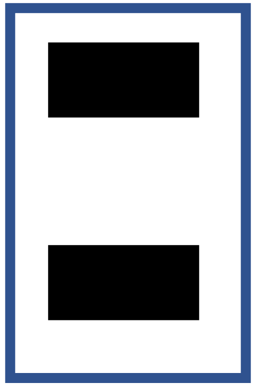
Design Space - Wheel Geometry

- Choice of wheel types and choice of wheel arrangement/geometry is tightly coupled
- Depending on the application, the number of wheels to be used and its configuration need to be determined
- Different wheel configurations are possible for vehicles with different number of wheels
- We will examine configurations for 2, 3, 4 and 6 wheeled systems

Wheel Geometry – 2 wheels

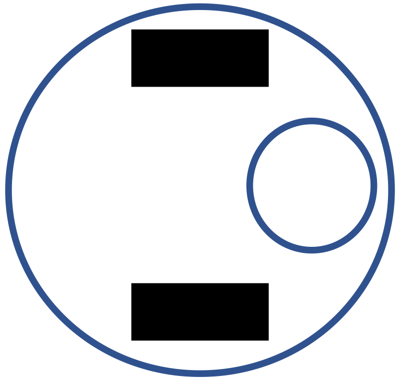
1) One steering wheel in the front, one traction wheel in the rear. E.g. bicycle, motorcycle

2) Two-wheeled differential drive with center-of-mass below the axle.

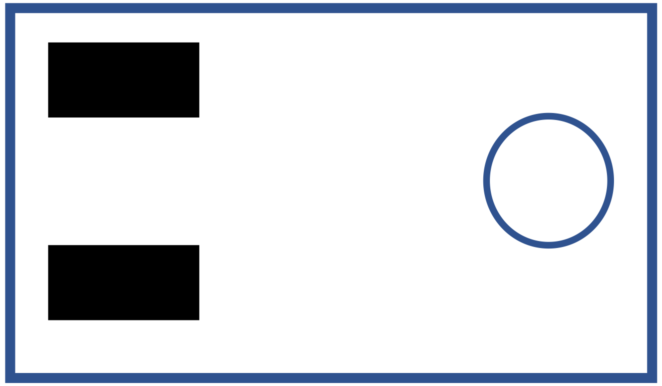


Wheel Geometry – 3 wheels

1) Two-wheeled centered differential drive with third point of contact

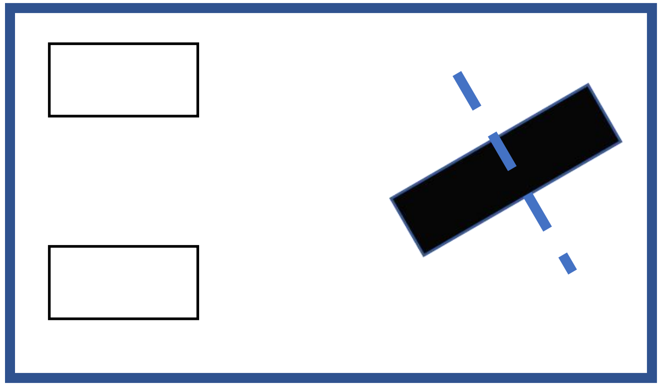


2) Two-wheeled differential drive in the rear or front and one passive omnidirectional wheel at the other end

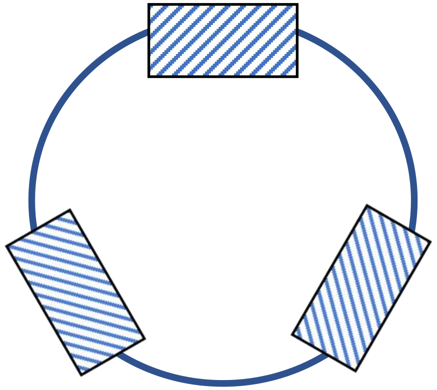


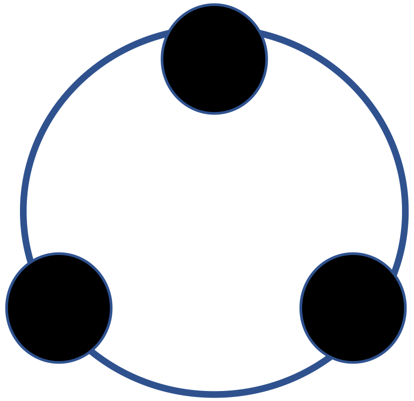
Wheel Geometry – 3 wheels

3) Two free wheels in rear, one steered traction wheel in front



4) Three motorized Swedish or spherical wheels arranged in a triangle configuration providing omnidirectional motion

