Locomotion Systems and Kinematics

Lecture 2 – Wednesday October 5, 2016

Most of the slides are based on Chapter 2 of R. Siegwart and I. Nourbakhsh. *Introduction to Autonomous Mobile Robots*. MIT Press, 2004.

Objectives

When you have finished this lecture you should be able to:

- Understand different locomotion systems of ground vehicles.
- Understand legged locomotion (walking robots) characteristics
- Recognize different mobility configurations of wheeled mobile robots (WMR) or driving robots.
- Understand the concepts of Holonomicity, Mobility, Steerability and Maneuverability.
- Understand how to drive kinematics equations for wheeled mobile robots.

Outline

- Robot Locomotion
- Legged Mobile Robots (Walking Machines)
- Leg Configurations and Stability
- Wheeled Mobile Robots (Driving Robots)
- Wheels Types
- Wheel Arrangements
- Mobility Configurations
- Mobility, Steerability and Maneuverability
- Mobile Robot Kinematics
- Differential Drive Kinematics
- Summary

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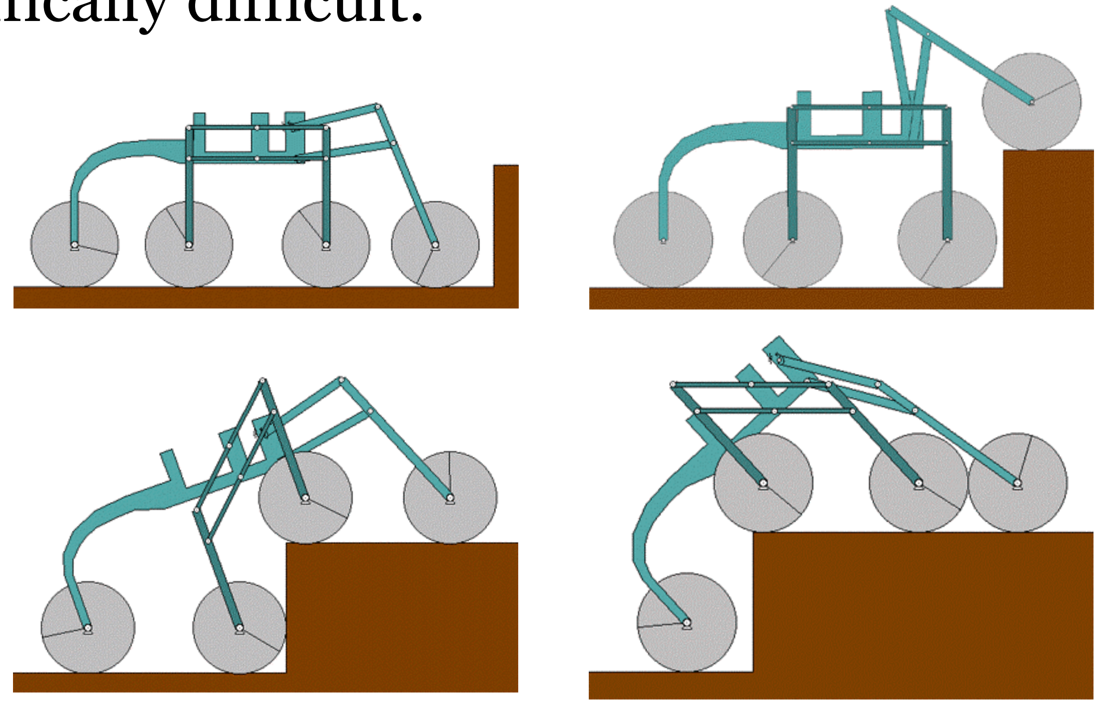
Robot Locomotion

- Robot locomotion is the study of how to design robot appendages and control mechanisms to allow robots to **move fluidly and efficiently**.
- What might seem a simple matter like negotiating stairs in practice has proved terrifically difficult.

Boston Dynamics BigDog Robot
The Army mule

Boston Dynamics
RHex



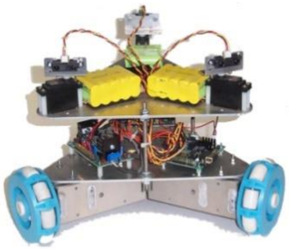
SHRIMP Robot, BlueBotics SA

Robot Locomotion

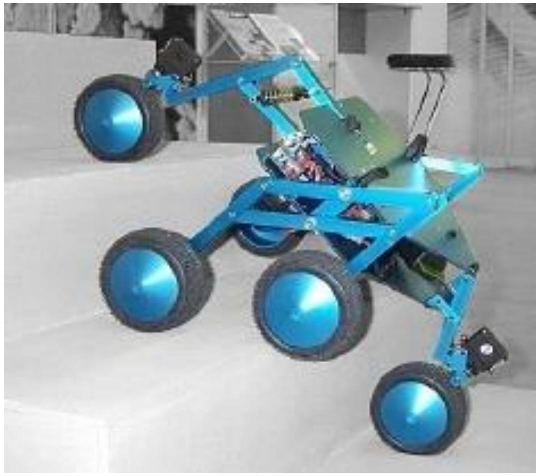
- In recent years, researchers have increasingly relied on motion capture studies of **insects and other organisms** to hone their designs.





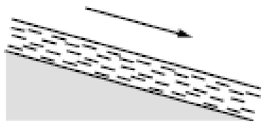
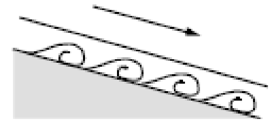
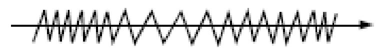
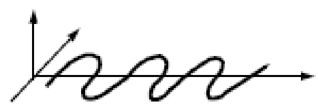
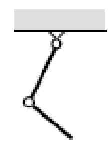
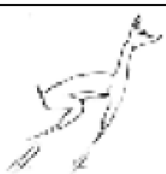
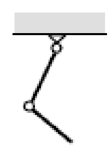
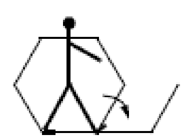




Robot Locomotion

- **Locomotion Mechanisms in Biological Systems**

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 

◇ Concepts found in nature **difficult** to imitate technically

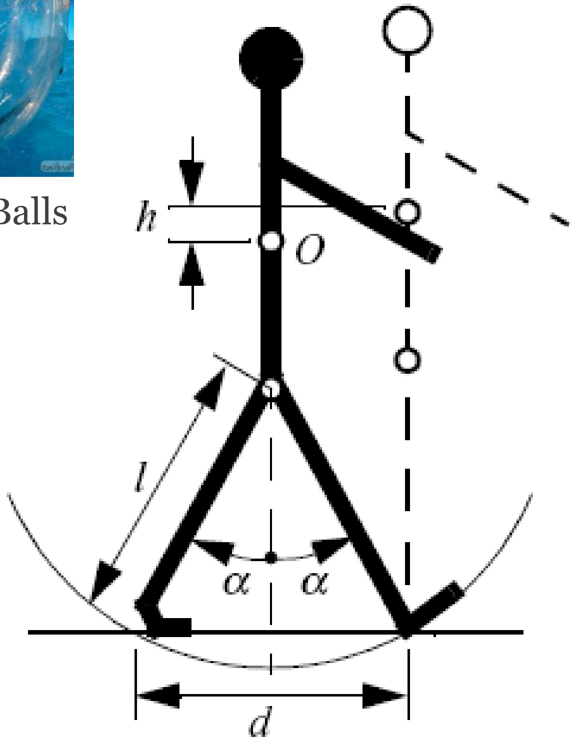
◇ Most technical systems use **wheels or caterpillars.**

◇ **Rolling** is most efficient, but not found in nature However, the movement of a **walking biped** is close to **rolling**.

Robot Locomotion

- **Walking of a Biped**
  - ◇ Biped walking mechanism
    - – not to far from real rolling.
    - – rolling of a polygon with side length equal to the length of the step.
    - – the smaller the step gets, the more the polygon tends to a circle (wheel).
  - ◇ However, fully rotating joint was not developed in nature.

Water Walking Balls



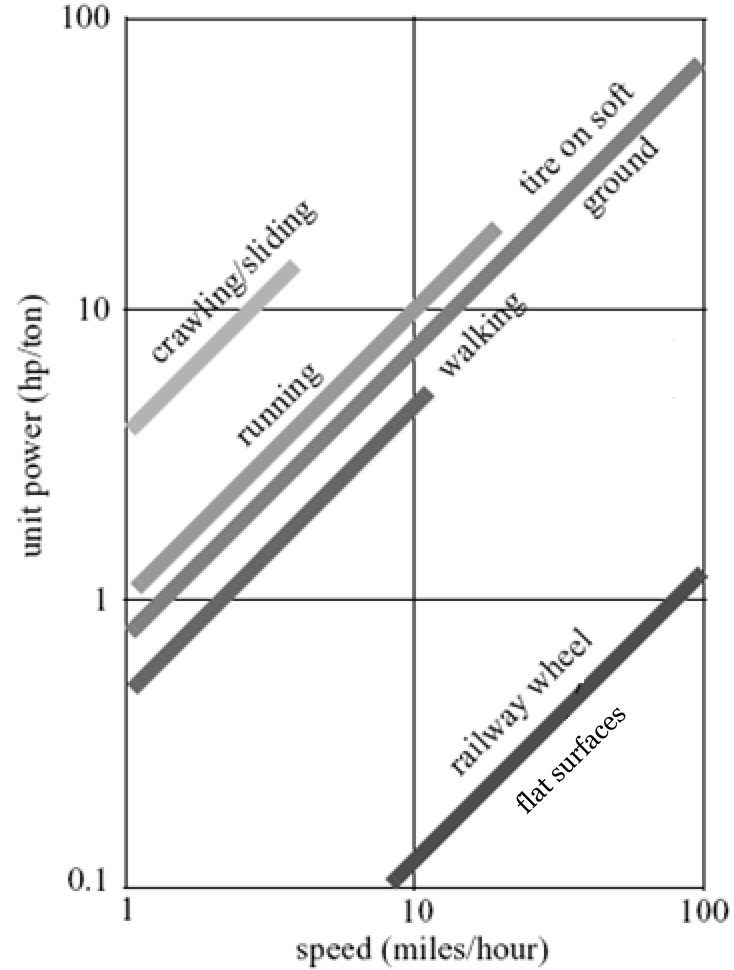
A biped walking system can be approximated by a rolling polygon, with sides equal in length *d* to the span of the step. As the step size decreases, the polygon approaches a circle or wheel with the radius *l*.

Robot Locomotion

- **Walking or rolling?**
  - ◇ **On flat surfaces**

    Wheeled locomotion is one to two orders of magnitude **more efficient than legged locomotion**.

    The **railway** is ideally engineered for wheeled locomotion because **rolling friction is minimized** on a hard and flat steel surface.



Specific power versus attainable speed of various locomotion mechanisms

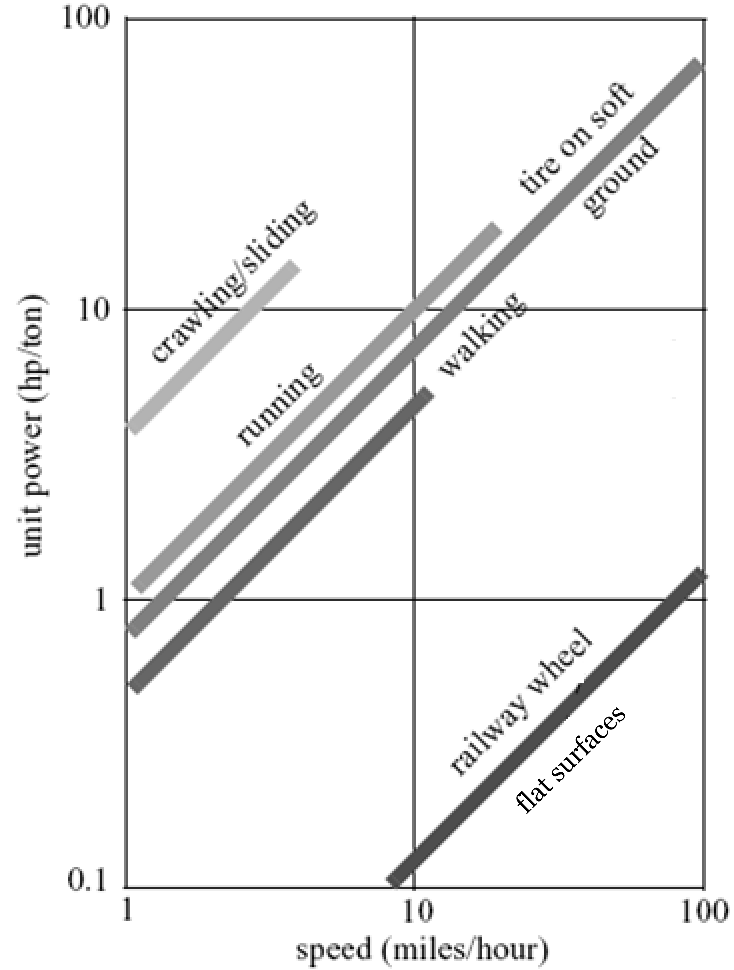
Source of Figure: D. J. Todd. *Walking Machines: An Introduction to Legged Robots*. Kogan Page Ltd, 1985.

Robot Locomotion

- **Walking or rolling?**
  - ◊ **On soft surfaces**

    Wheeled locomotion accumulates inefficiencies due to rolling **friction** whereas **legged locomotion** suffers **much less** because it consists only of point contacts with the ground.

    This is demonstrated in the figure by the dramatic loss of efficiency in the case of a tire on soft ground.



Nature favors legged locomotion, since locomotion systems in nature must operate on rough and unstructured terrain.

Robot Locomotion

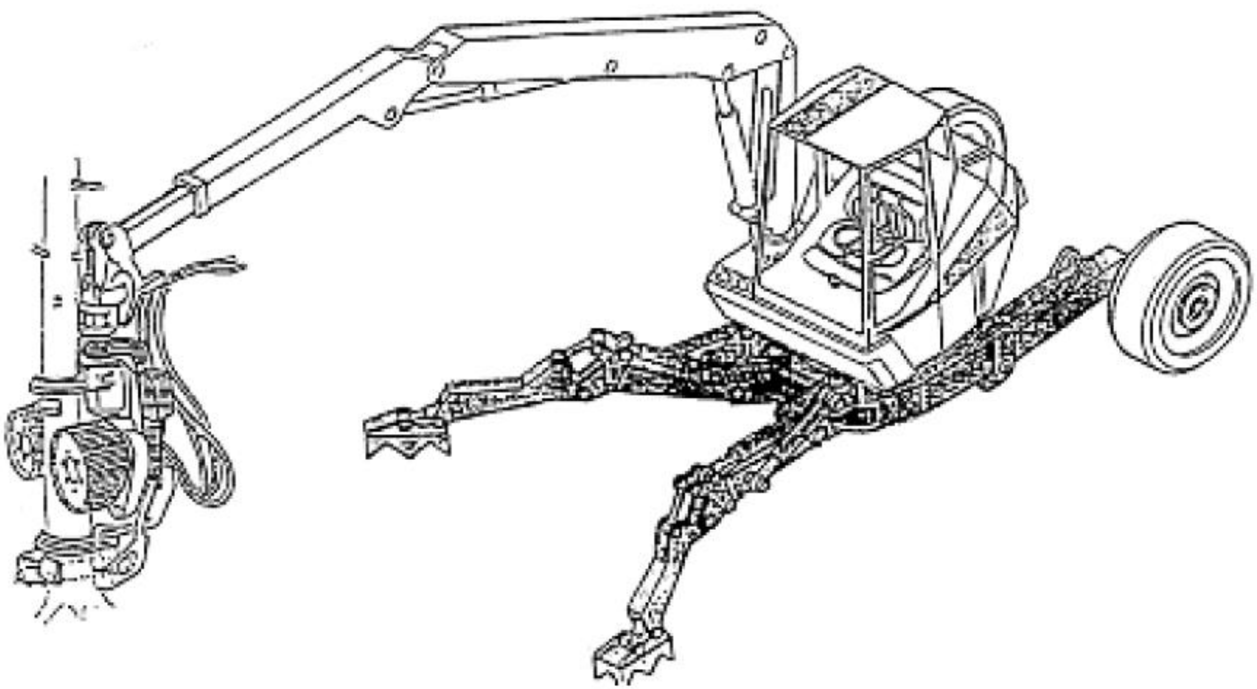
- **Walking or rolling?**
  - ◊ Mobile robots generally locomote either using:
    - – **Wheeled mechanisms**, a well-known human technology for vehicles,

or

- – using a small number of **articulated legs**, the simplest of the biological approaches to locomotion.

