1

MOBILE ROBOT

Introduction to robotics

Lecturer:

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Aims

This course teaches the foundations of autonomous mobile robots, covering topics such as Locomotion, motion control, and navigation. It also teaches how to choose a suitable sensors packs to equip the mobile robot. The course will feature several practical sessions with hands-on robot programming. The students will undertake an assignment (mini-projects), which will be formally evaluated through a report and presentation.

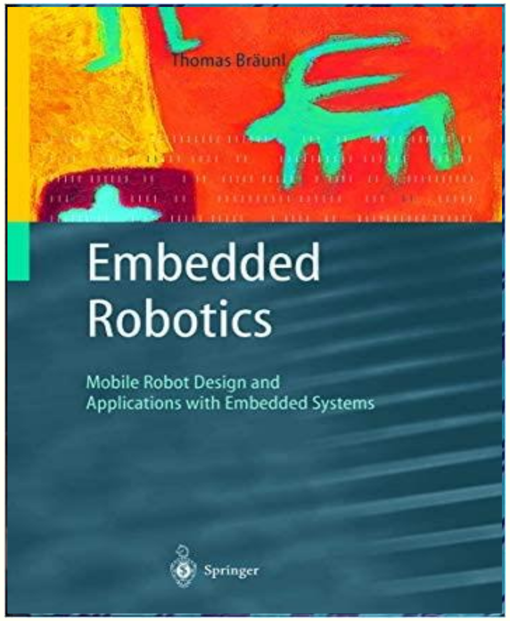
Course Outline

- **Introduction to Robotics** – History, mobile robot, applications (~ 1 *Lecture*)
- **Locomotion** - Types of robots, maneuverability (~ 2 *Lectures*)
- **Modelling I** - Kinematics of wheeled robots (~ 1 *Lecture*)
- **Tutorial** – Modelling I (~ 1 *Lecture*)
- **Modelling II** - Kinematics using a constraints approach (~ 2 *Lectures*)
- **Tutorial** – Modelling II (~ 1 *Lecture*)
- **Sensors** – Active, passive, analysis (~ 2 *Lectures*)
- **Localization** – Errors, Markov localization, Kalman filtering (~ 2 *Lecutres*) (*Depends on time*)

Objectives

By the end of this course students should:

1. Intro to history and types of mobile robot.
2. Understand the main components of a mobile robotic system, including sensors, actuators and power options.
3. Learn how to build the mathematical model of mobile robot.
4. Understand different sensors that will be used in mobile robot.
5. Understand different approaches to robot localization (if we have time!).



Recommended reading

Essential:

Introduction to Autonomous Mobile Robots
R. Siegwart, I. R. Nourbakhsh, MIT Press, 2004.

Recommended:

Introduction to Robotics
P. McKerrow, Addison-Wesley, 1991.

Background:

Embedded robotics : mobile robot design and applications with embedded systems
Thomas Bräunl, Springer, 2003.

What is a Robot?

- Etymology of the word ‘robot’

  Czech playwright Karel Capek, 1921 Play ‘Rossums’s Universal Robots (R.U.R)’

  Czech words ‘rabota’ + ‘robotnik’ (obligatory work + serf)

- **Definition:** A **robot** is an autonomous system which exists in the **physical** world, can **sense** its environment, and can **act** on it to achieve some **goals**.

- **Definition:** A mechanical system that has sensing, actuation and computation capabilities.

Karel Capek
Source: Google image

Autonomous Robots

educational robots
[Cozmo]

autonomous vehicles
[Google]

consumer-grade drones
[e.g., DJI]

Microrobots
[Wood et al.; Harvard]

Mobile robot

History

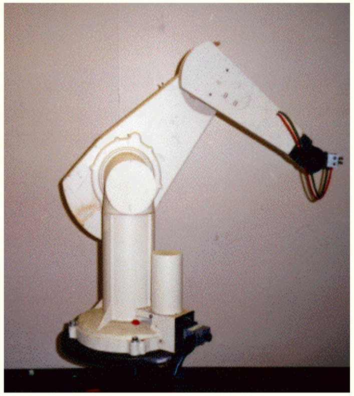
•**1968** - Mobile Robot with Vision (Shaky) developed at Stanford Research Institute.

•**1978** - Programmable Universal Machine for Assembly (PUMA) developed at General Motors.

•**1979** - SCARA (Selective Compliant Articulated Robot for Assembly) introduced in Japan (by Adept Technologies).

•**2000** - Honda debuts humanoid robot (ASIMO).

Shaky



PUMA

SCARA

1990s to Today - A Few Highlights

- 1996: P2, Honda
- 2002: First Roomba vacuum cleaner
- 2004: DARPA Grand Challenge
- 2005: self-replication (Cornell)
- 2011: agressive control for UAVs (UPenn)
- 2012: Amazon buys Kiva
- 2014: swarm robotics (Harvard)

2015 and onwards: trend away from first principles-based approaches to data-driven approaches (black box control)

Classifications

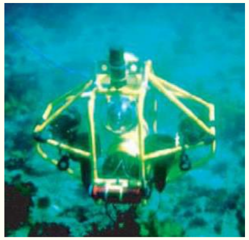
- **Fixed robots (Manipulators):**
  Several links are connected through various joints. The base is attached to the ground/fixed.

Serial

Parallel

- **Mobile robots (Locomotion):**
  Mobile robots can move, interact, and perform several tasks in different environments.

Ground



AUV

UAV

- **Hybrid robots/Humanoid:**
  Mobile robot which is provided by an arm

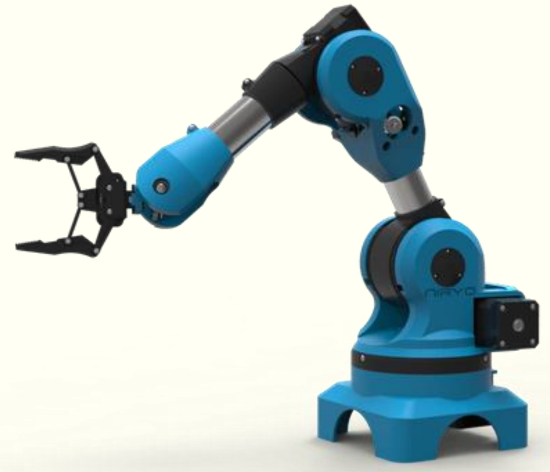
Why Robots?