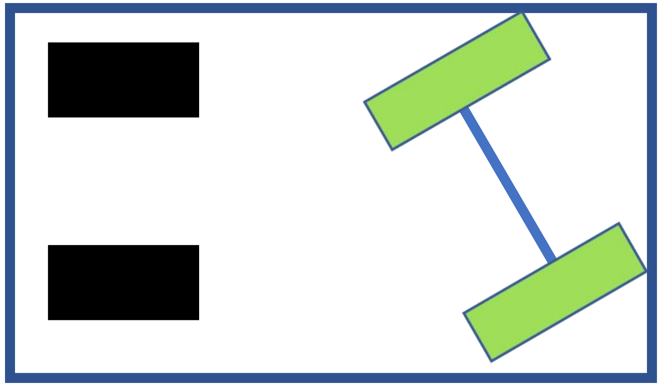




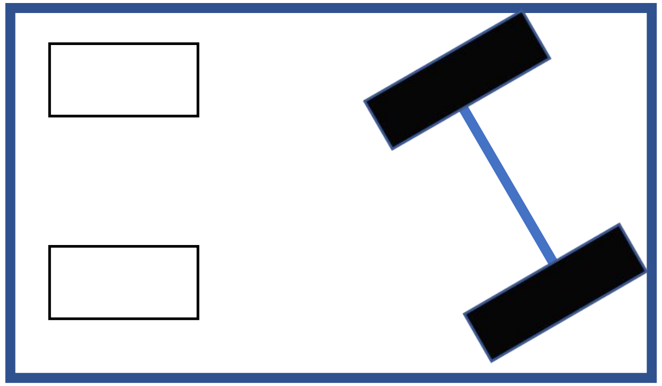
5) Synchro Drive

Wheel Geometry – 4 wheels

1) Two motorized wheels in the rear, two steered wheels in the front. E.g. car with rear-wheel drive

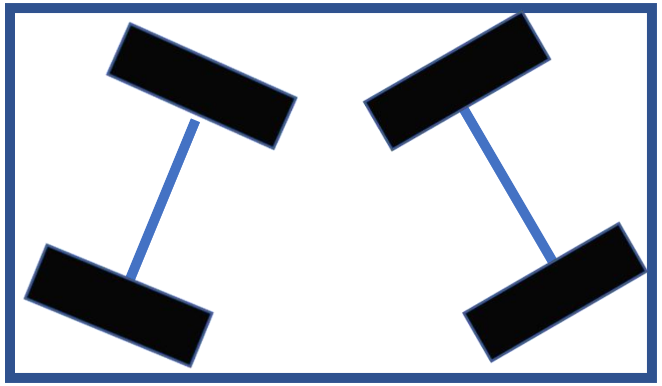


2) Two motorized and steered wheels in the front, two free wheels in the rear. E.g. car with front wheel drive