Robot Locomotion

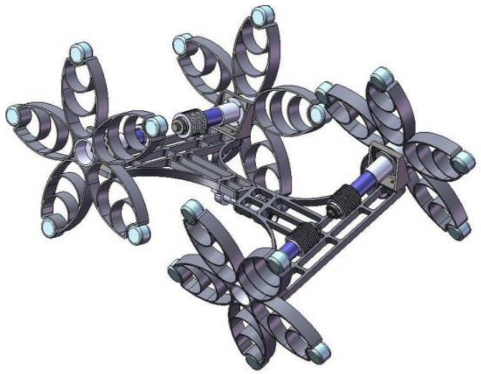
- **Walking or rolling?**
  - ◊ Recently, for more natural outdoor environments, there has been some progress toward **hybrid** and legged industrial robots such as the forestry robot.



RoboTrac, a hybrid wheel-leg vehicle for rough terrain

Robot Locomotion

- **Walking or rolling?**



Asguard, hybrid locomotion

Ref.: Markus Eich, Felix Grimminger, Stefan Bosse, Dirk Spenneberg, Frank Kirchner, Asguard: A Hybrid -Wheel Security and SAR-Robot Using Bio-Inspired Locomotion for Rough Terrain, Robotics Lab, German Research Center for Artifcial Intelligence (DFKI). http://robotik.dfki-bremen.de/en/research/robot-systems/asguard-i-1.html

Robot Locomotion

- **Walking or rolling?**

Bicycling robot muRata Boy

http://www.murata.com/corporate/boy_girl/boy/index.html

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Legged Mobile Robots (Walking Machines)

Legged locomotion is characterized by a series of point contacts between the robot and the ground.

Toyota's One-Legged Robot (Uniped)

Honda Asimo (Biped)

WowWee Robotics (Tripod or three-leeged robot)

Pentapod Robot (5-Legged Robot)

Sony Aibo (Quadruped)

Hexapod (6-Legged Robot)

Legged Mobile Robots (Walking Machines)

- **Advantages of legged locomotion:**
  - ◇ **Adaptability and maneuverability in rough terrain:** because only a set of point contacts is required, the quality of the ground between those points does not matter so long as the robot can maintain adequate ground clearance. In addition, a walking robot is capable of crossing a hole or chasm so long as its reach exceeds the width of the hole.
  - ◇ **Potential to manipulate objects in the environment with great skill:** an excellent insect example, the dung beetle, is capable of rolling a ball while locomoting by way of its dexterous front legs.

Legged Mobile Robots (Walking Machines)

- **Disadvantages of legged locomotion:**
  - ◇ **Power:** the leg, which may include **several degrees of freedom**, must be capable of sustaining part of the robot's total weight, and in many robots must be capable of **lifting and lowering** the robot.
  - ◇ **Mechanical Complexity:** high maneuverability will only be achieved if the legs have a sufficient number of degrees of freedom to impart forces in a number of different directions.

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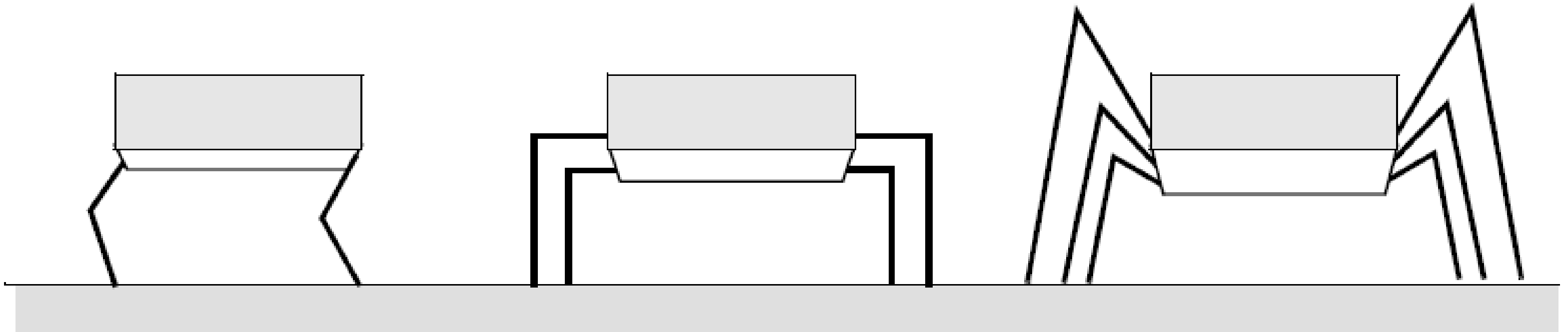
Leg Configurations and Stability



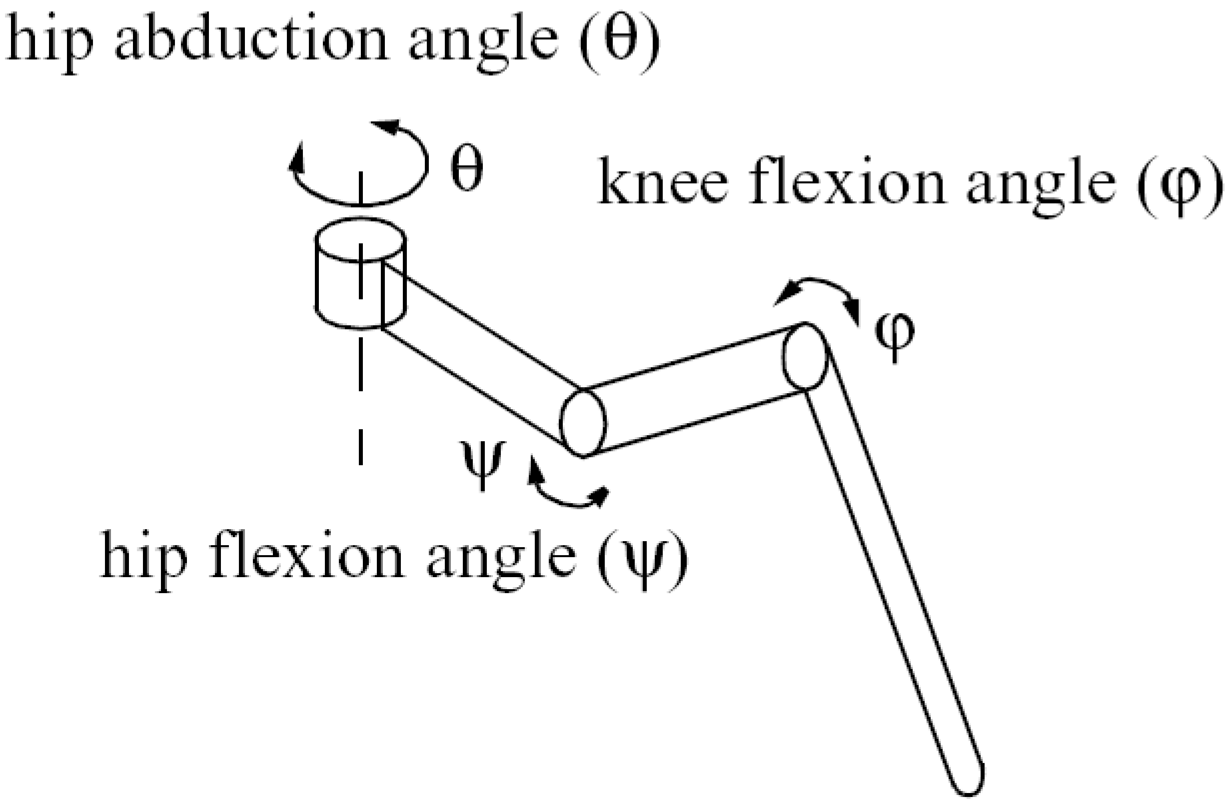
- Babies require months to stand and walk, and even longer to learn to jump, run, and stand on one leg.
- The **fewer legs** the **more complicated** becomes locomotion.
- **Stability:** at least three legs are required for **static stability**.
- During walking some legs are lifted, thus loosing stability?
- For **static walking** at least 6 legs are required.

Leg Configurations and Stability

- **Degrees of Freedom (DOF)**
  - ◇ A minimum of **two DOF** is required to move a leg forward
    - – Lifting the leg
    - – Swinging it forward.
  - ◇ Three DOF for each leg in most cases for more complex maneuvers.

Leg Configurations and Stability

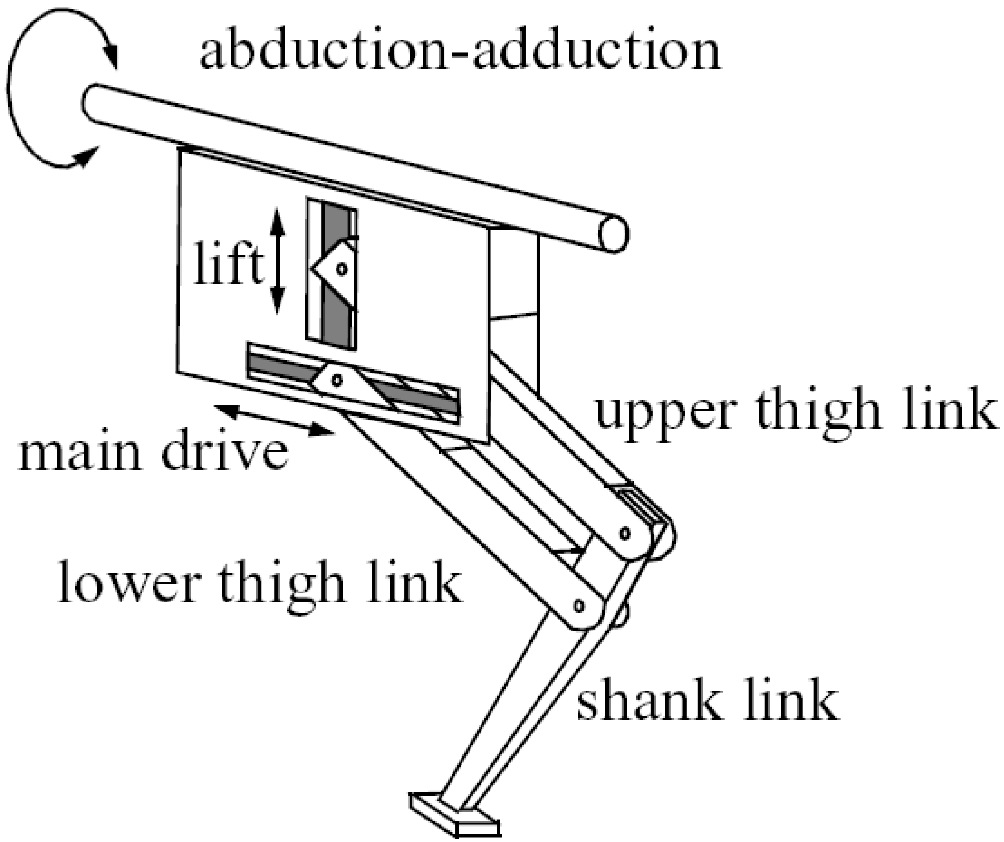
- **Degrees of Freedom (DOF)**



Example of a leg with three degrees of freedom.

Leg Configurations and Stability

- **Degrees of Freedom (DOF)**



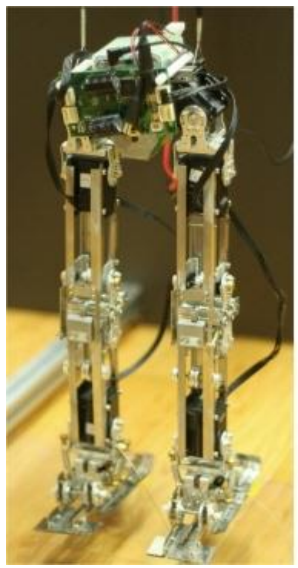
Example of a leg with three degrees of freedom.

Leg Configurations and Stability

- **Degrees of Freedom (DOF)**
  - ◇ In general, **adding degrees of freedom** to a robot leg **increases the maneuverability** of the robot, both augmenting the range of terrains on which it can travel and the ability of the robot to travel with **a variety of gaits**.
  - ◇ The primary **disadvantages** of additional joints and actuators are, of course, **energy, control, and mass**.
  - ◇ Additional actuators require energy and control, and they also add to leg mass, further increasing power and load requirements on existing actuators.

Leg Configurations and Stability

- **Number of Possible Gaits**
  - ◇ The gait is characterized as the **sequence of lift and release** events of the individual legs.




– it depends on the number of legs.

– the number of possible events N for a walking machine with k legs is:

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

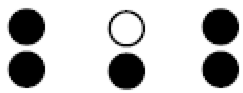
Leg Configurations and Stability

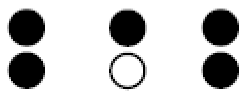
- **The number of possible gaits**
  - ◇ With two legs (biped) one can have four different **states**:
    1. Both legs down
    2. Right leg down, left leg up
    3. Right leg up, left leg down
    4. Both leg up
  - ◇ A distinct **event sequence** can be considered as a change from **one state to another and back**.