- The three D's: **dirty, dull, and dangerous** tasks that no human desires to do, but they have to be done.
- But there is more!

Optimization: with the introduction of programmable autonomous robots, processes become computable, and can be optimized!

Optimization **objectives**:

- Efficiency
- Safety
- Comfort
- etc…



What is a Mobile Robot?

- Mobile robotics is the industry related to creating mobile robots, which are robots that can move around in a physical environment.

- Mobile robots are generally controlled by software and use sensors and other gear to identify their surroundings.

- Mobile robots combine the progress in artificial intelligence with physical robotics, which allows them to navigate their surroundings.

The Future of Mobile Robots

smart infrastructure / mobility-on-demand

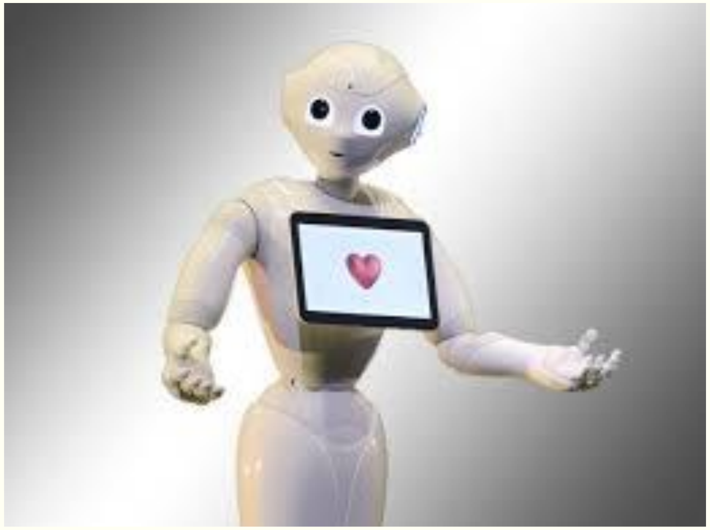
connected vehicles / automated highways

drone swarms / surveillance

truck platoons / long-haul transport

autonomy on any terrain
[Big Dog; Boston Dynamics]

personal robots
[iCub robot]



emotional robots
[Pepper]

What's next?

Why do we study mobile robots?

- Job prospects in…
  - Transport
    - autonomous driving, taxis, buses
    - self-driving market estimated at over $500 billion
  - Warehouses and logistics
    - E.g.: Amazon have doubled size of robot fleet in recent years
    - Delivery services (e.g., Ocado, Uber Eats)
  - Civilian and humanitarian
    - search and rescue
    - environmental monitoring
    - force multiplication (military)

Self-Driving Trucks for Mining

- 17 Self-driving trucks deployed for mining in Australia
- Increased accuracy in operation as compared to humans
- Improved earth excavation

Autonomous Driving

- Market for advanced driver assistance systems to grow from $10 billion now to $130 billion in 2016
- Projected to reach $500 billion by 2020

Tesla—90% autonomous vehicle within few years

For 5-star safety rating, vehicle has to be 'robotic'

Defense: Unmanned Aerial Vehicles

- Drones-combat, surveillance
- First appeared during the Vietnam war
- First recorded targeted killing– 2002
- (afghanistan)
- Global UAV market--$5.9 billion now to $8.35 billion in 2018

Defense: Driverless Vehicles

- 1/3 of all U.S Military vehicles to be autonomous by 2015
- Black Knight– Unmanned Tank

Unmanned Agricultural Machines

- Efficient utilization of resources
- UAVs for spraying insecticides
- Driverless tractors

Humanitarian

- Landmine detection
- Bomb disposal
- Prosthetic limbs—full restoration of original capabilities

Surgical Robots

- Surgical robotics-higher precision, repeatability, cost-effective
- Significantly lower blood loss
- Minimally invasive surgery

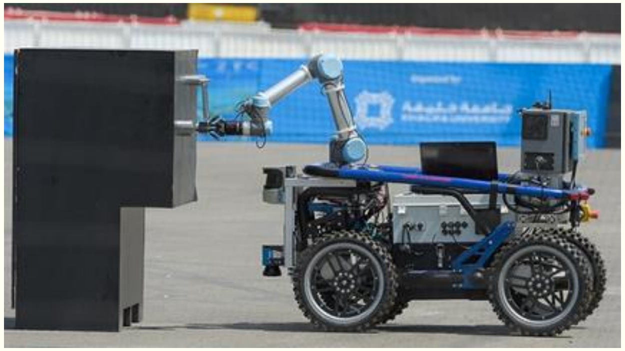
Surgical Robots

- Surgical robot market to reach significant growth
- Market size: $3.2 billion in 2012, anticipated to reach $19.96 billion by 2019

Assistive Robots

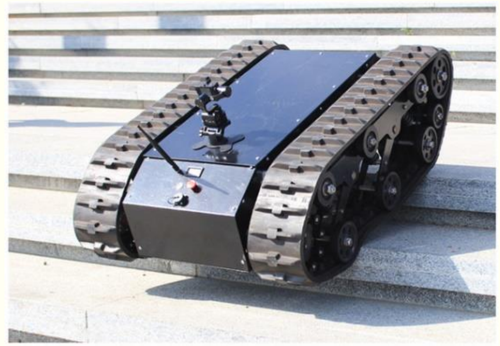
- Robotic vacuum cleaners
- Global market share of robotic vacuum cleaners -- 12% of $680 million