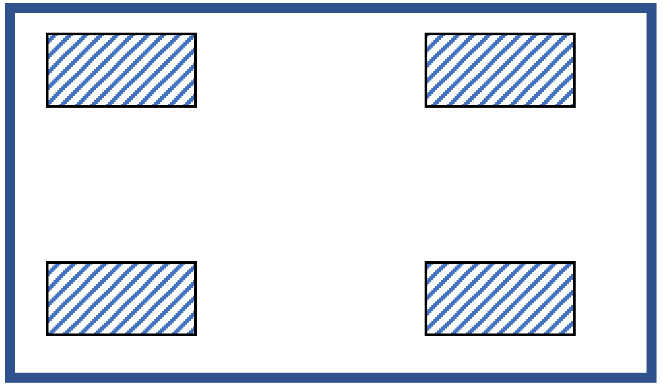


Wheel Geometry – 4 wheels

3) Four steered and motorized wheels

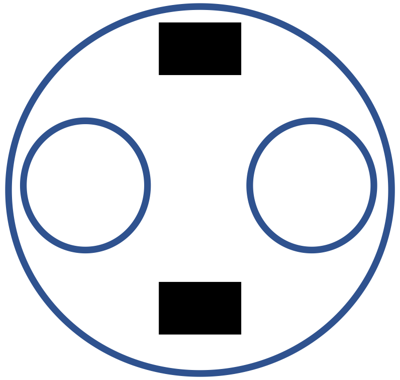


4) Four omnidirectional wheels



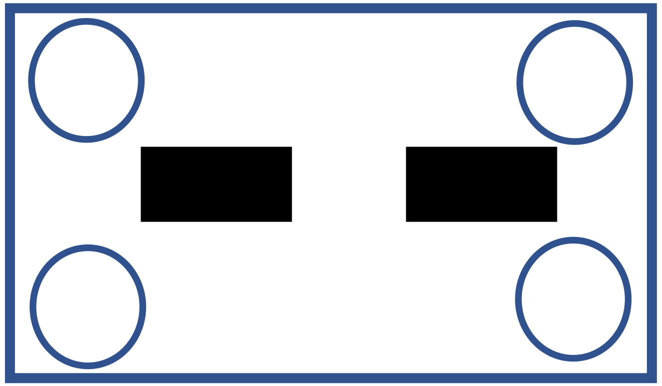
Wheel Geometry – 4 wheels

5) Two-wheel differential drive with two additional points of contact

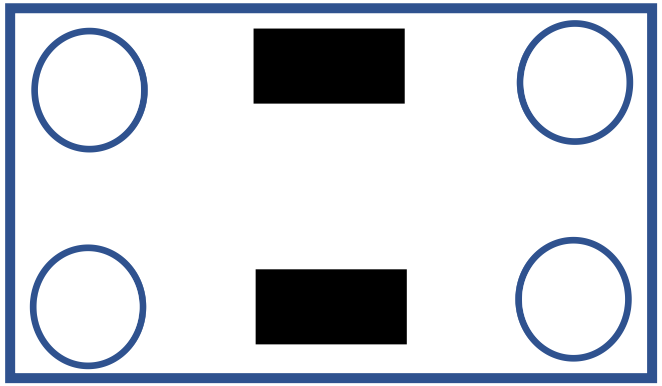


Wheel Geometry – 6 wheels

1) Two motorized and steered wheels aligned in center, omnidirectional wheels at corner

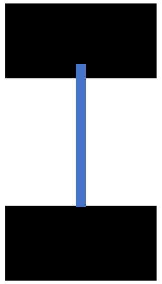
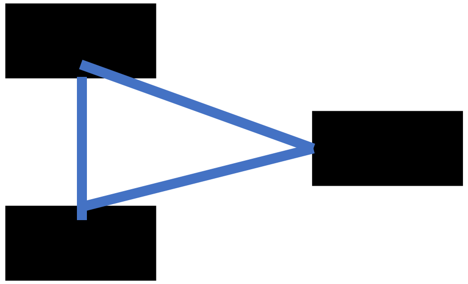


2) Two differential drive wheel in center, omnidirectional wheels at corner



Design Space - Stability

1) Minimum number of wheels required for static stability is 2
2) For a two-wheeled system, the centre of mass needs to fall below the wheel axle
3) Conventionally, static stability requires a minimum of 3 wheels and centre of mass needs to fall within the triangle formed by contact points

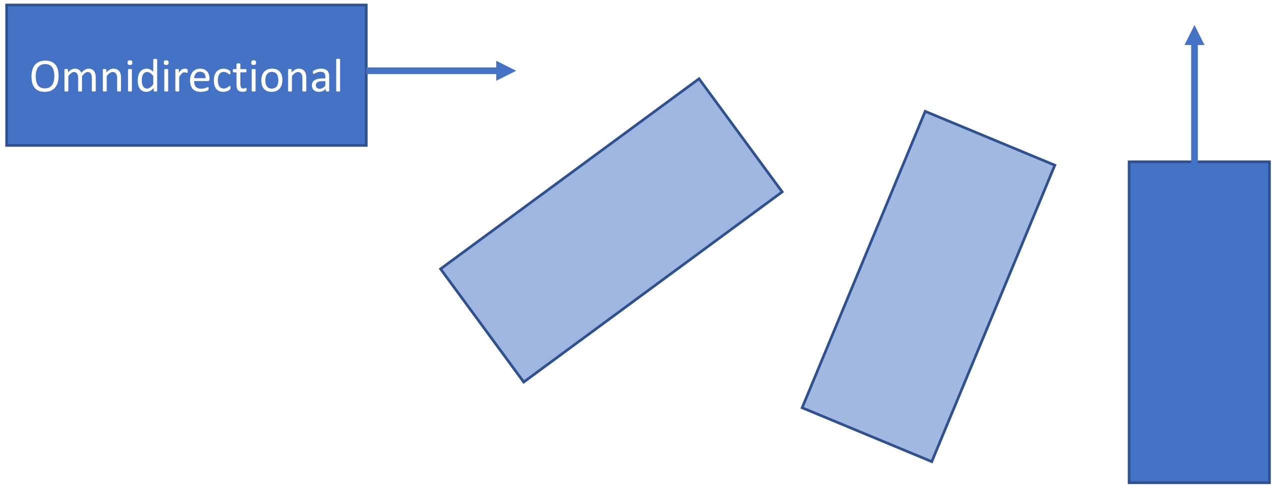
Design Space - Maneuverability

1) The level of maneuverability that a robot has indicates how easily it can move in any direction at any time, regardless of its current state
2) Higher levels of maneuverability requires that wheels can move in more than just one direction
3) A robot made with omnidirectional wheels has a higher level of maneuverability in comparison to robots with standard wheels alone or some other configurations