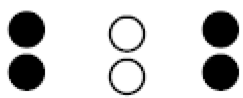
Leg Configurations and Stability

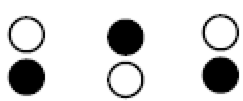
- **The number of possible gaits**
  - ◇ The number of possible events N is:

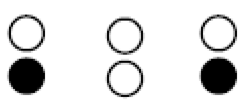
$$N = (2k-1)! = 3! = 3 \cdot 2 \cdot 1 = 6$$

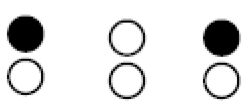
1→2 →1  → turning on right leg

1→3 →1  → turning on left leg

1→4 →1  → hopping with two legs

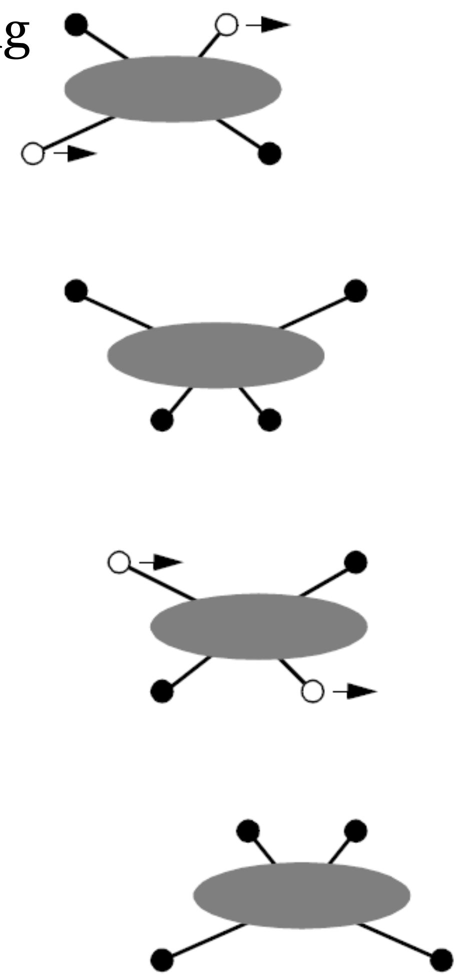
2→3 →2  → walking running

2→4 →2  → hopping right leg

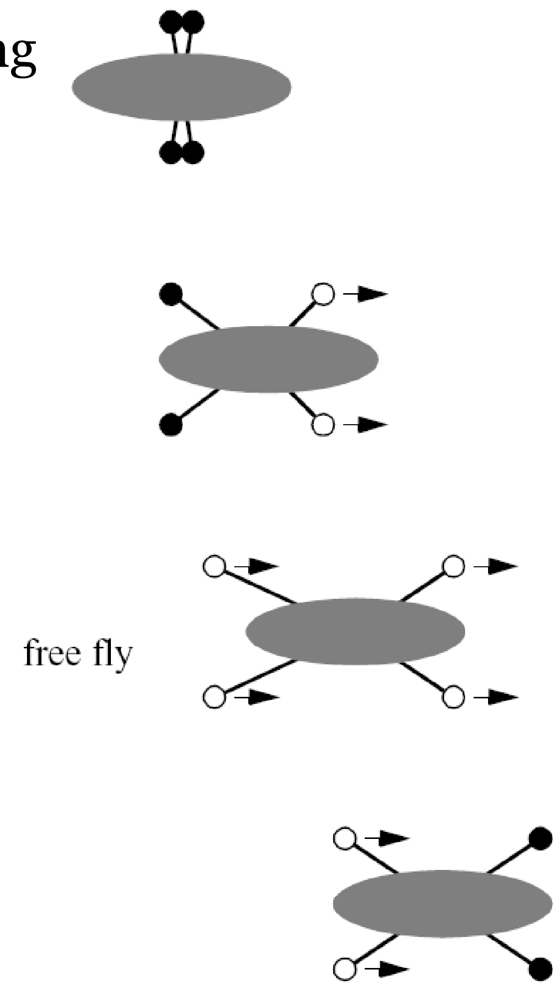
3→4 →3  → hopping left leg

Leg Configurations and Stability

- **The number of possible gaits**
  - ◇ For a robot with 4 legs (Quadruped): $N = 7! = 5040$
    - ▪ Changeover walking



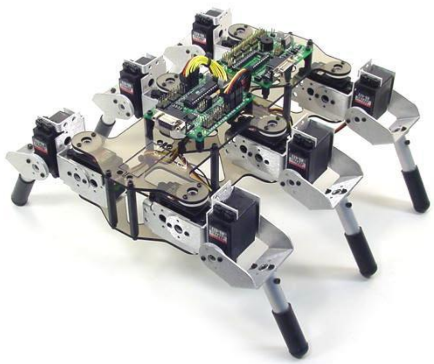
    - ▪ Galloping



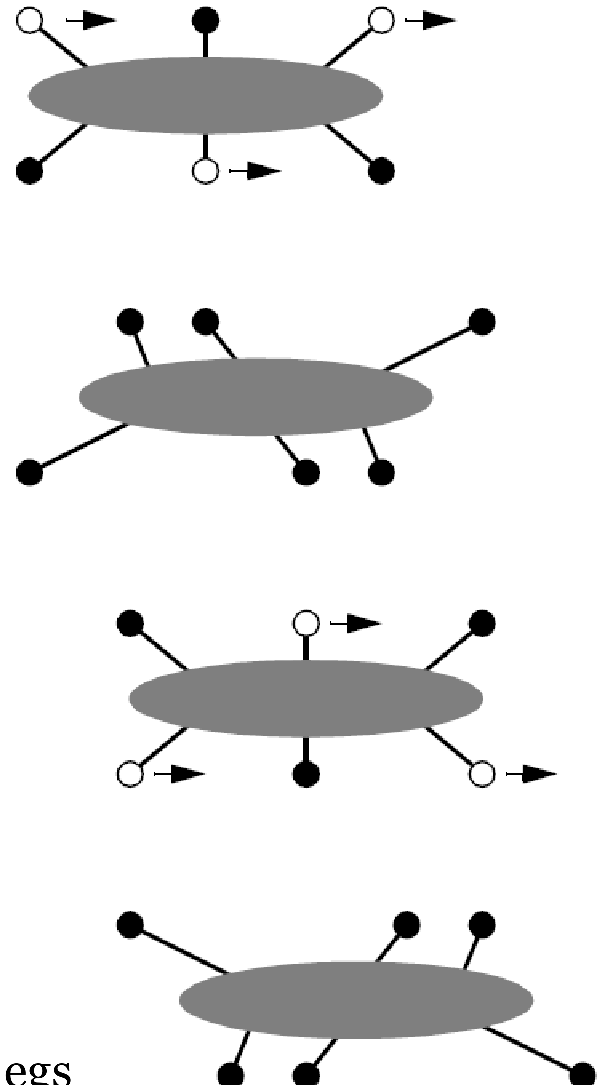
Leg Configurations and Stability

- **The number of possible gaits**
  - ◇ For a robot with 6 legs (hexapod):

$$N = 11! = 39{,}916{,}800$$



Hexapod



Most obvious gaits with 6 legs

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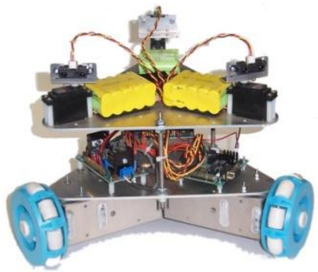
Wheeled Mobile Robots

- Wheels are the most appropriate solution for most applications
- **Three wheels** are sufficient and to guarantee stability.
- With more than three wheels a **flexible suspension** is required.

- Selection of wheels depends on the application.



- **Bigger wheels** allow overcoming **higher obstacles** but they require higher torque or reductions in the gear box.

- Combining **actuation and steering** on one wheel makes the design **complex** and adds additional errors for odometry.

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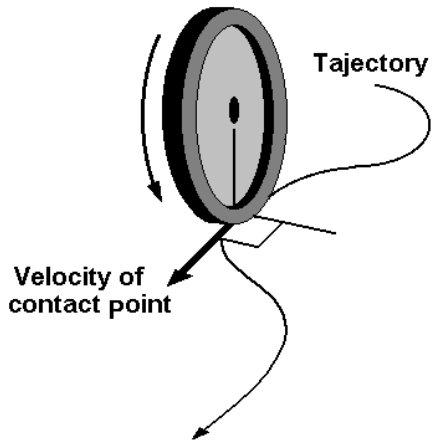
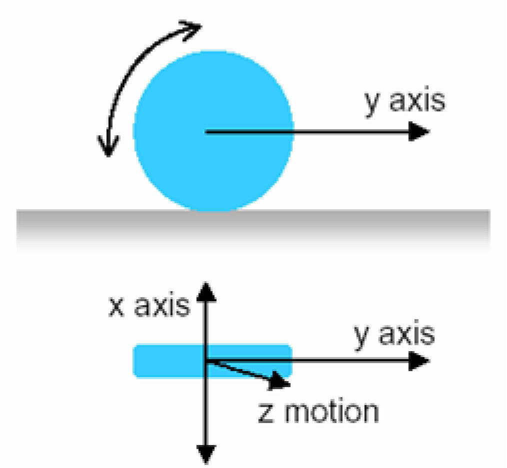
Wheels Types

- **Wheels: Idealized Rolling Wheel**



Non-slipping and pure rolling



Lateral slip

Assumptions:

- No slip occurs in the orthogonal direction of rolling (non-slipping).
- No translation slip occurs between the wheel and the floor (pure rolling).
- At most one steering link per wheel with the steering axis perpendicular to the floor.

Wheel parameters:

- r = wheel radius
- v = wheel linear velocity
- ω = wheel angular velocity
- t = steering velocity

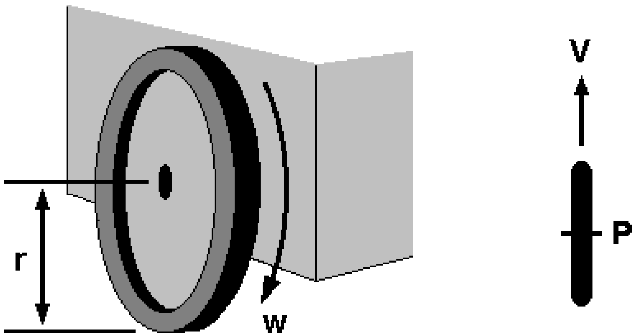
Source: Prof. Jizhong Xiao, "Mobile Robot Locomotion," Department of Electrical Engineering City College of New York.

Wheels Types

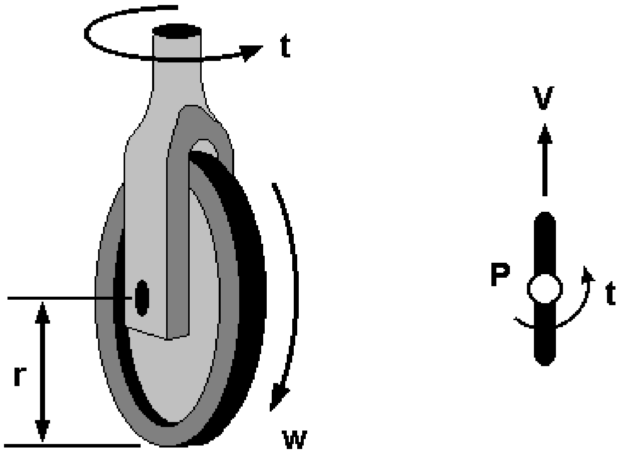
- **Wheels: Standard Wheel**

Two degrees of freedom; rotation around the (motorized) wheel axle and the contact point.

Fixed wheel



Centered orientable wheel

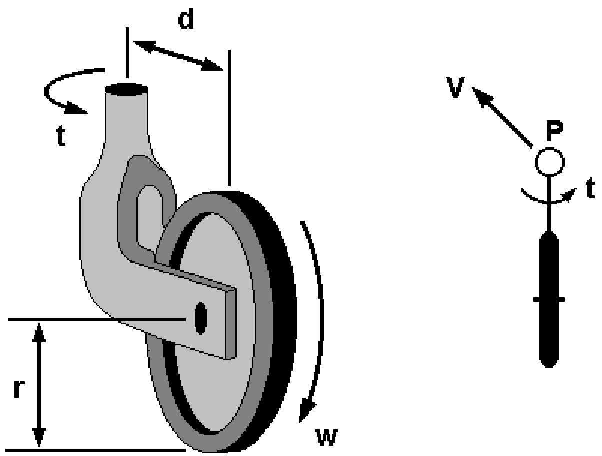


Wheels Types

- **Wheels: Castor Wheel**

Three degrees of freedom; rotation around the wheel axle, the contact point and the castor axle.

Off-centered orientable wheel
(Castor wheel)



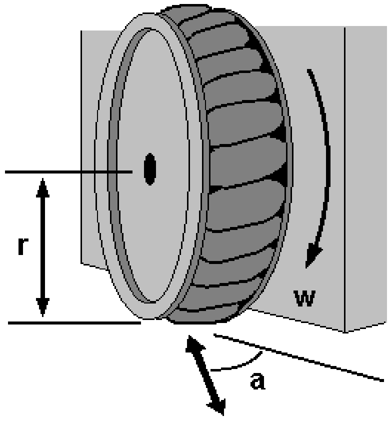
Swivel wheels

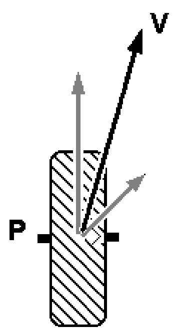
Wheels Types

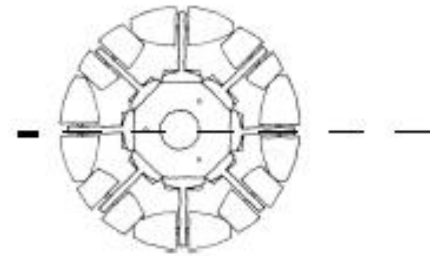
- **Wheels: Swedish Wheel**

Three degrees of freedom; rotation around the (motorized) wheel axle, around the rollers and around the contact point.

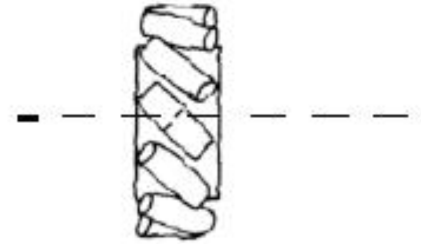
Swedish wheel: omnidirectional property







swedish 90°



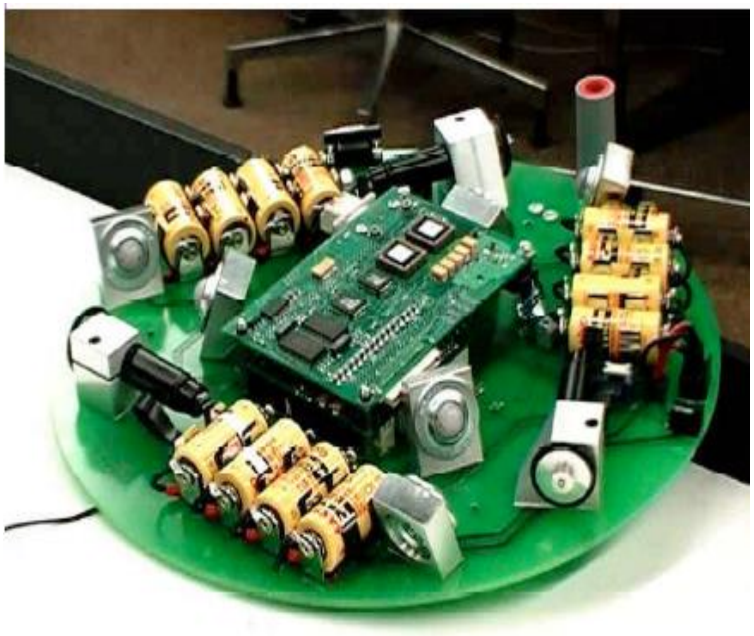
swedish 45°

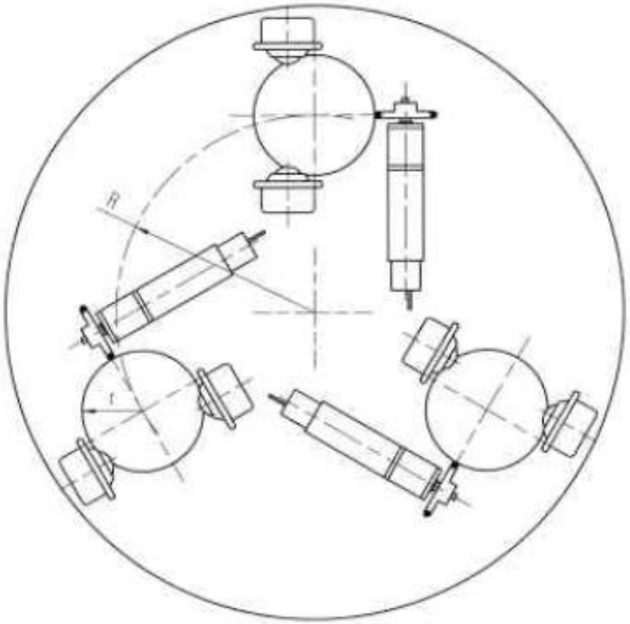
Wheels Types

- **Wheels: Ball or Spherical Wheel**

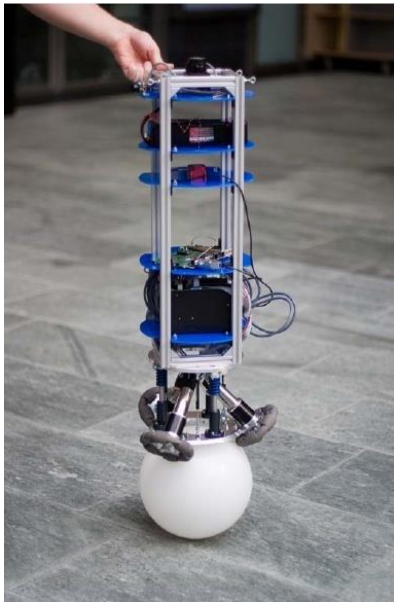
Suspension technically not solved.