Popular Types of Mobile robots

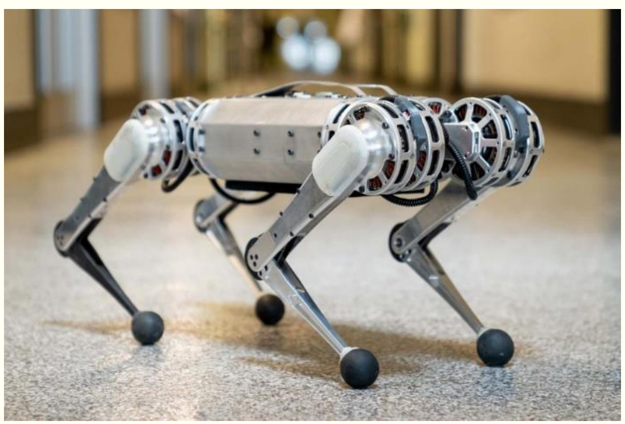


Land-based wheeled robot (UGV)

UGV: Unmanned Ground Vehicle



Land-based tracked robot



Land-based legged robot

Under water-based robot

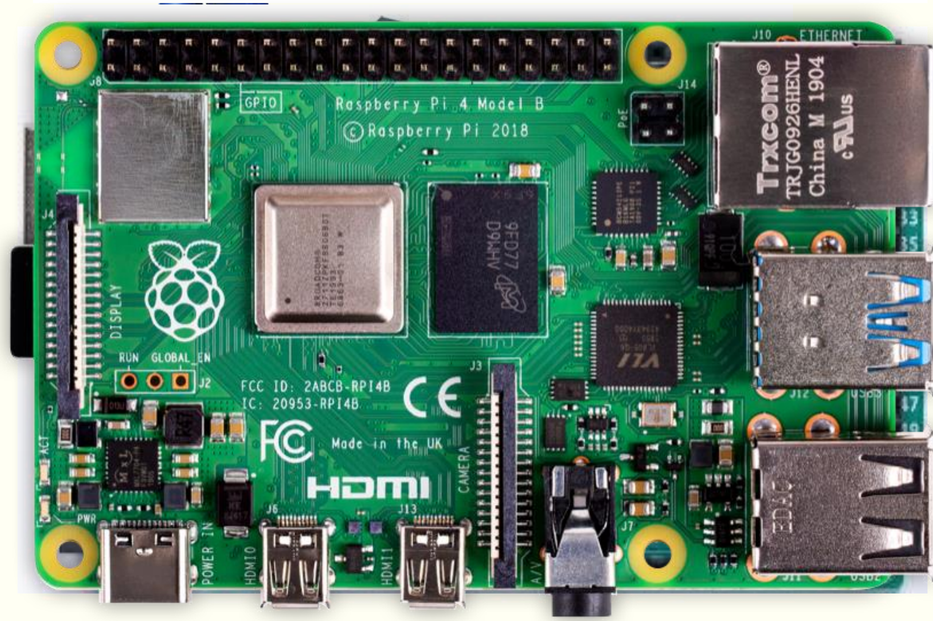
UUV: Unmanned Undersea (underwater) Vehicle

Air-based: plane ,helicopter , blimp (UAV)

UAV: Unmanned Aerial Vehicle

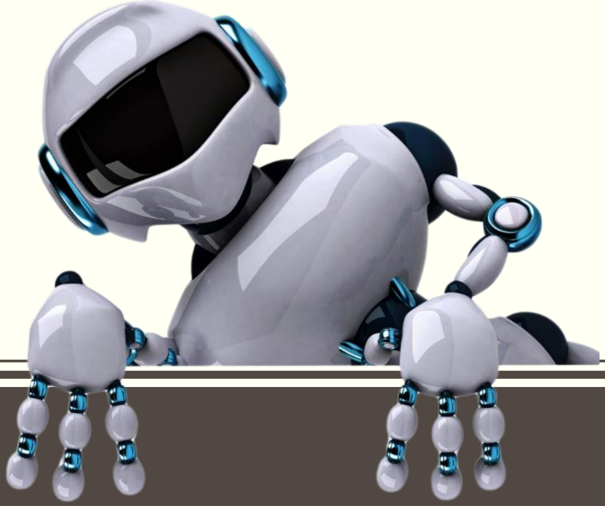
Components

- **Mechanical structure:** Body, frames, gears, belts, etc.
- **Sensors:** Vision, force, proximity, etc.
- **Actuators:** Electric (DC, stepper, AC), hydraulic, etc.
- **Power:** Battery, AC/DC, or Solar.
- **Electronics :** Conditioning and power circuits.
- **Controller:** Process sensory information and provides appropriate commands.
- **Software and user interface.**



Applications

- Industry
- Military
- Space Exploration
- Transportation
- Healthcare
- Entertainment
- Household



THANK YOU FOR LISTENING

ANY QUESTIONS ?