Design Space - Maneuverability

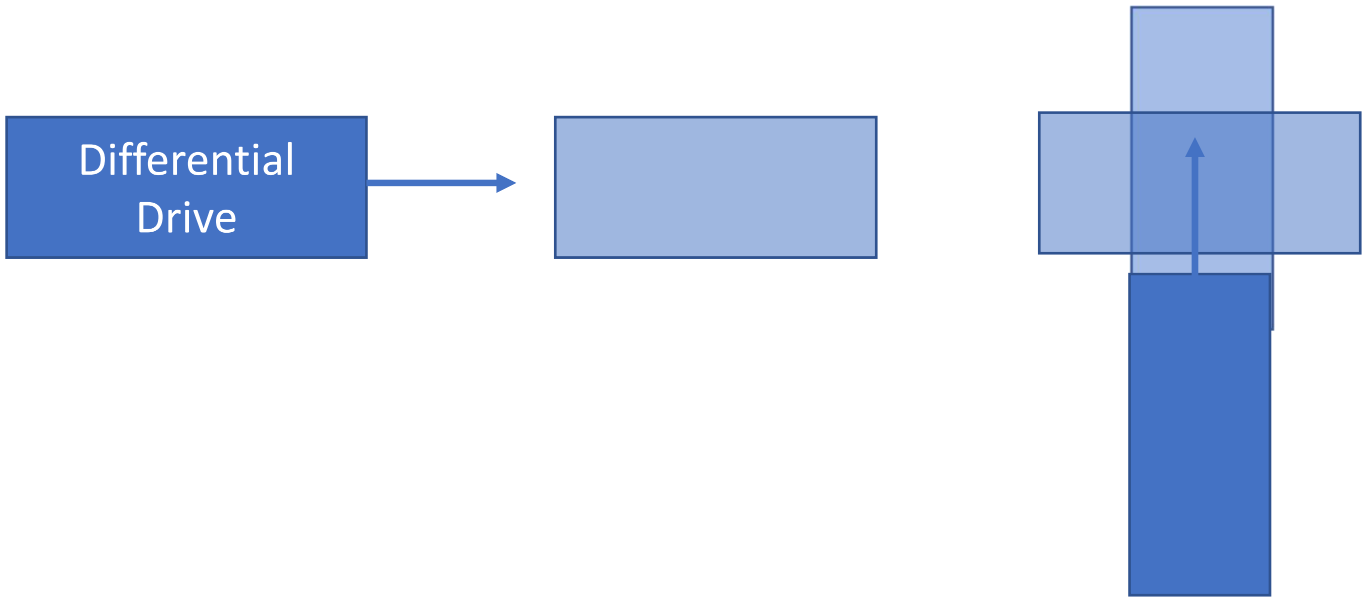
4) A robot with omnidirectional wheels can translate and rotate in any direction at any given point of time

Compare the movements required of an omnidirectional robot and a differential drive robot to reach a goal point



Design Space - Maneuverability

Differential drive robot to reach a goal point



Independent translation and rotation is possible in Omnidirectional robots, but not in differential drive

Design Space - Controllability

1) There is an inverse correlation between maneuverability and controllability.
2) An omnidirectional robot is highly maneuverable, but it requires some complexity in processing to convert desired rotational and translational velocities to wheel commands
3) Omnidirectional wheels using Swedish or Spherical wheel are also more susceptible to slippage in difference directions due to more degrees of freedom, hence controlling needs to be tighter
4) The more the degrees of freedom, the more likely there is variability in different directions and lower controllability