Tribolo, Omnidirectional Drive with 3 Spheric Wheels





Omni Wheel



Ball Wheel Caster with Swivel Plate

Source: R. Siegwart and I. Nourbakhsh. *Introduction to Autonomous Mobile Robots*. Chapter 2, MIT Press, 2004.

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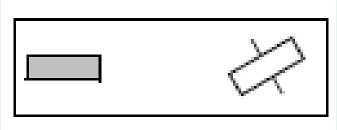
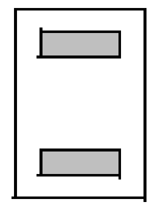
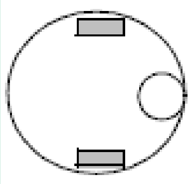
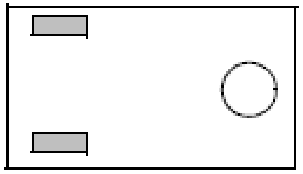
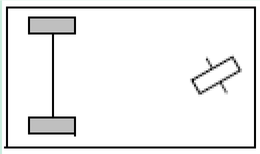
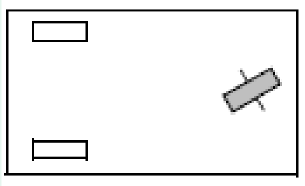
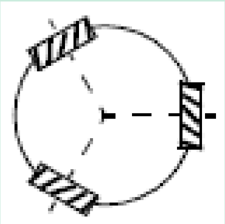
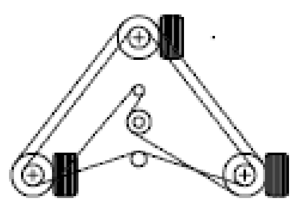
- Mobile Robot Kinematics
- Differential Drive Kinematics
- Summary

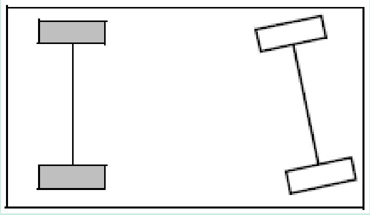
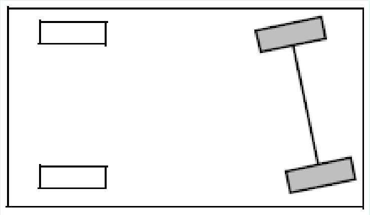
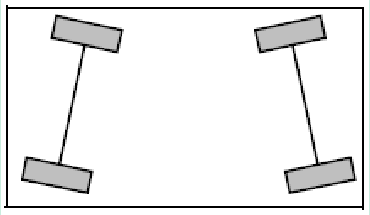
Wheel Arrangements

# of wheels	Arrangement	Description	Typical examples
2		One steering wheel in the front, one traction wheel in the rear	Bicycle, motorcycle
2		Two-wheel differential drive with the center of mass (COM) below the axle	Cye personal robot 
3		Two-wheel centered differential drive with a third point of contact.	Nomad Scout, smartRob EPFL
3		Two independently driven wheels in the rear/front, 1 unpowered omnidirectional wheel in the front/rear	Many indoor robots, including the EPFL robots Pygmalion and Alice

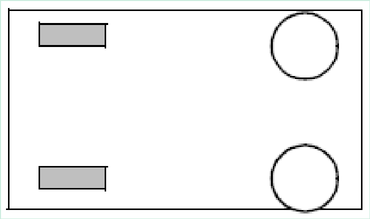
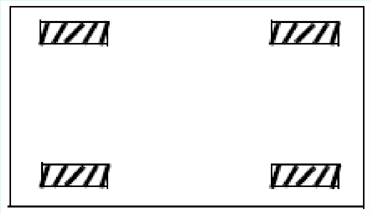
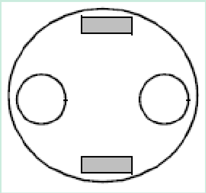
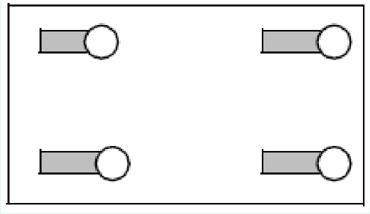
Wheel Arrangements

# of wheels	Arrangement	Description	Typical examples
3		Two connected traction wheels (differential) in rear, 1 steered free wheel in front	Piaggio minitrucks
3		Two free wheels in rear, 1 steered traction wheel in front	Neptune (Carnegie Mellon University), Hero-1
3		Three motorized Swedish or spherical wheels arranged in a triangle; omnidirectional movement is possible	Stanford wheel Tribolo EPFL, Palm Pilot Robot Kit (CMU), **Robotino**
3		Three synchronously motorized and steered wheels; the orientation is not controllable	Three synchronously motorized and steered wheels; the orientation is not controllable

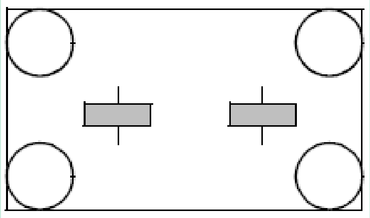
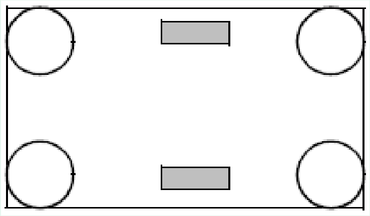
Wheel Arrangements

# of wheels	Arrangement	Description	Typical examples
4		Two motorized wheels in the rear, 2 steered wheels in the front; steering has to be different for the 2 wheels to avoid slipping/skidding.	Car with rear-wheel drive
4		Two motorized and steered wheels in the front, 2 free wheels in the rear; steering has to be different for the 2 wheels to avoid slipping/skidding.	Car with front-wheel drive
4		Four steered and motorized wheels	Four-wheel drive, fourwheel steering Hyperion (CMU)

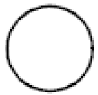
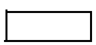
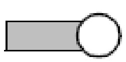
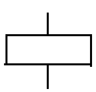
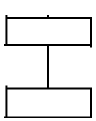
Wheel Arrangements

# of wheels	Arrangement	Description	Typical examples
4		Two traction wheels (differential) in rear/front, 2 omnidirectional wheels in the front/rear.	Charlie (DMT-EPFL)
4		Four omnidirectional wheels	Carnegie Mellon Uranus
4		Two-wheel differential drive with 2 additional points of contact	EPFL Khepera, Hyperbot Chip
4		Four motorized and steered castor wheels	Nomad XR4000

Wheel Arrangements

# of wheels	Arrangement	Description	Typical examples
6		Two motorized and steered wheels aligned in center, 1 omnidirectional wheel at each Corner.	First
6		Two traction wheels (differential) in center, 1 omnidirectional wheel at each corner	Terregator (Carnegie Mellon University)

Wheel Arrangements

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.

Outline

- Robot Locomotion
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- Leg Configurations and Stability
- Wheeled Mobile Robots (Driving Robots)
- Wheels Types
- Wheel Arrangements
- **Mobility Configurations**
- Mobility, Steerability and Maneuverability
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Mobility Configurations

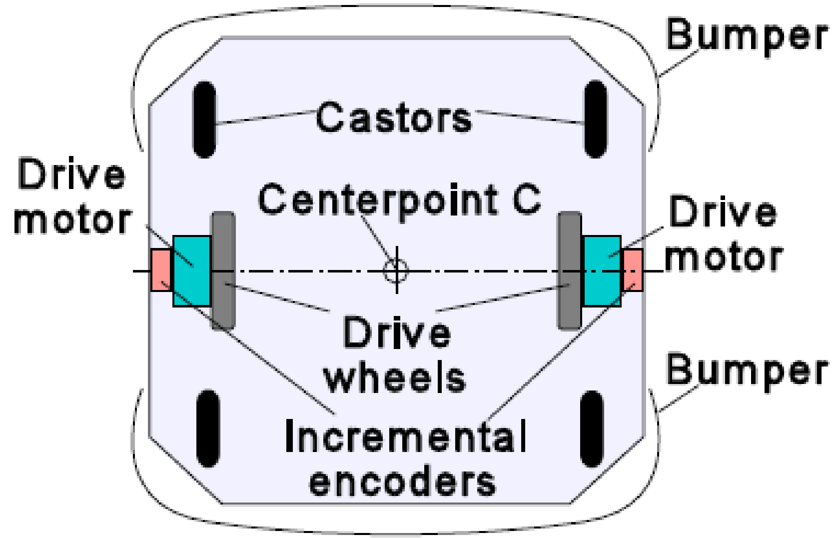
Typical Mobility Configurations

- Differential Drive
- Tricycle Drive
- Ackerman Steering
- Synchro Drive
- Omnidirectional Drive
- Multi-Degree-of-Freedom Vehicles
- MDOF Vehicle with Compliant Linkage
- Tracked Vehicles

Mobility Configurations

- **Differential Drive**

  Differential steered vehicles have two drive wheels, which are responsible for driving and steering. The **steering action** is accomplished by having each wheel to rotate at **different speeds**. This type of configuration provides some additional advantages like forward and backward movements which can be performed at the same speed. In addition, the vehicle requires a smaller area to maneuver.



TRC LabMate platform

Magellan Pro

Cybor

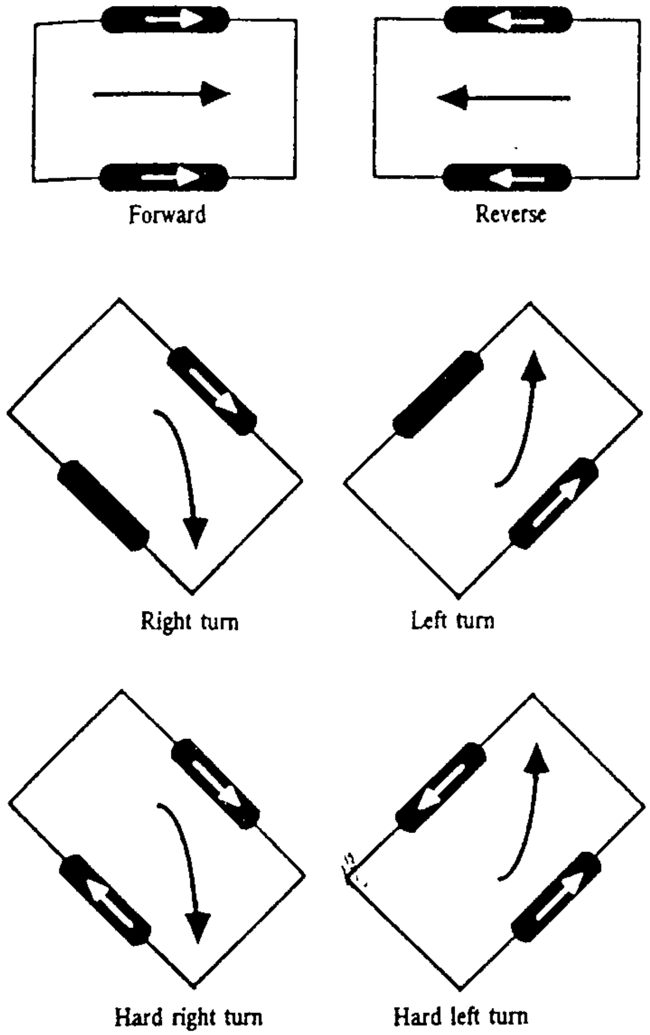
Mobility Configurations

- **Differential Drive**

V_R is the right motor voltage

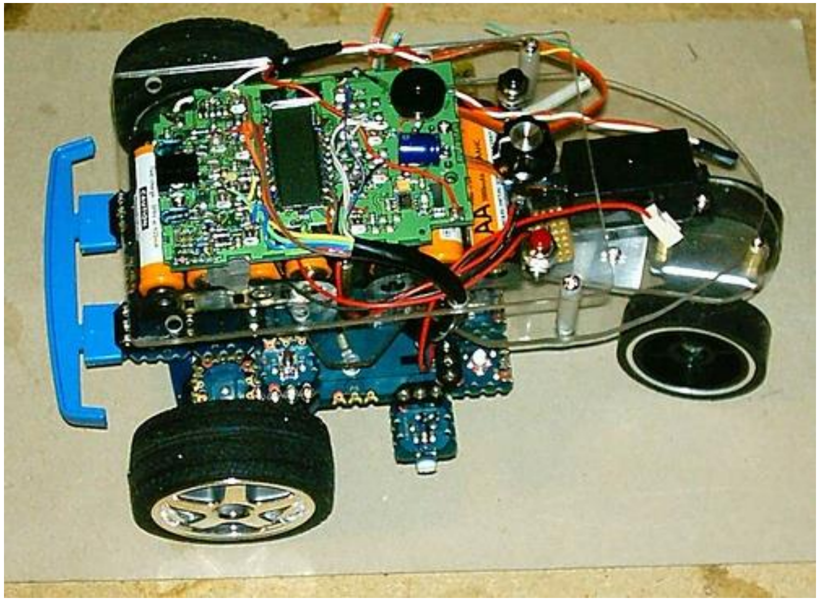
V_L is the left motor voltage.

Voltage	Polarity	Motion	Direction
$V_R=V_L$	+	Translational	Forward
$V_R>V_L$	+	Rotational	CCW
$V_R<V_L$	+	Rotational	CW
$V_R=V_L$	-	Translational	Backward
$V_R>V_L$	-	Rotational	CW
$V_R<V_L$	-	Rotational	CCW



Mobility Configurations

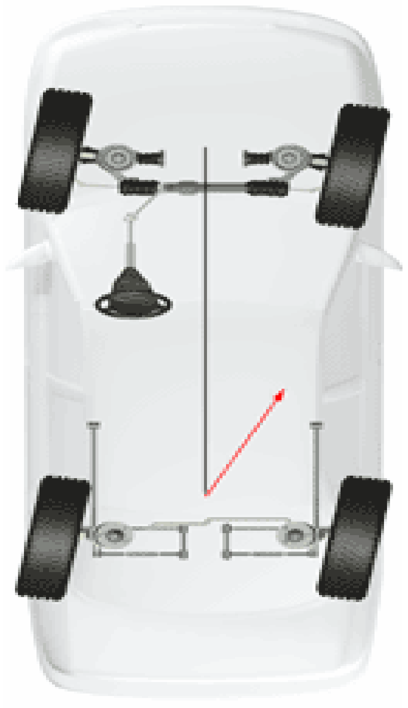
- **Tricycle Drive**
  - ◇ Tricycle-drive configurations employing **a single driven front wheel** and **two passive rear wheels** (or vice versa) are fairly common in AGV applications because of their inherent simplicity.
  - ◇ One problem associated with the tricycle-drive configuration is that the **vehicle's center of gravity** tends to move away from the front wheel when **traversing up an incline**, causing a **loss of traction**.



bulldog2

Mobility Configurations

- **Ackerman Steering (Car Drive)**
  - ◇ Used almost exclusively in the automotive industry, Ackerman steering is designed to ensure that the inside front wheel is rotated to a slightly sharper angle than the outside wheel when turning, thereby eliminating geometrically induced tire slippage.



  - ◇ Ackerman steering provides a **fairly accurate odometry** solution while supporting the traction and ground clearance needs of all-terrain operation. Ackerman steering is thus the method of choice for **outdoor autonomous vehicles**.