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Locomotion

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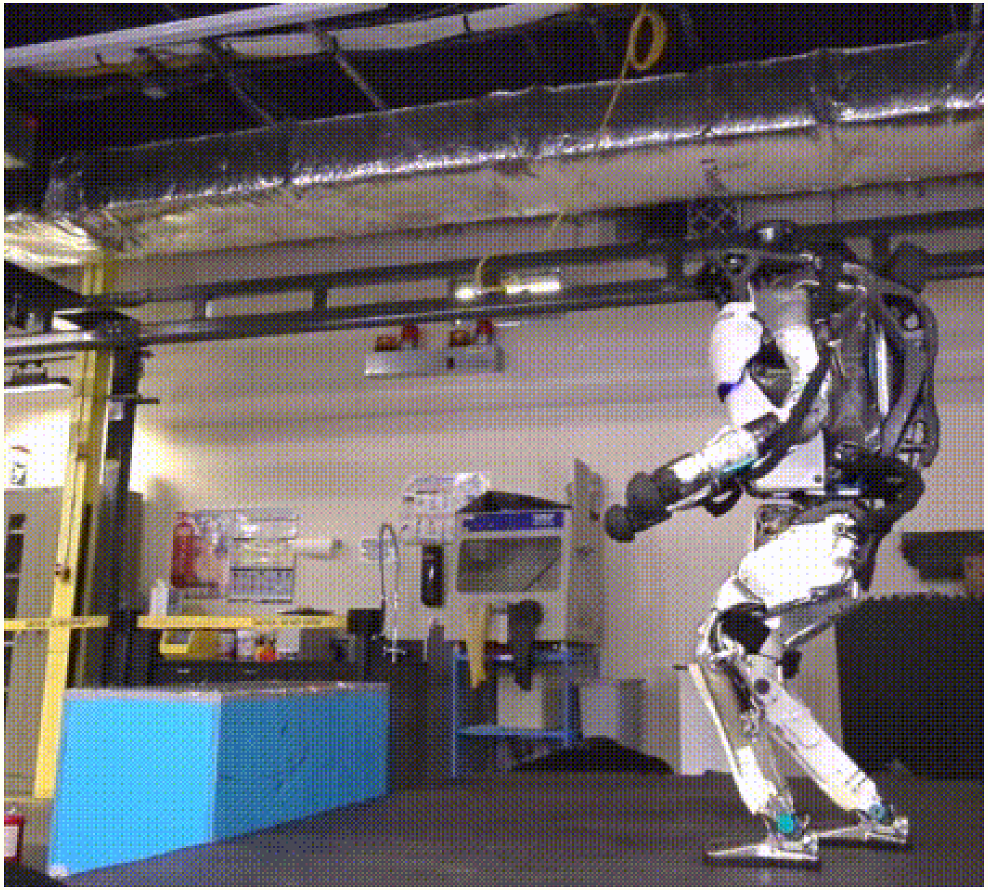


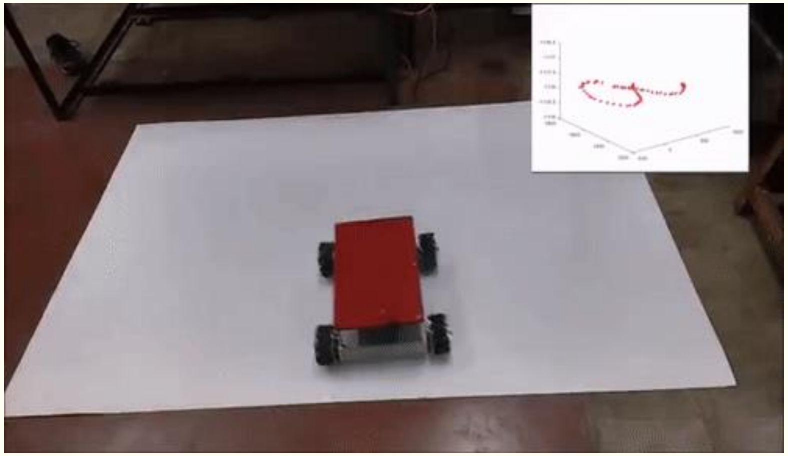
Introduction to Locomotion Concepts

Locomotion : is the means of movement from one place to another for the mobile robot.

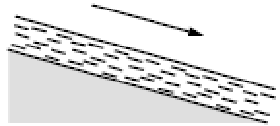
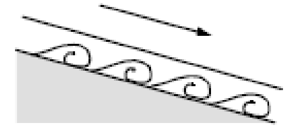
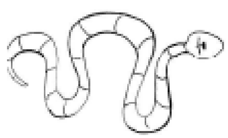
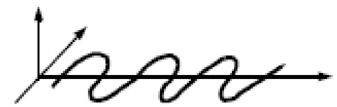
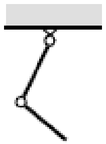
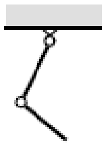
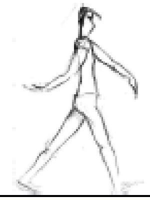
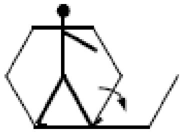
Locomotion is derived from the Latin "locus", place + "movere", move = move place.

- In manipulation, the robot arm is fixed but moves objects in the workspace by imparting force to them.

- In locomotion, the environment is fixed and the robot moves by imparting force to the environment.



Locomotion Concepts: Principles Found in Nature

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

1- Wheels

Wheels are used commonly for the most popular mobile robots. Four and six wheeled robots have the advantage of using multiple drive motors(one connected to each wheel) which reduces slip. Omni directional wheels , mounted properly, can give the robot significant mobility advantages.

Advantages

- Usually low-cost
- Simple design and construction
- Near infinite different dimensions cater to your specific project
- Six wheels can replace a track system
- Diameter, width, material, weight, tread etc. can all be custom to your needs
- Excellent choice for beginners

Disadvantages

- May lose traction (slip)
- Small contact area (small rectangle or line)

2- Tracks

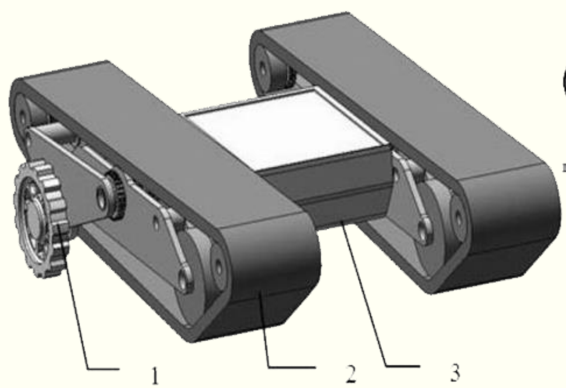
Track drive is the best for robots used outdoors and on soft ground. This kind of drive distribute the weight of the robot on the surface that the robot walk on.