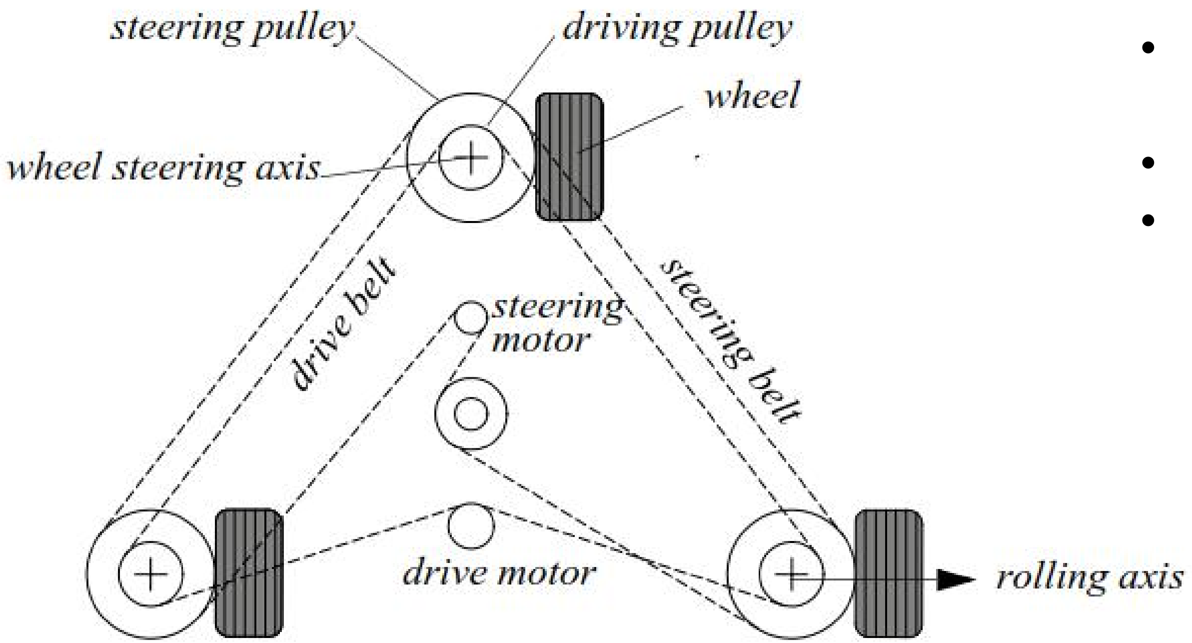
Design Space - Controllability

Suppose a vehicle needs to travel in the forward direction

- If the vehicles uses an Ackerman steering, if steerable wheels are locked, the drive wheels will move in sync and move the vehicle straight ahead
- If the vehicle uses differential drive, with independence control of two motors for the two wheels, the motors must operate exactly identically to ensure straight movement
- If the vehicle uses 4 Swedish wheels, all 4 wheels needs to move exactly at the same speed to ensure straight movement

Wheeled Locomotion – Case Studies

Synchrodrive



- There are 3 wheels which are driven and steered
- But it uses only two motors for this purpose
- The drive motor sets the speeds of all the three wheels together
- The steering motor makes all wheels rotate together about a vertical steering axis
- Vehicle is omnidirectional in nature
- **Examine its controllability and maneuverability**

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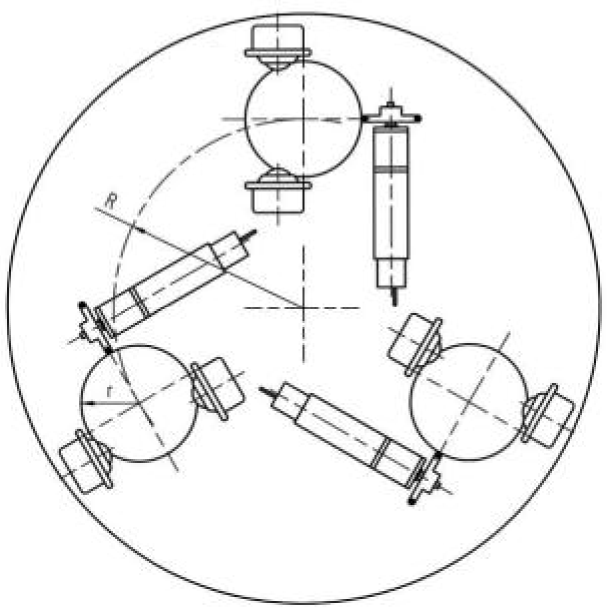
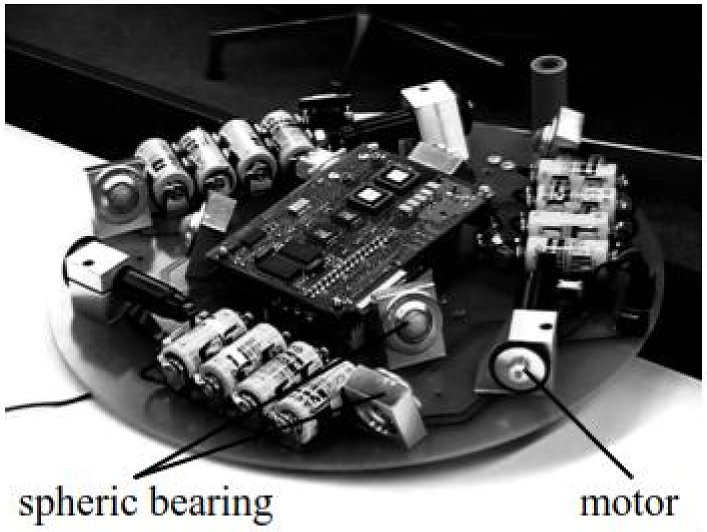
Wheeled Locomotion – Case Studies