Mobility Configurations

- **Ackerman Steering (Car Drive)**
  - ◇ Associated drive implementations typically employ a gasoline or diesel engine coupled to a manual or automatic transmission, with **power applied to four wheels** through a transfer case, a differential, and a series of universal joints.

USMC Tele-Operated Vehicle (TOV)

STV (Surrogate Teleoperated Vehicle)

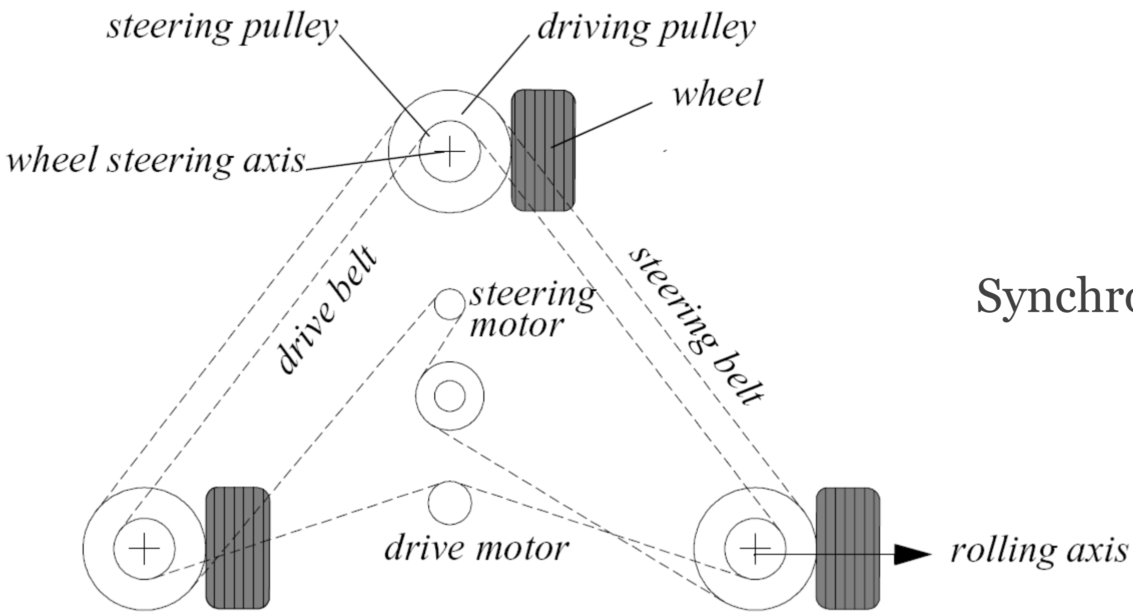
Mobility Configurations

- **Ackerman Steering (Car Drive)**
  - ◇ From a **military** perspective, the use of **existing-inventory equipment** of this type simplifies some of the logistics problems associated with vehicle maintenance.
  - ◇ In addition, **reliability** of the drive components is high due to the **inherited stability** of a proven power train. (Significant **interface problems** can be encountered, however, in retrofitting **off-the-shelf vehicles** intended for human drivers to accommodate remote or computer control.)

Mobility Configurations

- **Synchro Drive**

  This configuration known as synchro drive or **all-wheel steering** features three or more wheels **mechanically coupled** in such a way that all rotate in the same direction at the same speed, and similarly pivot in unison about their respective steering axes when executing a turn.



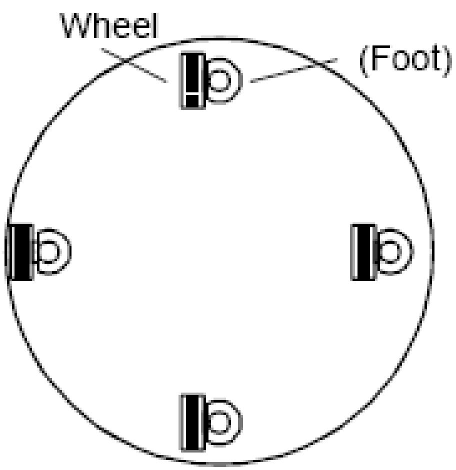
Synchro drive

Mobility Configurations

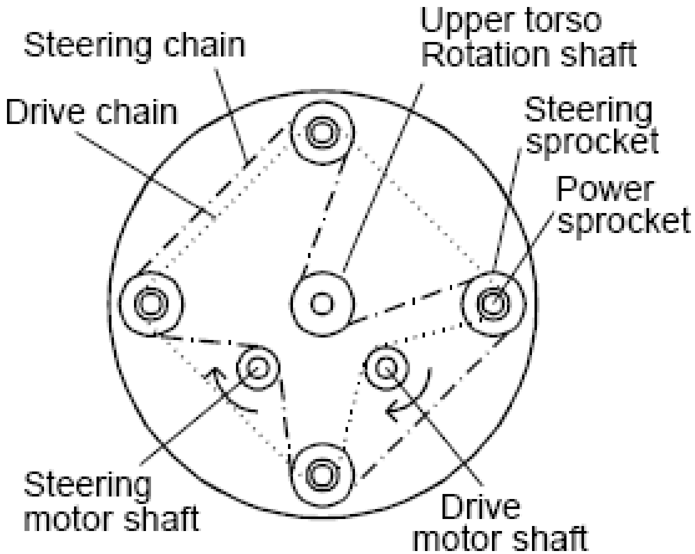
- **Synchro Drive**

This drive and steering "**synchronization**" results in **improved odometry** accuracy through reduced slippage, since all wheels generate equal and parallel force vectors at all times.

This configuration allows the vehicle to move transversally and a diagonal movement is also possible.



B21 Robot Top view



B21 Robot Bottom view

Mobility Configurations

- **Synchro Drive**

The required mechanical synchronization can be accomplished in a number of ways, the most common being a chain, belt (like in B21), or gear drive.

Carnegie Mellon University has implemented an electronically synchronized version on one of their Rover series robots, with dedicated drive motors for each of the three wheels.

Chain- and belt-drive configurations experience some degradation in steering accuracy and alignment due to uneven distribution of slack, which varies as a function of loading and direction of rotation. In addition, whenever chains (or timing belts) are tightened to reduce such slack, the individual wheels must be realigned. These problems are eliminated with a completely enclosed gear-drive approach.

iRobot B21


Denning Blacky

Mobility Configurations

- **Synchro Drive**

In a synchronous drive robot, each wheel is capable of being driven and steered.

Typical configurations

◇ Three steered wheels arranged as vertices of an equilateral

◇ Triangle often surmounted by a cylindrical platform

◇ All the wheels turn and drive in unison

This leads to a **holonomic behavior**.

Mobility Configurations

- **Synchro Drive**

In robotics **holonomicity** refers to the relationship between the controllable and total degrees of freedom of a given robot (or part thereof). If the **controllable degrees of freedom** are **equal** to the **total degrees of freedom** then the robot is said to be **holonomic**.

If the controllable degrees of freedom is less than the total degrees of freedom it is non-holonomic.

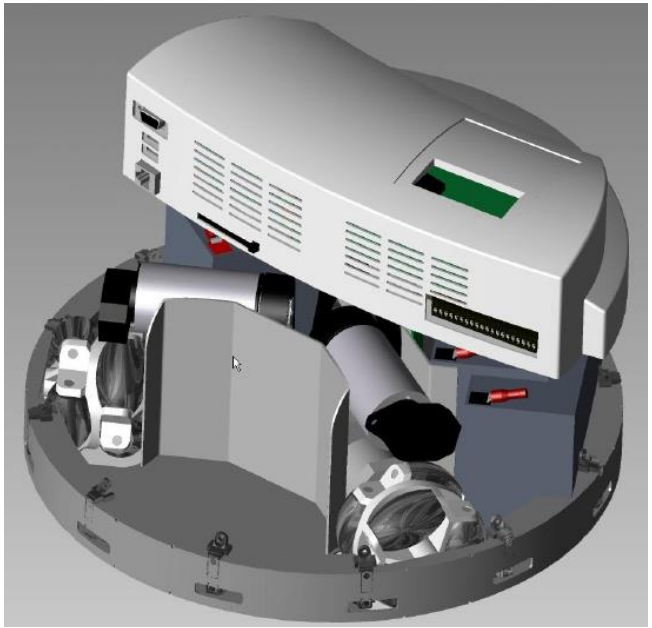
Holonomic Robot

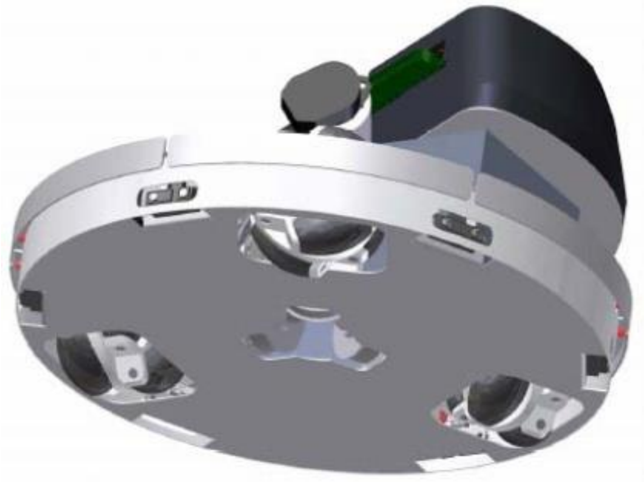
Non-holonomic Robot
Robot can move in some directions (forwards and backwards), but not others (side to side).

Mobility Configurations

- **Omnidirectional Drive**
  - ◇ This configuration is a multi-degree of freedom configuration.
  - ◇ Movement in the plane has 3 DOF thus only three wheels can be independently controlled.
  - ◇ It might be better to arrange three Swedish wheels in a triangle.

Uranus, CMU: Omnidirectional Drive with 4 Wheels

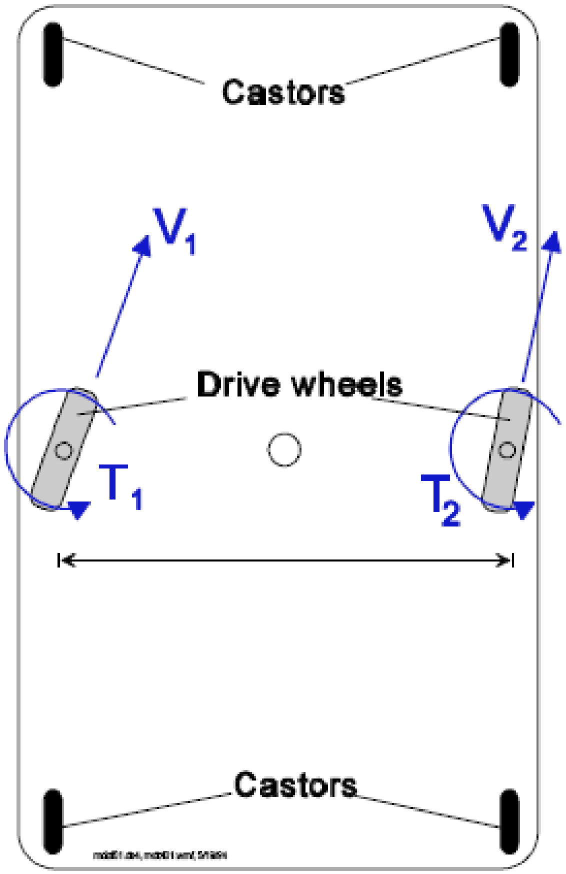




Festo Robotino

Mobility Configurations

- **Multi-Degree-of-Freedom Vehicles**
  - ◇ Multi-degree-of-freedom (MDOF) vehicles have multiple drive and steer motors.
  - ◇ MDOF configurations display exceptional maneuverability in tight quarters in comparison to conventional 2-DOF mobility systems, but have been found to be difficult to control due to their overconstrained nature. Resulting problems include increased wheel slippage and thus reduced odometry accuracy.



A 4-degree-of-freedom vehicle platform can travel in all directions, including sideways and diagonally. The difficulty lies in coordinating all four motors so as to avoid slippage.

Mobility Configurations

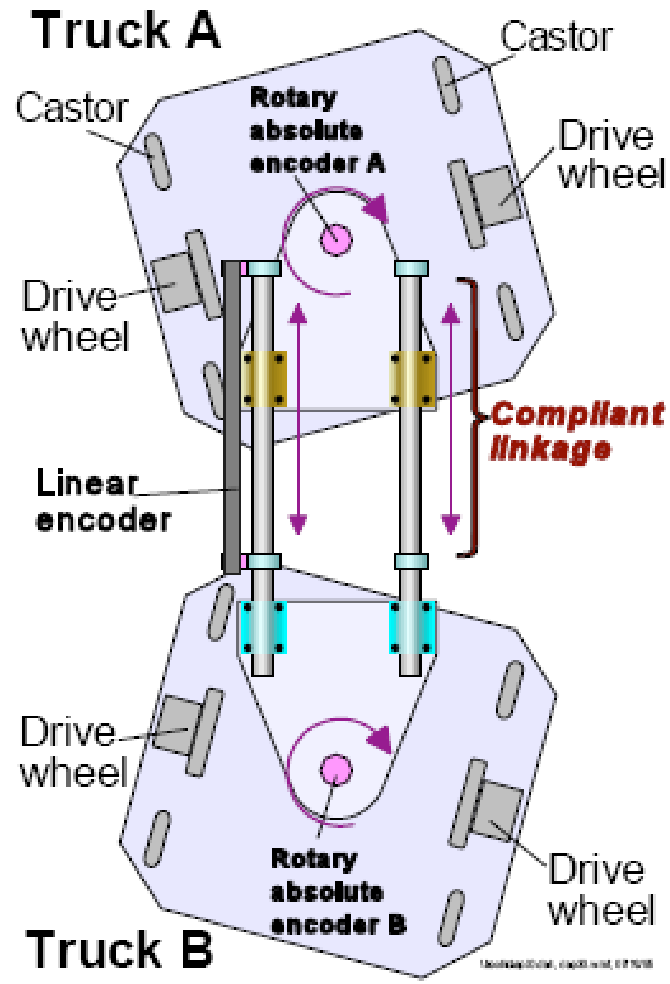
- **Multi-Degree-of-Freedom Vehicles**
  - ◇ Unique Mobility, Inc. built an **8-DOF vehicle** for the U.S. Navy under an SBIR grant. Unique Mobility engineers faces some difficulties in controlling and coordinating all eight motors.

An 8-DOF platform with four wheels individually driven and steered.

Mobility Configurations

- **MDOF Vehicle with Compliant Linkage**

To overcome the problems of control and the resulting excessive wheel slippage described above, researchers at the University of Michigan designed a Multi-Degree-of-Freedom (MDOF) vehicle with compliant linkage.