Advantages

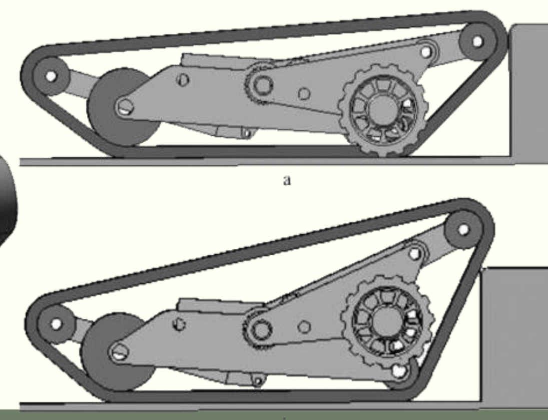
- Constant contact with the ground prevents slipping that might occur with wheels.
- Evenly distributed weight helps your robot tackle a variety of surfaces.

Disadvantages

- When turning, there is a side ways force that acts on the ground; this can cause damage to the surface the robot is being used on, and cause the tracks to wear.
- Not many different tracks are available (robot is usually constructed around the tracks)
- Increased mechanical complexity and connections



1. drive wheel mechanism 2.track mechanism
3. control system unit



3- Legs

Robots used legs when the surface is very uneven terrain. More legs is easiest to balance and fewer is harder . Researchers have experimented with monopod (one legged "hopping") designs, though bipeds (two legs) and quadrupeds (four legs) and hexapods (6 legs) are most popular.

Advantages:

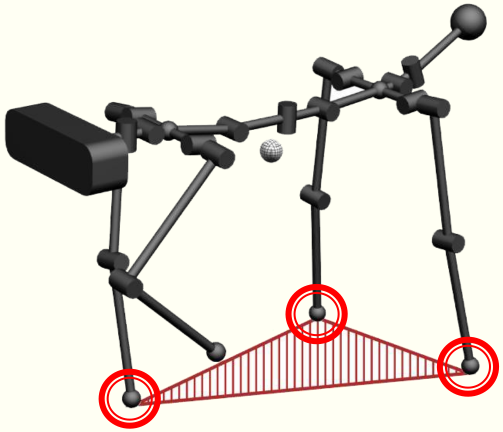
- Closer to organic/natural motion
- Can potentially overcome large obstacles and navigate very rough terrain

Disadvantages:

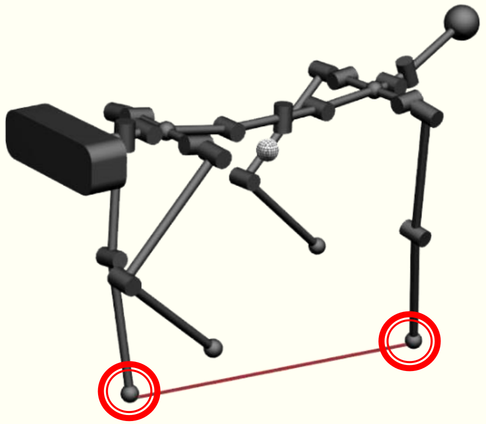
- Increased mechanical, electronic and coding complexity
- Lower battery size despite increased power demands
- Higher cost to build

Robot stability

- A robot is **statically stab**le if its center of gravity lies within the triangle formed by 3 contacts points to the ground.
  - Bodyweight supported by at least three legs
  - Even if all joints “freeze” instantaneously, the robot will not fall
  - Safe, slow and inefficient

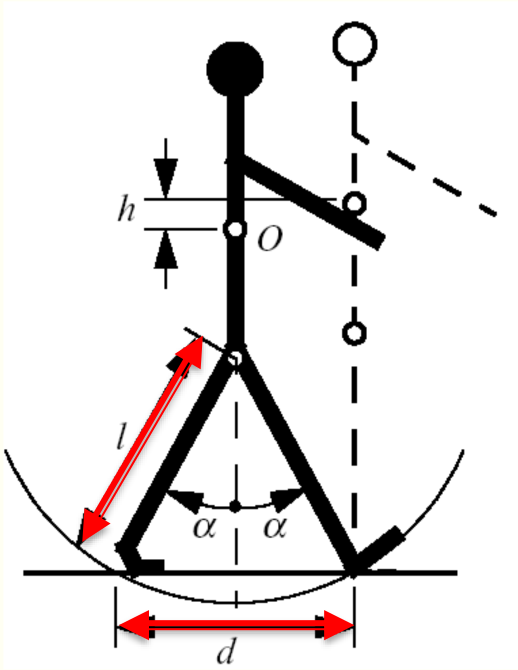


- Less than 3 contacts points usually results in the robot falling over. If it does not then the robot is **dynamically stable**.
  - The robot will fall if not continuously moving.
  - Less than three legs can be in ground contact.
  - fast, efficient, demanding for actuation and control.



Locomotion Concepts: Biped Walking

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.