Tribolo





Tribolo, Copyright EPFL
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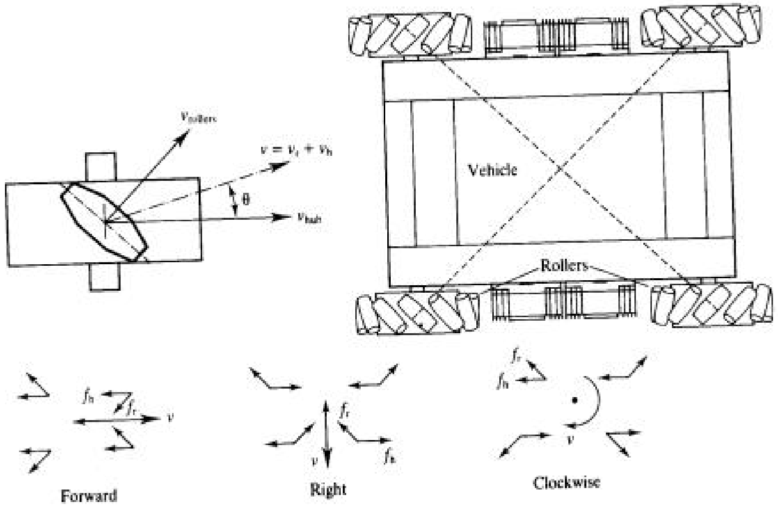
- Omnidirectional robot based on three wheels and three motors
- Two spherical bearings are used along with a motor drive to create three contact points for the spherical wheel
- Excellent maneuverability, but difficult to create round wheels with high friction coefficient

Wheeled Locomotion – Case Studies

Uranus Robot



Uranus Robot, Copyright Carnegie Mellon University
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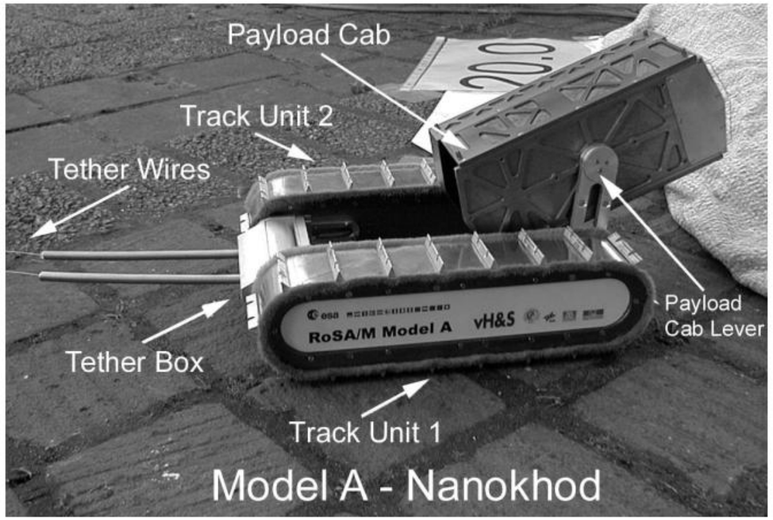
- Omnidirectional robot based on four 45° Swedish wheels each driven by separate motor
- By varying the direction of rotation and relative speeds of the 4 wheels, robot can move in x, y axes and rotate about z-axis
- When all 4 wheels spin forward/backward => robot goes forward/backward
- When one diagonal pair is spun in one direction and other pair spun in opposite direction => robot moves laterally

Wheeled Locomotion – Case Studies

Tracked slip/skid locomotion



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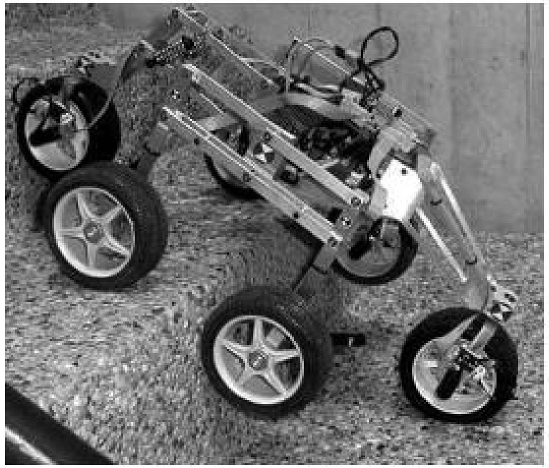
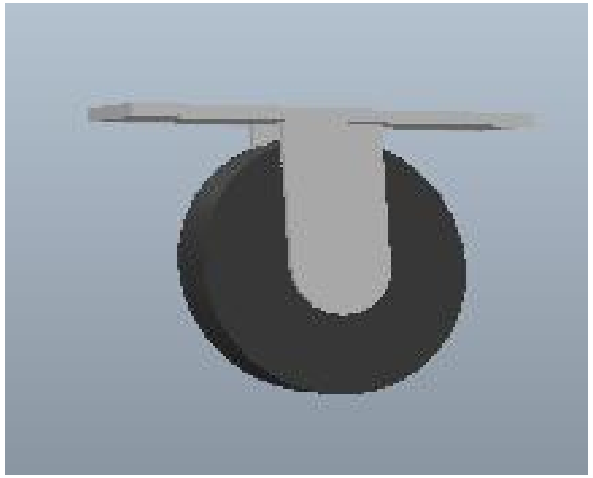