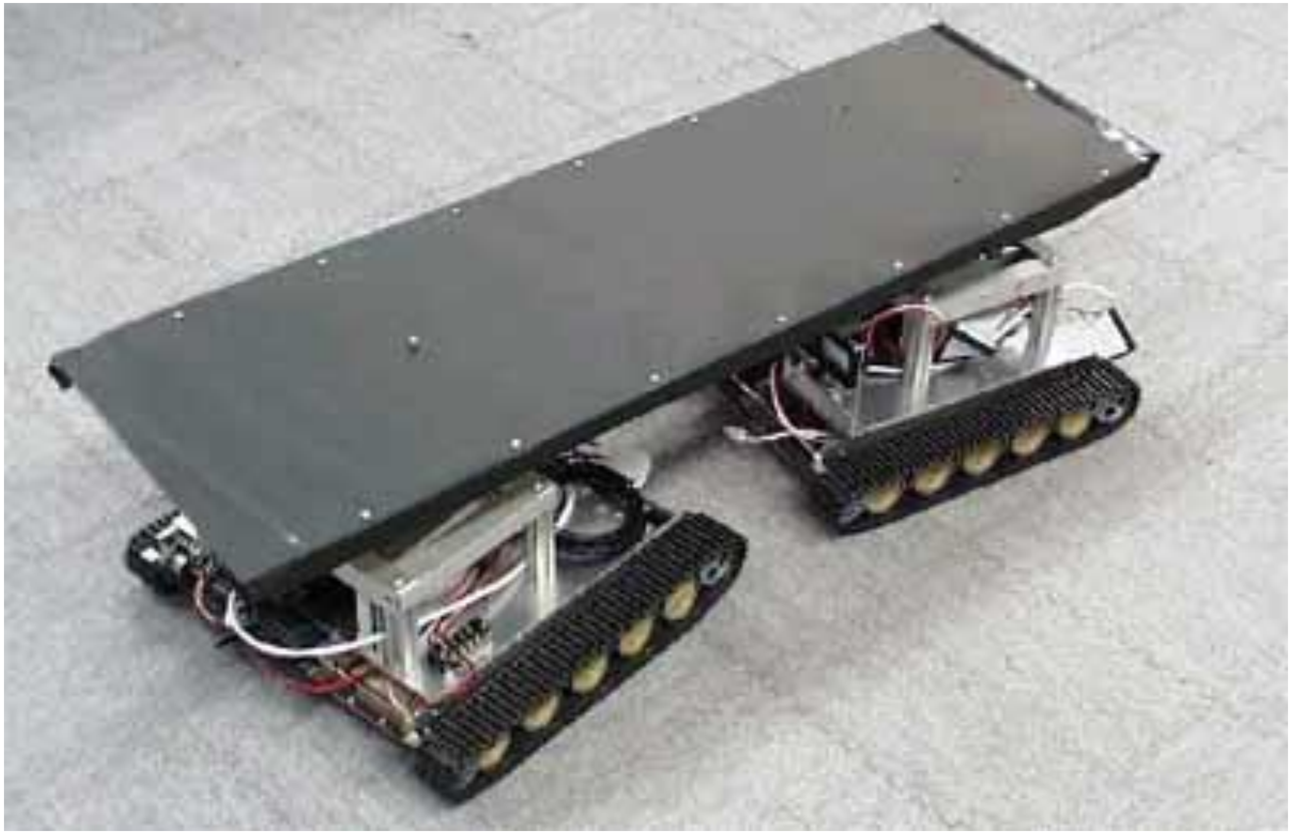


Mobility Configurations

- **MDOF Vehicle with Compliant Linkage**
  - ◊ This vehicle comprises **two differential-drive** LabMate robots. The two LabMates, here referred to as "**trucks**," are connected by a **compliant linkage and two rotary joints**, for a total of three internal degrees of freedom.
  - ◊ The purpose of the compliant linkage is to accommodate momentary controller errors without transferring any mutual force reactions between the trucks, thereby eliminating the excessive wheel slippage reported for other MDOF vehicles.

Mobility Configurations

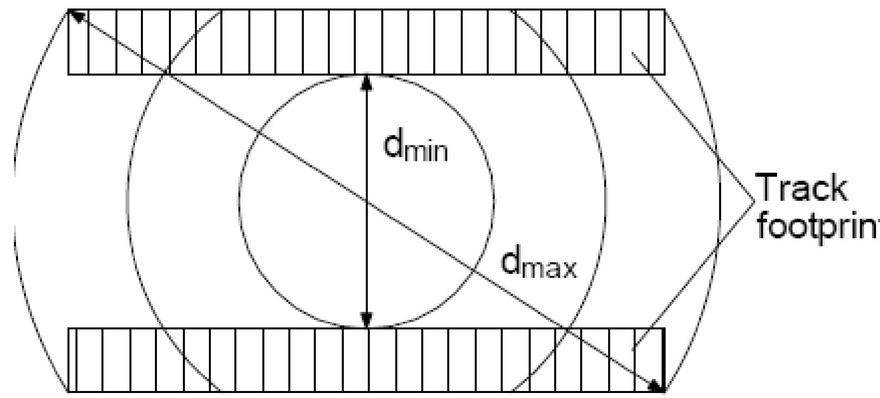
- **MDOF Vehicle with Compliant Linkage**



Kosuge and Hirata Lab, Japan

Mobility Configurations

- **Tracked Vehicles**
  - This very special implementation of a **differential drive** is known as **skid steering** and is routinely implemented in track form on bulldozers and armored vehicles.
  - Such **skid-steer** configurations intentionally rely on **track or wheel slippage** for normal operation, and as a consequence provide rather poor dead-reckoning information.

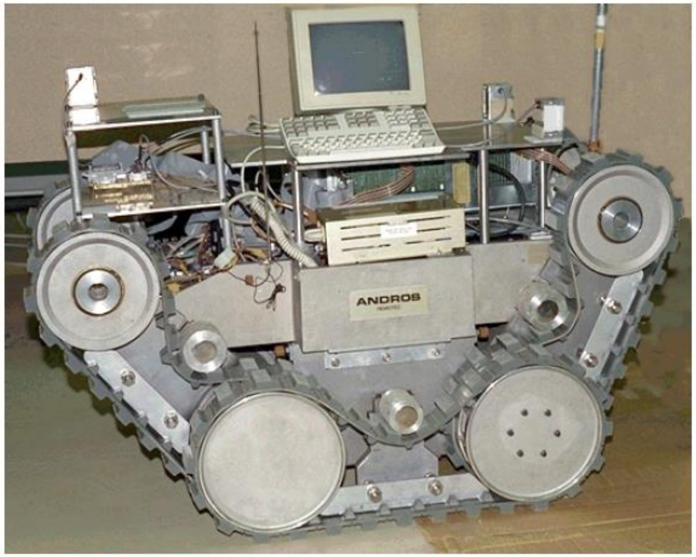


The effective point of contact for a skid-steer vehicle is roughly constrained on either side by a rectangular zone of ambiguity corresponding to the track footprint. As is implied by the concentric circles, considerable slippage must occur in order for the vehicle to turn.

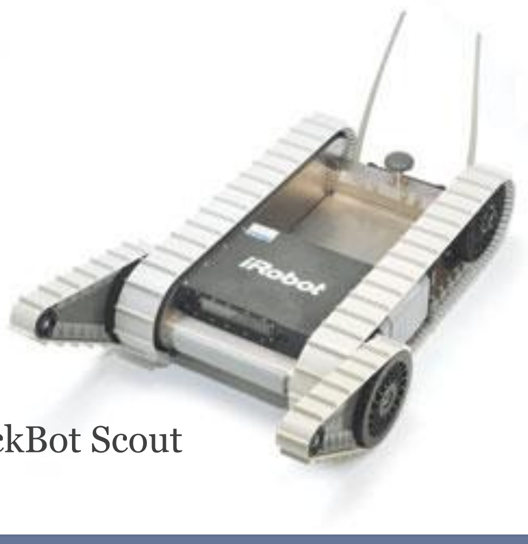
More information: Tracked Vehicle Steering, http://www.gizmology.net/tracked.htm

Mobility Configurations

- **Tracked Vehicles**
  - ◇ **Skid steering** is generally employed only in **tele-operated** as opposed to **autonomous** robotic applications, where the ability to surmount significant floor discontinuities is more desirable than accurate odometry information.
  - ◇ An example is seen in the track drives popular with remote-controlled robots intended for explosive ordnance disposal.



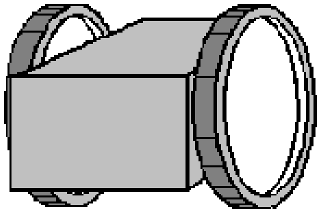
Remotec Andros V tracked vehicle



PackBot Scout

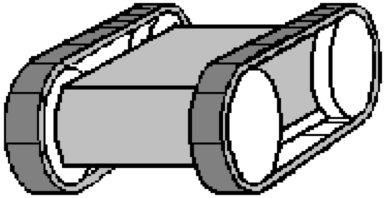
Mobility Configurations

- **Other classification**



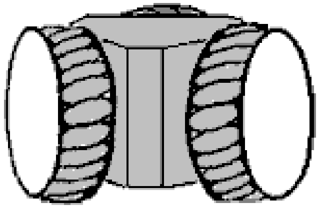
Bi-wheel type robot

- Smooth motion
- Risk of slipping
- Some times use roller-ball to make balance



Caterpillar type robot

- Exact straight motion
- Robust to slipping
- Inexact modeling of turning



Omnidirectional robot

- Free motion
- Complex structure
- Weakness of the frame

Source: Prof. Jizhong Xiao, "Mobile Robot Locomotion," Department of Electrical Engineering City College of New York.

Outline

- Robot Locomotion
- Legged Mobile Robots (Walking Machines)
- Leg Configurations and Stability
- Wheeled Mobile Robots (Driving Robots)
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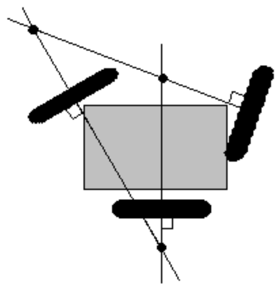
Mobility, Steerability and Maneuverability

- **Mobility**

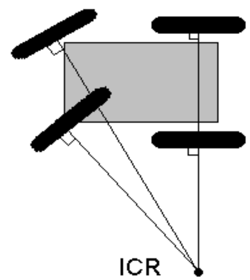
Degree of mobility is the degree of freedom of the robot motion.

Note: Instantaneous center of rotation (ICR) or Instantaneous center of curvature (ICC) is a cross point of all axes of the wheels.



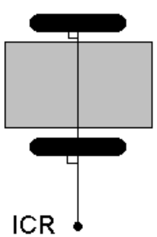
Cannot move anywhere (No ICR)

Degree of mobility : 0



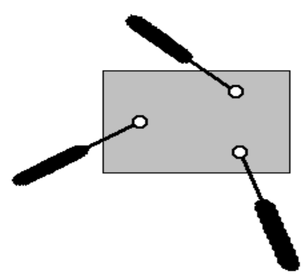
Fixed arc motion (Only one ICR)

Degree of mobility : 1



Variable arc motion (line of ICRs)

Degree of mobility : 2



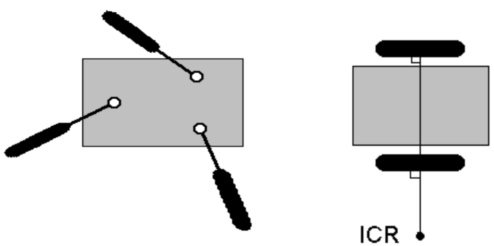
Fully free motion (ICR can be located at any position)

Degree of mobility : 3

Mobility, Steerability and Maneuverability

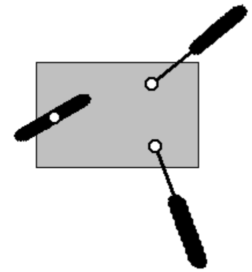
- **Steerability**

Degree of steerability is the number of centered orientable wheels that can be steered independently in order to steer the robot.

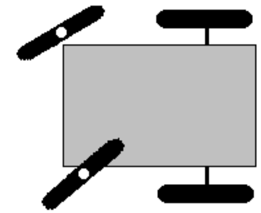


No centered orientable wheels

Degree of steerability : 0

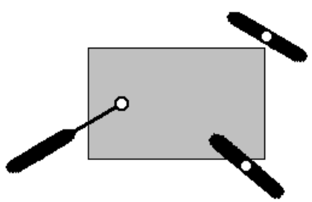


One centered orientable wheel



Two mutually dependent centered orientable wheels

Degree of steerability : 1



Two mutually independent centered orientable wheels

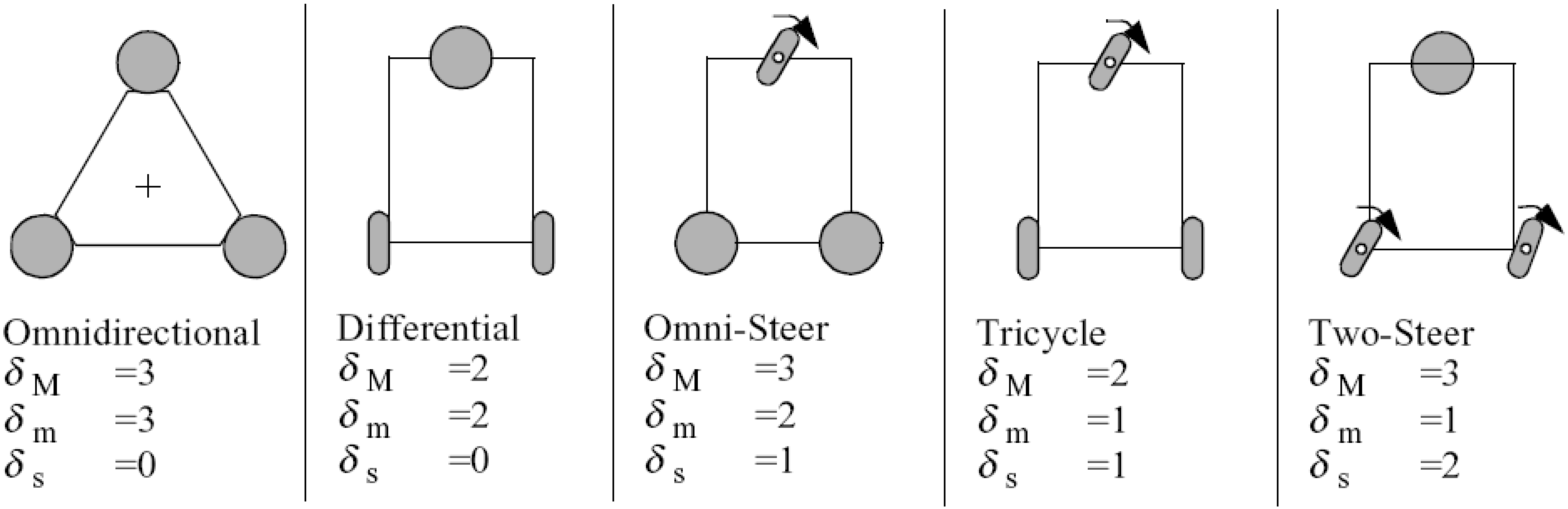
Degree of steerability : 2

Mobility, Steerability and Maneuverability

- **Maneuverability**

Degree of maneuverability is the overall degrees of freedom that a robot can manipulate.