Biped walking mechanism

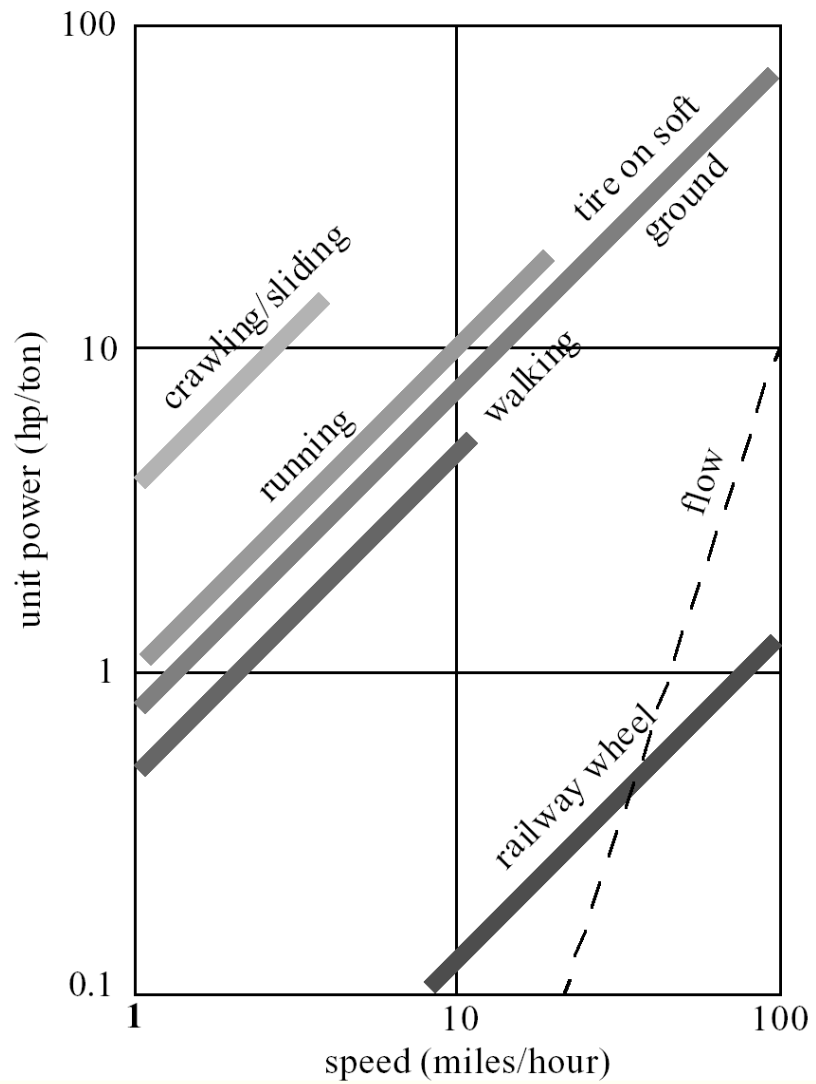
- not too far from real rolling
- rolling of a polygon with side length equal to the length of the step
- the smaller the step gets, the more the polygon tends to a circle (wheel)

But…

- rotating joint was not invented by nature
- Work against gravity is required
- More detailed analysis follows later in this presentation

Walking or rolling?

- number of actuators
- structural complexity
- control expense
- energy efficient
  - terrain (flat ground, soft ground, climbing..)
- movement of the involved masses
  - walking / running includes up and down movement of COG
  - some extra losses



Characterization of locomotion concept

- **Locomotion :**
  physical interaction between the vehicle and its environment.

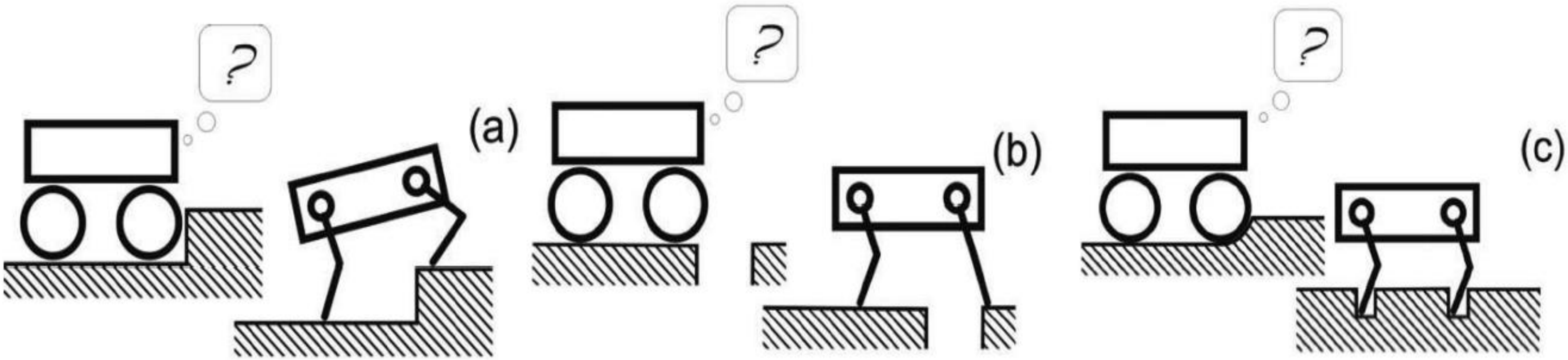
- Locomotion is concerned with **interaction forces**, and the **mechanisms** and **actuators** that generate them.

- The most important issues in locomotion are:

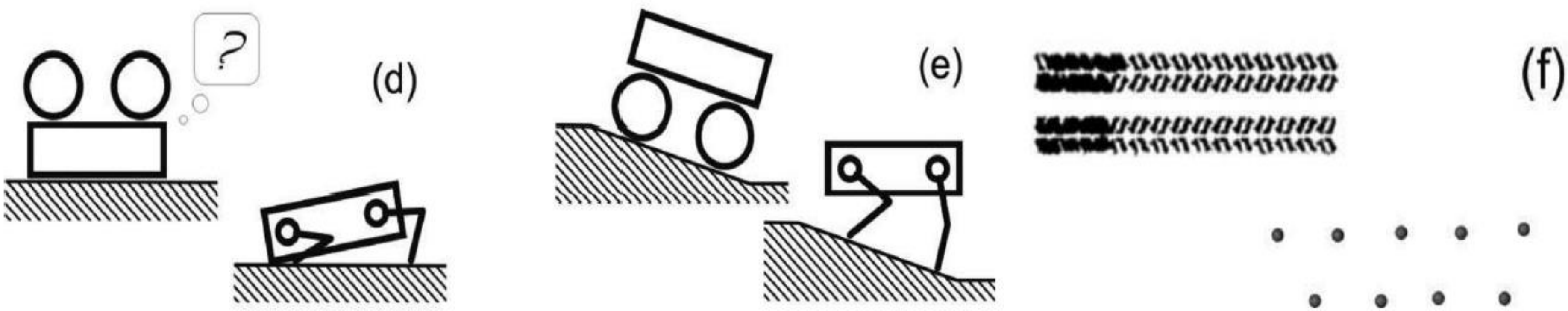
- **stability**
  - number of contact points
  - center of gravity
  - static/dynamic stabilization
  - inclination of terrain

- **characteristics of contact**
  - contact point or contact area
  - angle of contact
  - friction
- **type of environment**
  - structure
  - medium (water, air, soft or hard ground)

Locomotion for Legged Mobile Robots



able to traverse obstacles such as steps (a), gaps (b), or sandy patches (c) that are impassable for wheeled systems.