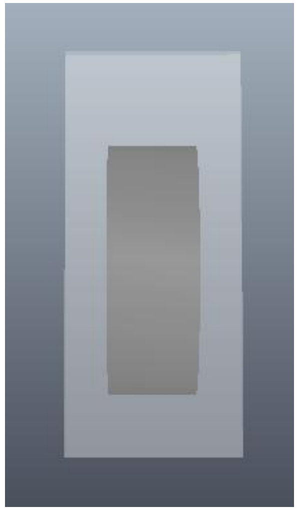
Mobile Robot Maneuverability

- Kinematic mobility of a robot is its ability to move directly in the environment
- Each wheel introduces some form of constraint in its motion
- One such constraint is the sliding constraint
- Each wheel will introduce its sliding constraint to the robot
- The overall maneuverability of a robot is also dependent on steering ability of the robot

Mobile Robot Maneuverability

- If we consider a standard wheel, it cannot slip in the lateral direction
- The fixed and steerable standard wheels both impose this constraint in motion
- Maneuverability depends on both mobility and steerability
- Constraints affect the degree of mobility



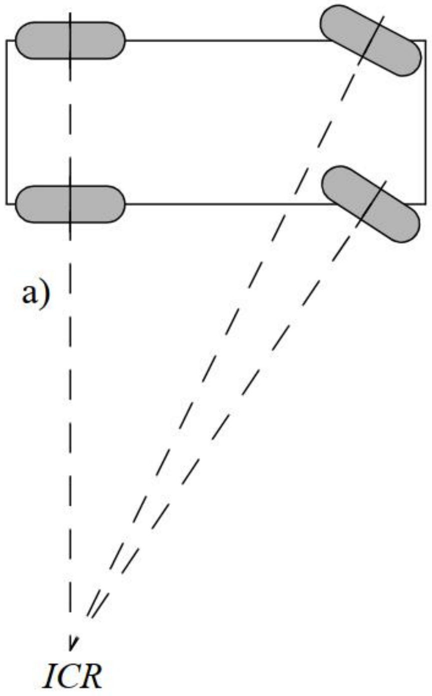


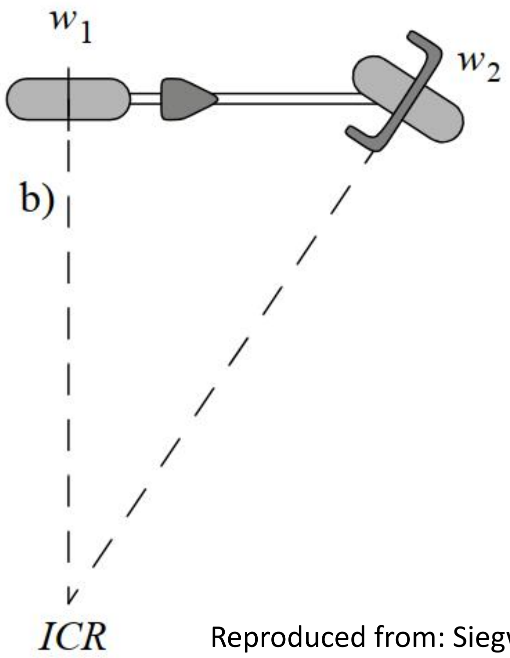
Mobile Robot Maneuverability

- The overall degrees of freedom that a robot can manipulate is called the *degree of maneuverability:* δ_M
- If the degree of mobility is given as δ_m and the degree of steerability is given as δ_s, then the degree of maneuverability is given as $\delta_M = \delta_m + \delta_s$
- Maneuverability captures degrees of freedom that robot manipulates through wheel velocity and through change in steering configuration

Mobile Robot – Degree of Mobility

- Zero-motion line for standard wheel based on sliding constraint
- Lines drawn for each intersects at Instantaneous center of rotation
- Even though many wheels may be present, constraints force vehicle to move in a circle with center at ICR