$$\delta_M = \delta_m + \delta_s$$

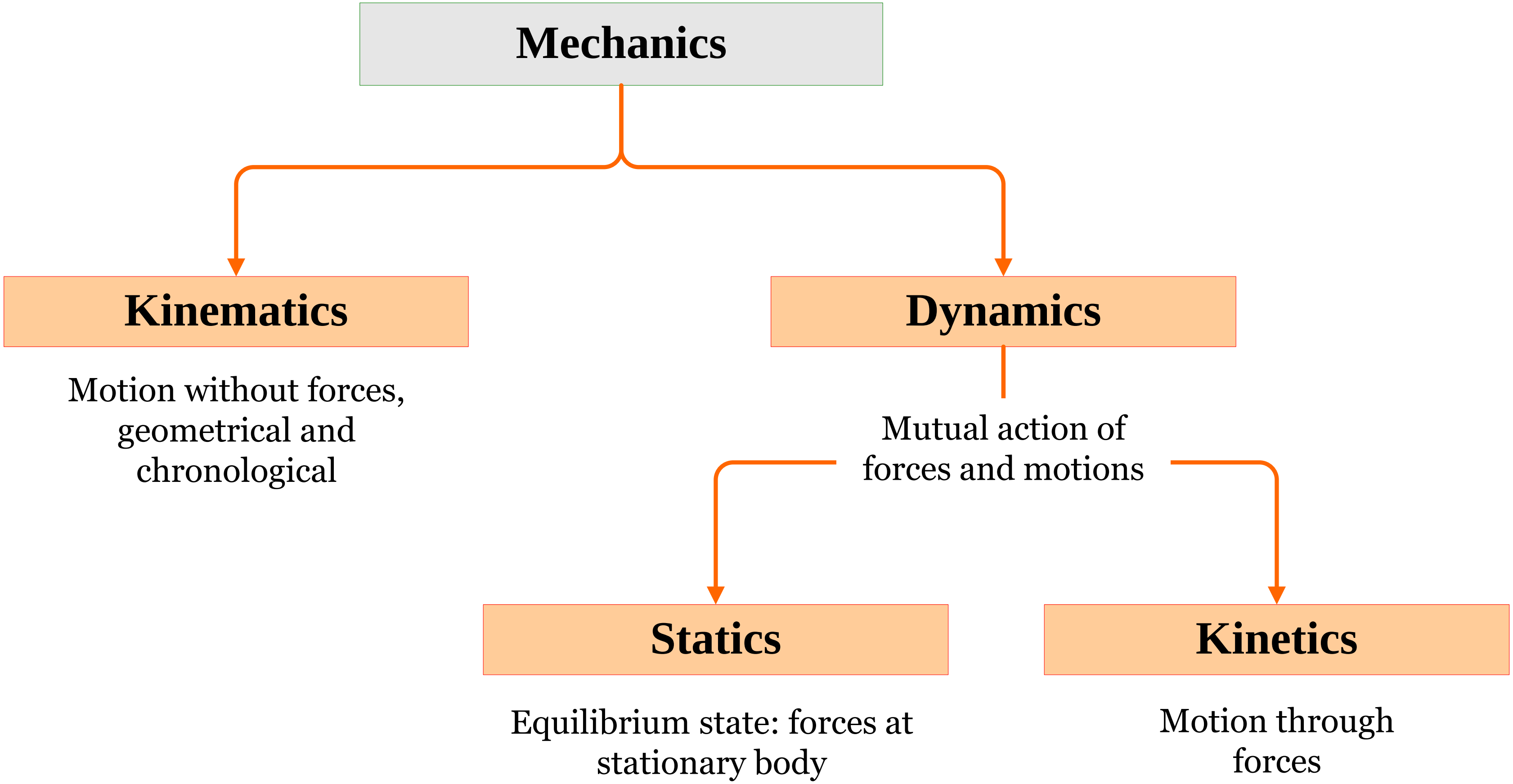


Outline

- Robot Locomotion
- Legged Mobile Robots (Walking Machines)
- Leg Configurations and Stability
- Wheeled Mobile Robots (Driving Robots)
- Wheels Types
- Wheel Arrangements
- Mobility Configurations
- Mobility, Steerability and Maneuverability
- **Mobile Robot Kinematics**
- Differential Drive Kinematics
- Summary

Mobile Robot Kinematics

Kinematics (Greek, to move) is the science of motion.



Mobile Robot Kinematics

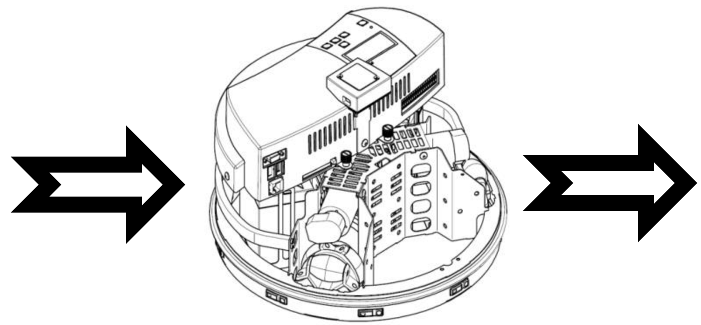
Kinematics is the most basic study of how mechanical systems behave.

In mobile robotics, we need to understand the **mechanical behavior** of the robot both in order to design appropriate mobile robots for tasks and to understand **how to create control software** for an instance of mobile robot hardware.

Mobile Robot Kinematics

To **control** a mobile robot, it is important to know the relationships between the actions on the actuators (e.g. linear and angular velocity commands) and the movement of the robot.

Actions on the actuators



Movement of the robot

These relationships are used for two purposes:

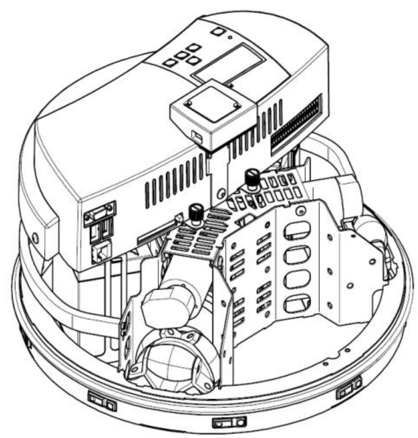
- To calculate the **actions** necessary to move the robot from one position to another.
- To evaluate the **displacements** of the robot from the movements of the wheels (i.e., **odometry**)

Mobile Robot Kinematics

- **Forward Kinematics**

How does the robot move, given its geometry and the speeds of its wheels?

Measurements of the Angular Velocities of the Wheels ⇒



⇒ **Robot's position and World Translational and Angular Velocity**

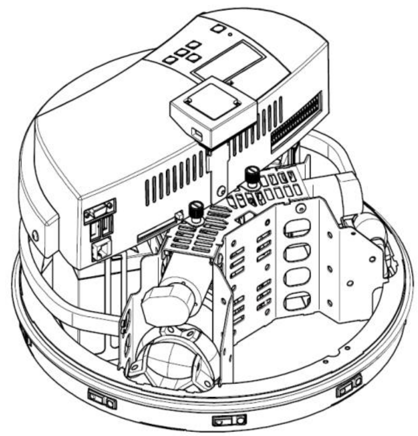
Forward Kinematics

Mobile Robot Kinematics

- **Inverse Kinematics**

Given a desired position or velocity, what can we do to achieve it (what are the corresponding vector of wheels velocities)?

Desired position or velocity ⇒



⇒ **Wheels position and velocities**

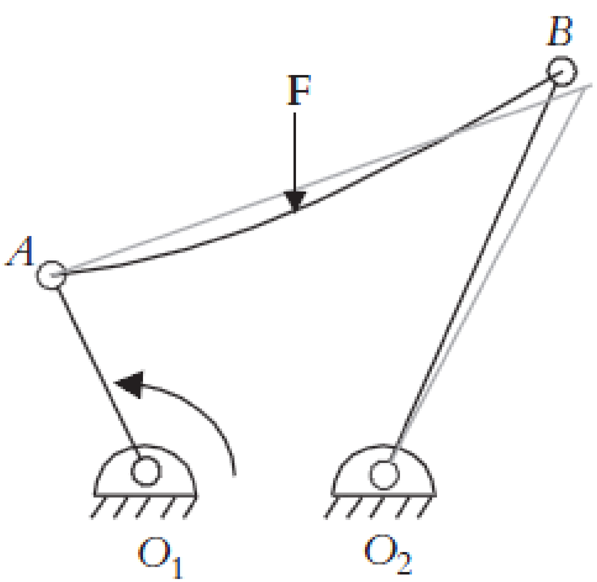
Inverse Kinematics

◇ There are lots of solutions... Finding some solution is not hard, but finding the **"best"** solution is.

◇ The best can be the **quickest time**, the **most energy efficient**, the **smoothest velocity profiles**, etc.

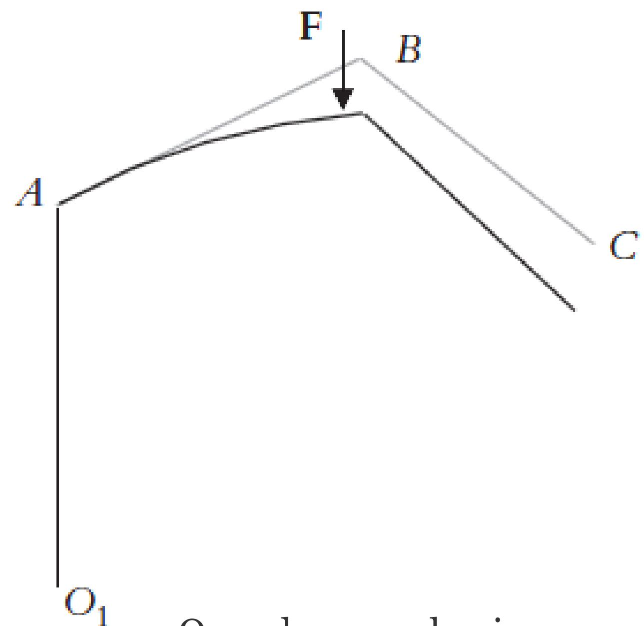
Mobile Robot Kinematics

- **Mobile Robots vs. Arms Kinematics: Modeling**



Closed-loop mechanism

$$\overline{O_1A} + \overline{AB} = \overline{O_1O_2} + \overline{O_2B}$$



Open-loop mechanism

$$\overline{O_1A} + \overline{AB} + \overline{BC} = \overline{O_1C}$$

In *open-loop mechanism*, unless O_1C is measured by feedback, the change will not be known.

Mobile Robot Kinematics

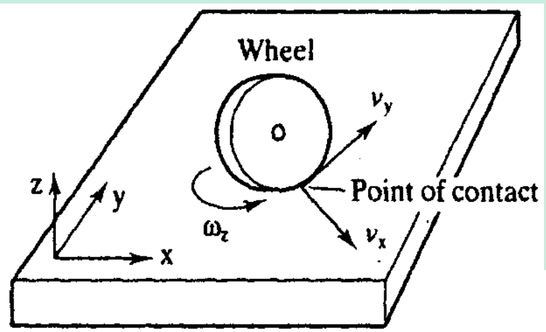
- **Mobile Robots vs. Arms Kinematics: Modeling**

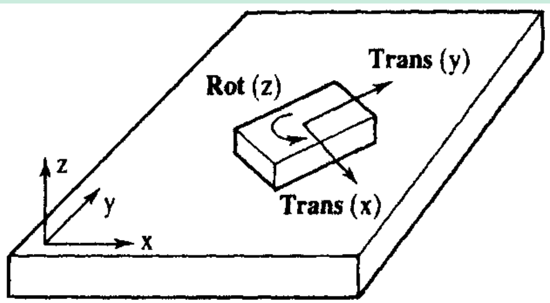
<table>
<tr><th rowspan="2">Manipulators</th><th colspan="2">Mobile Robots</th></tr>
<tr><th>Wheeled Robots</th><th>Legged Robots</th></tr>
<tr><td>An open-link chain when in free space, and a closed-link chain when in contact with a workpiece.
</td><td>A multiple closed-link chain as a wheeled mobile robot always has more than one wheel in contact with the surface it is travelling over.
</td><td>A chain for each leg, which opens and closes as the foot is lift off the ground and placed back on the ground.
</td></tr>
</table>

Mobile Robot Kinematics

- **Mobile Robots vs. Arms Kinematics: DOF**

Manipulators	Mobile Robots
Most of the joints of a robotic arm are restricted to **one degree of freedom**, and the degrees of freedom of the end-effector are constrained by the task.	The wheel of a mobile robot can both turn and translate with respect to the contact point between it and the floor. This pseudo joint is described as a **higher order pair**. A lower-order pair is constrained by a common surface of contact, such as a prismatic joint.





Mobile Robot Kinematics

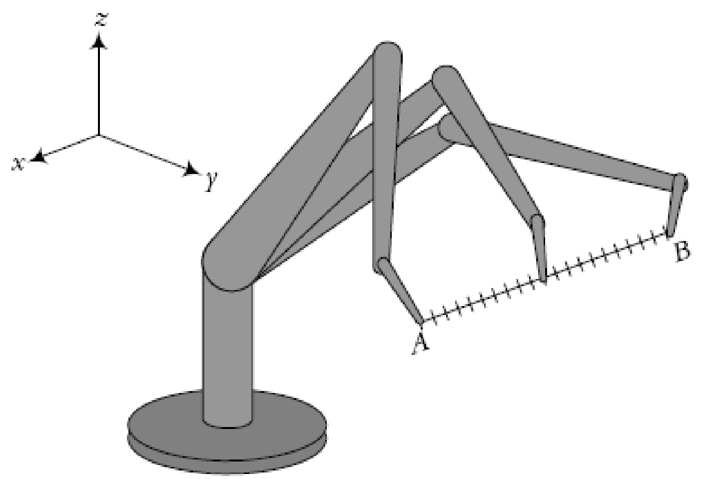
- **Mobile Robots vs. Arms Kinematics: Actuation**

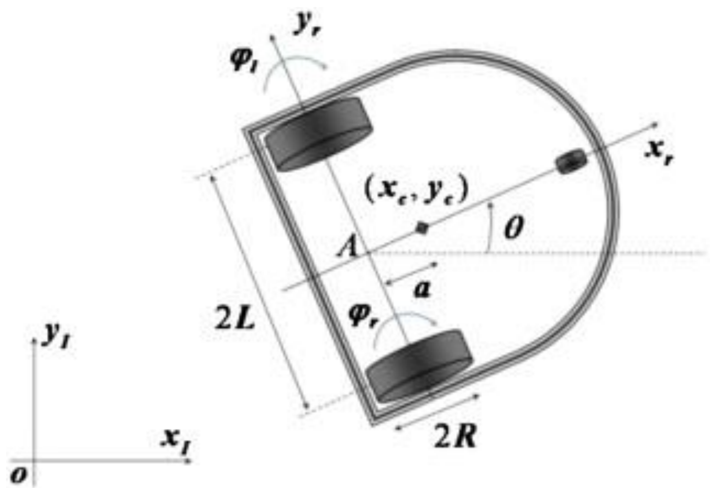
Manipulators	Mobile Robots
All the joints are actuated and are used to control the motion of the end-effector.	Some wheels are not actuated at all and some degrees of freedom are not actuated on some wheels.

Mobile Robot Kinematics

- **Mobile Robots vs. Arms Kinematics: Trajectory Control**

Manipulators	Mobile Robots
To control the trajectory of the end-effector, the position, velocity and acceleration of each joint must be measured.	When controlling the trajectory of a mobile robot, there is no need to measure the position, velocity and acceleration of each degree of freedom of each wheel.