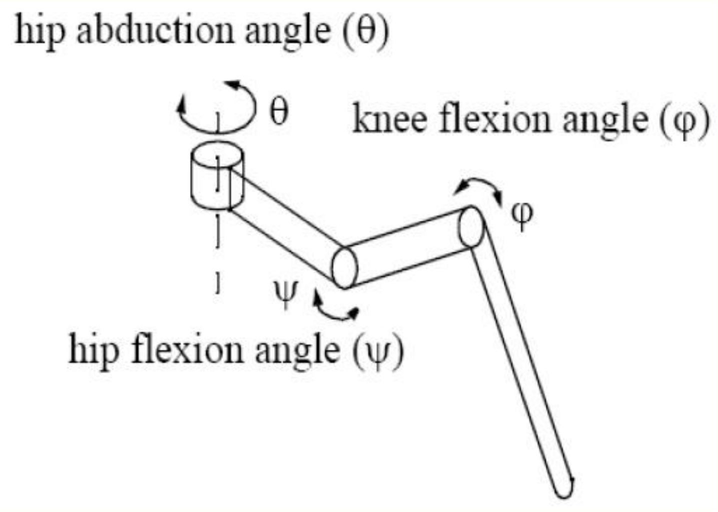


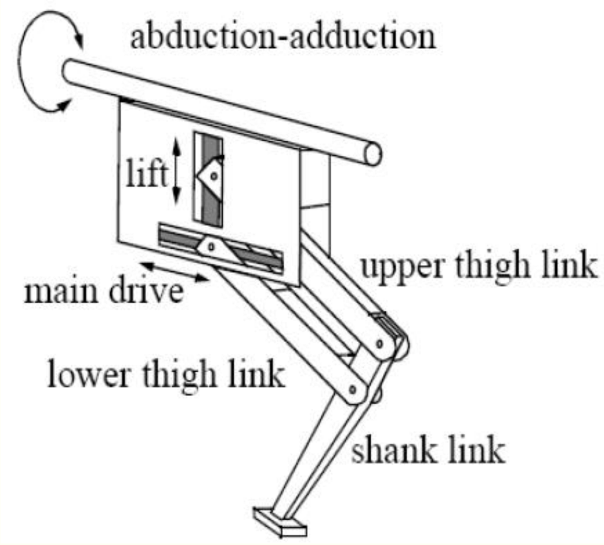
stand up when fallen (d) and keep its payload levelled (e) also reduces the environmental impact (f).

Number of Joints of Each Leg (DOF: degrees of freedom)

- **A minimum of two DOF is required to move a leg forward**
  - a lift and a swing motion.
  - Sliding-free motion in more than one direction not possible

- **Three DOF for each leg in most cases (as pictured below)**
- **4th DOF for the ankle joint**
  - might improve walking and stability
  - additional joint (DOF) increases the complexity of the design and especially of the locomotion control.





Leg configurations and stability

When we have multi-legged robot we face a problem with leg coordination for Locomotion or gait control.

For a mobile robot with legs, the total number of distinct event sequences N for a walking machine is:

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

- Where K is the number of legs.

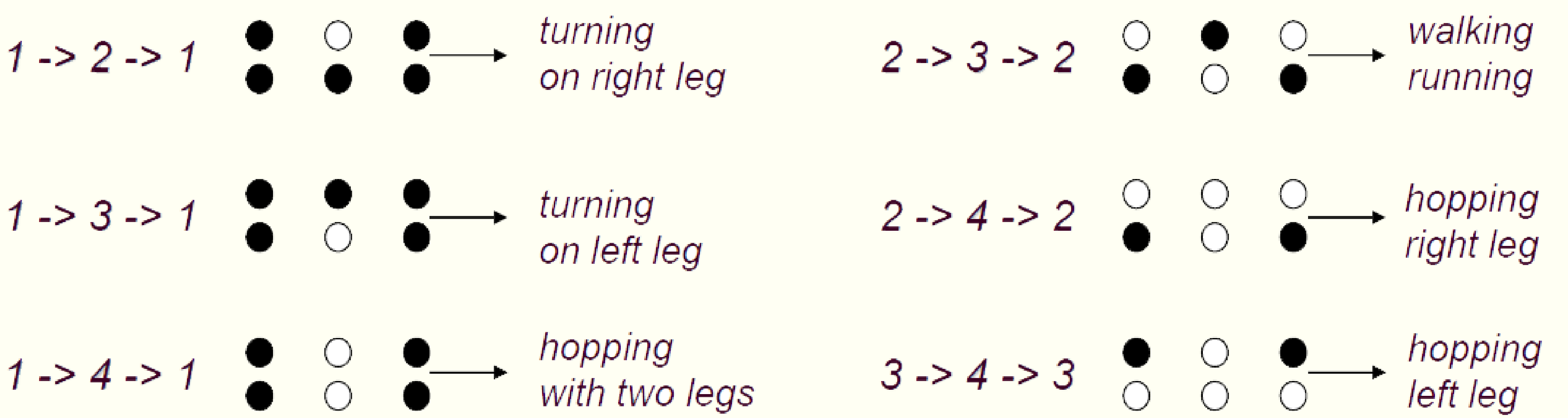
A **distinct event sequence** can be considered as a change from one state to another and back.

For a biped walker $k = 2$ legs, what are the number of distinct event sequences?