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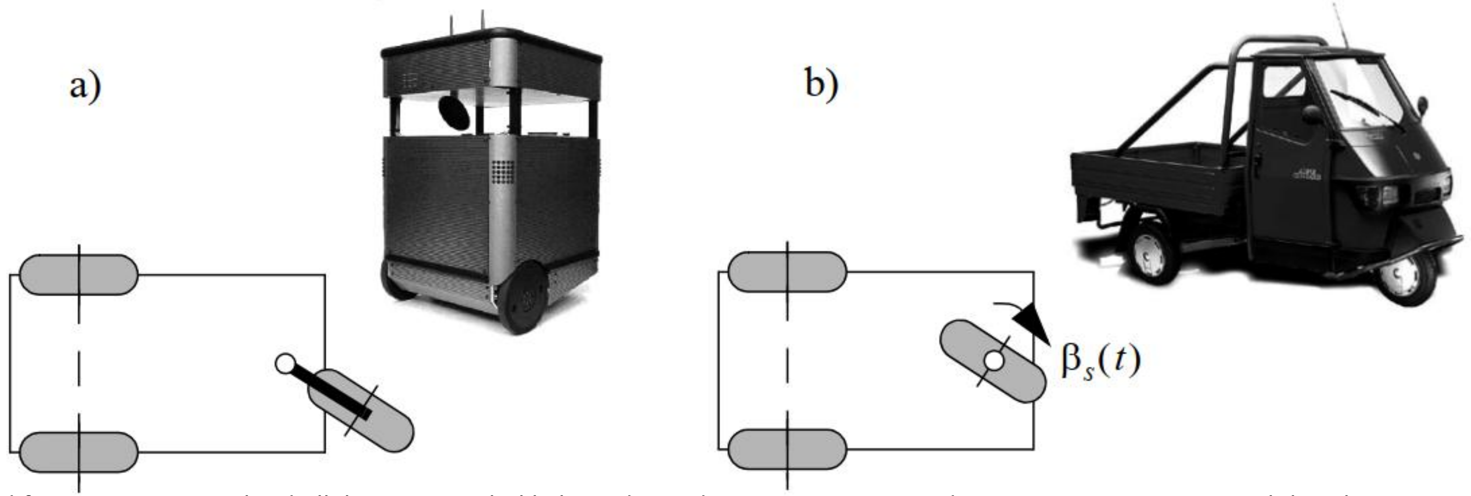
Mobile Robot – Degree of Mobility

- Differential drive robots have two wheels which have same line of zero-motion
- The second wheel does not impose any more additional kinematic constraints on robot motion
- Bicycle and differential drive robots have same number of wheels, but bicycle has two independent kinematic constraints while latter has only one



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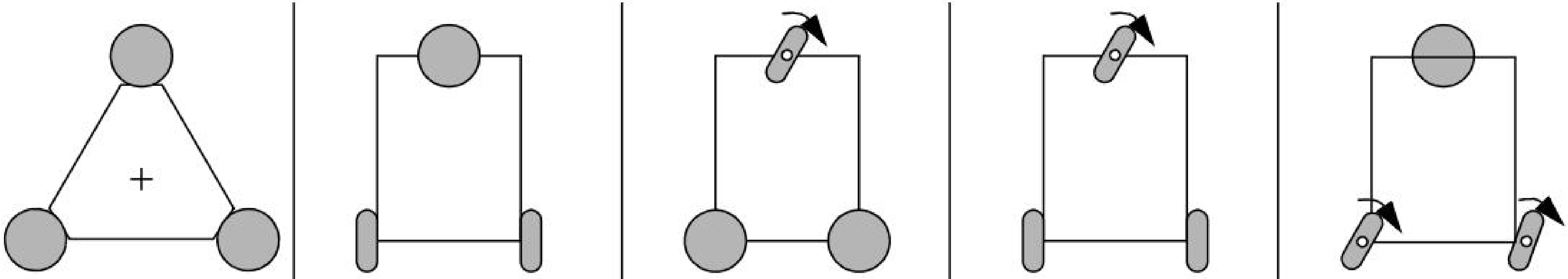
Mobile Robot – Degree of Steerability

- Steering also determines the eventual pose of the robot, by independently changing the angle of steering wheel



Omnidirectional	Differential	Omni-Steer	Tricycle	Two-Steer
$\delta_M = 3$	$\delta_M = 2$	$\delta_M = 3$	$\delta_M = 2$	$\delta_M = 3$
$\delta_m = 3$	$\delta_m = 2$	$\delta_m = 2$	$\delta_m = 1$	$\delta_m = 1$
$\delta_s = 0$	$\delta_s = 0$	$\delta_s = 1$	$\delta_s = 1$	$\delta_s = 2$

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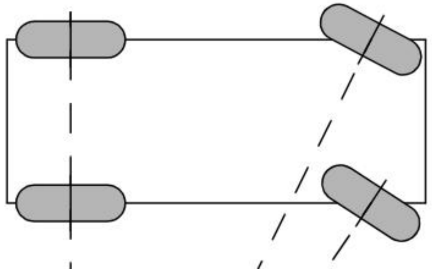
Mobile Robot – Workspace

- The robot is situated in some environment, how can it control degrees of freedom to position itself in the environment.
- Considering the car-type robot, δ_M =2, one for steering and other for actuation
- The workspace is concerned with the total degrees of freedom of the vehicle in its environment – which is 3, referring to x, y location and orientation angle
- The workspace of a mobile robot refers to the space of possible configurations it can take



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Mobile Robot – Motion Control

- Controlling the mobile robot so as to ensure it reaches specific pose configurations at specific time is an important task referred to as motion control
- This is necessary for executing trajectory following/tracking
- **Open-loop control:** If a robot needs to go from a start point to a goal point, divide the trajectory into segments of lines and curves and precompute a smooth trajectory (vehicle motor commands) based on the segments. In this case, position or velocity is not measured for feedback
- **Closed-loop control:** Divide the trajectory into a set of points and use sensor measurements to determine the positions of the robot and apply control to track the prescribed position