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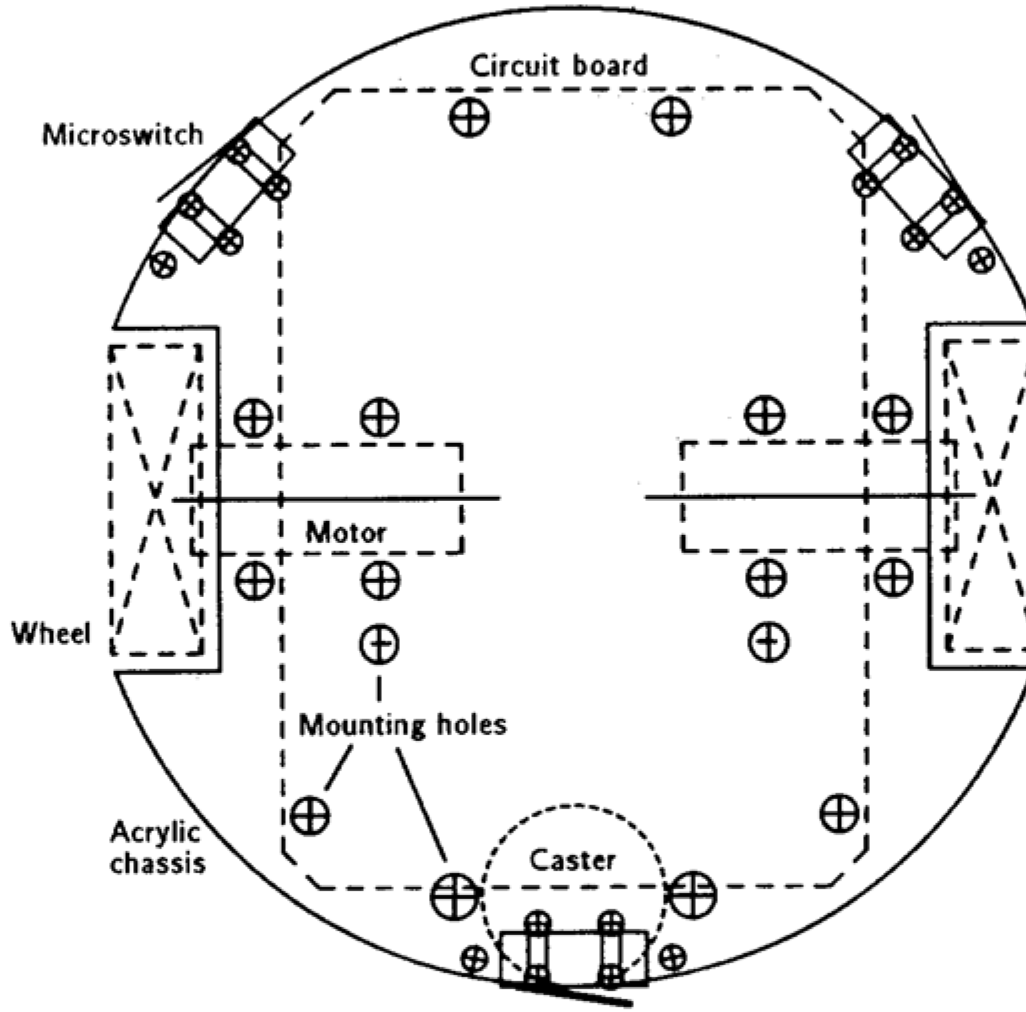
Differential Drive Kinematics

Differential steered vehicles **have two drive wheels**, which are responsible for driving and steering.

Usually differential drive mobile robots have an additional **castor wheel for stability**.

As it can rotate freely in all directions, in our calculation we can **omit the castor wheel** because it only has a very little influence over the robot's kinematics.

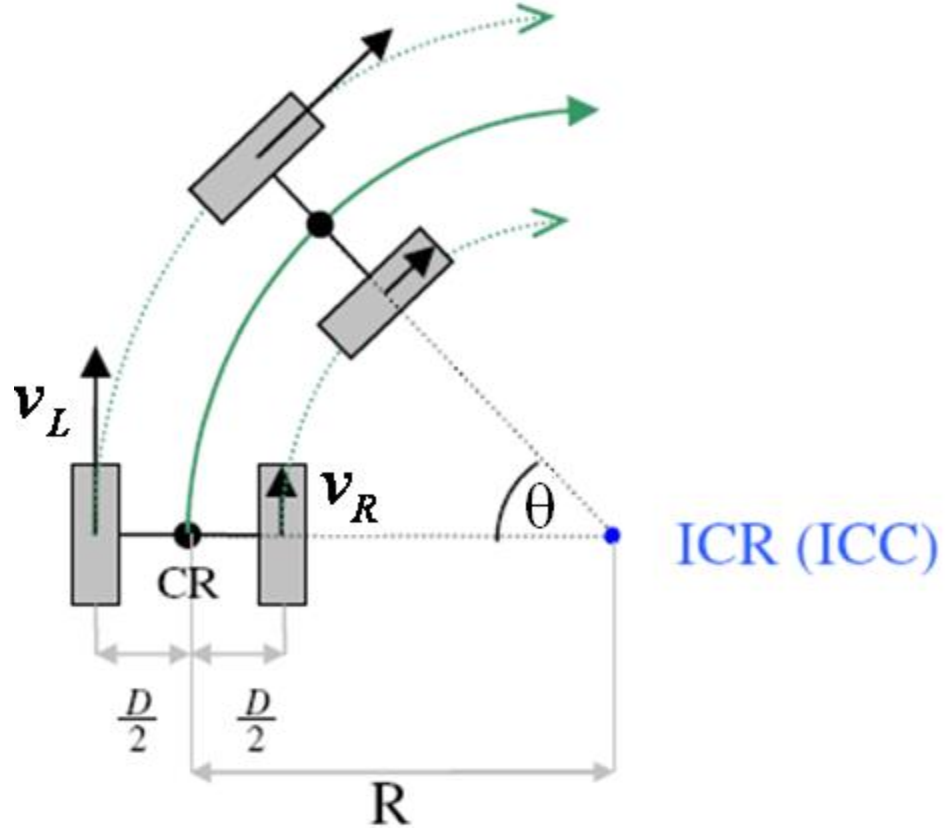


Differential Drive Kinematics

To **avoid slippage** and have only a **pure rolling motion**, the robot must rotate around a point that lies on the common axis of the two driving wheels.

This point is known as the instantaneous center of curvature (ICC) or the instantaneous center of rotation (ICR).

By **changing the velocities** of the two wheels, the instantaneous center of rotation will move and **different trajectories** will be followed.



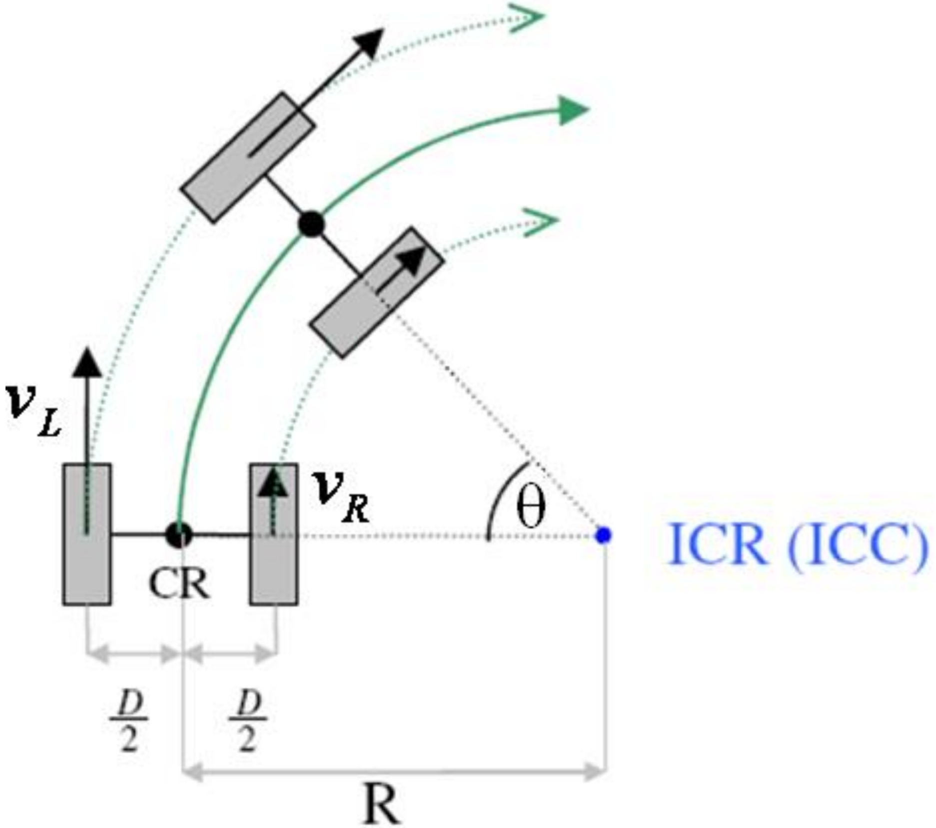
Differential Drive Kinematics

At each moment in time the left and right wheels follow a path that moves around the ICR with the same **angular rate** **$\omega = d\theta/dt$**, and thus:

$$\omega.R = v_{CR}$$

$$\omega.\left(R+\frac{D}{2}\right) = v_L$$

$$\omega.\left(R-\frac{D}{2}\right) = v_R$$



where R is the signed distance from the ICC to the midpoint between the two wheels.

Note that v_L, v_R, and R are all functions of time.

Differential Drive Kinematics

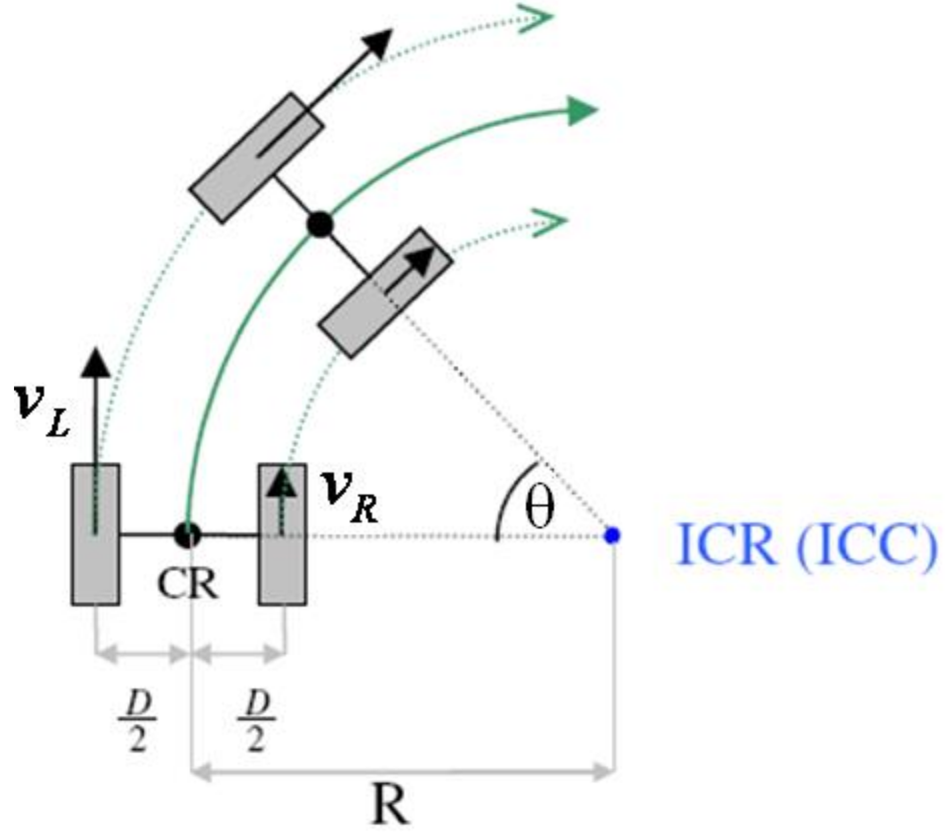
At any moment in time:

$$R = \frac{v_R + v_L}{v_R - v_L} \cdot \frac{D}{2}$$

$$\omega = \frac{v_R - v_L}{D}$$

The velocity of the CR point, which is the **midpoint** between the two wheels, can be calculated as the average of the velocities v_L and v_R:

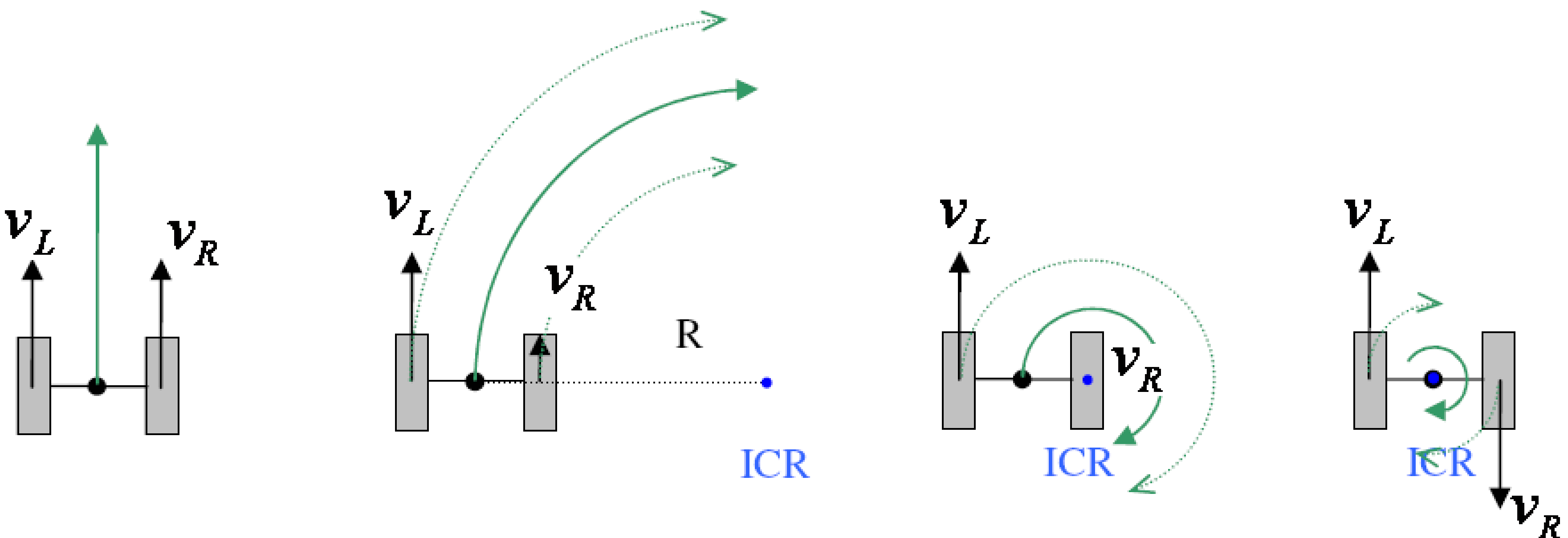
$$v_{CR} = \frac{v_L + v_R}{2}$$



Differential Drive Kinematics

$$v_{CR} = \frac{v_L + v_R}{2}$$

$$R = \frac{v_R + v_L}{v_R - v_L} \cdot \frac{D}{2}$$



$v_L = v_R$ — Motion Forward or Backward, R is infinite

$v_L > v_R$ — Turning R>D/2

$v_R = 0$ — Turning R=D/2

$v_L = -v_R$ — Turning R=0

Differential Drive Kinematics

- A differential drive mobile robot is very sensitive to the relative velocity of the two wheels.
- Small differences between the velocities provided to each wheel cause different trajectories, not just a slower or faster robot.
- Differential drive mobile robots typically have to use castor wheels for balance. Thus, differential drive vehicles are sensitive to slight variations in the ground plane.

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Summary

- Locomotion addresses how the robot moves through its environment.
- A mobile robot needs locomotion mechanisms that enable it to move unbounded throughout its environment. But there are a large variety of possible ways to move, and so the selection of a robot's approach to locomotion is an important aspect of mobile robot design.
- In the laboratory, there are research robots that can walk, jump, run, slide, skate, swim, fly, and, of course, roll. Most of these locomotion mechanisms have been inspired by their biological counterparts.
- Nature favors legged locomotion, since locomotion systems in nature must operate on rough and unstructured terrain. Most of mobile robots generally locomote using wheeled mechanisms.

Summary

- Kinematics (Greek, to move) is the science of motion.
- To control a mobile robot, it is important to know the relationships between the actions on the actuators (e.g., linear and angular speed commands) and the movements of the robot.
- The kinematic modeling of wheeled robots differs from the modeling of manipulators.
- Deriving a model for the whole robot's motion is a bottom-up process. Each individual wheel contributes to the robot's motion and, at the same time, imposes constraints on robot motion. Wheels are tied together based on robot chassis geometry, and therefore their constraints combine to form constraints on the overall motion of the robot chassis. But the forces and constraints of each wheel must be expressed with respect to a clear and consistent reference frame.

For reading

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- Thomas THÜER. Mobility evaluation of wheeled all-terrain robots Metrics and application: Metrics and application. PhD Thesis, ETH Zurich, 2009.
- Roland Siegwart. Robots for Space: Exploration Robot Examples.
- Working Model 2D (WM2D) Tool
- Motor Sizing Calculations, Technical Reference