● *Leg down*
○ *Leg up*

- 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

- So we have the following $N = (2k-1)! = 6$ distinct event sequences (change of states) for a biped: For a biped walker $k = 2$ legs, the number of distinct event sequences N is : $N = (2k-1)! = 3! = 3 \cdot 2 \cdot 1 = 6$



Most Obvious Gait with 4 Legs

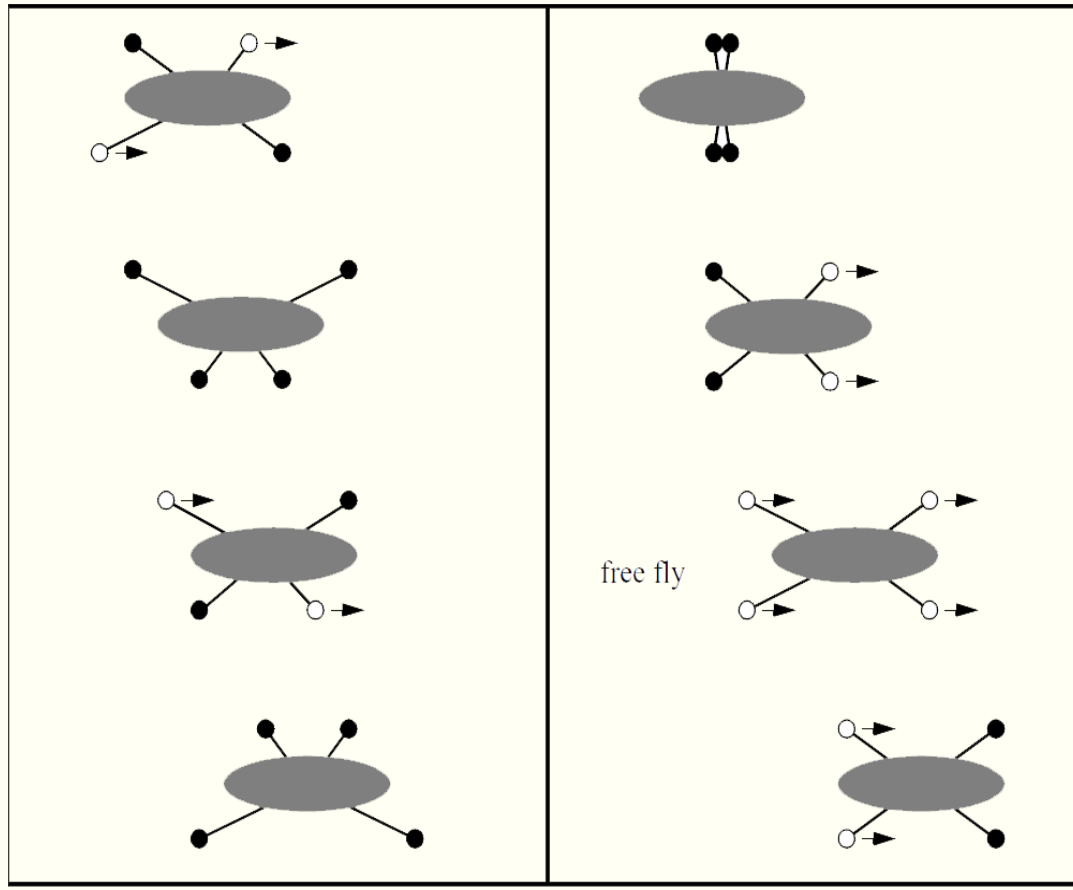
Two gaits with four legs. One of them is using opposite legs and the other parallel legs.

X-walker robot – 4 legs

https://www.youtube.com/watch?v=qrUSzcKZ3VQ

Gait with 4 Legs

https://www.youtube.com/watch?v=FVnmrvptmrM



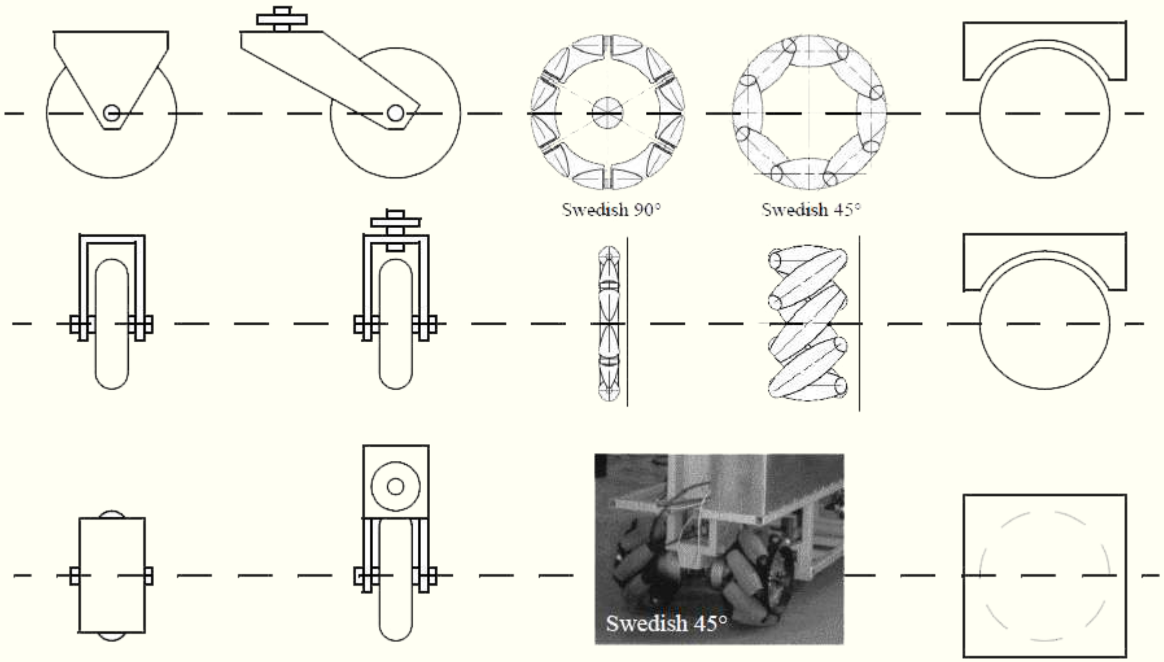
changeover walking

galloping

Mobile Robots with Wheels

Instead of worrying about balance, wheeled robot research tends to focus on the problems of traction and stability, maneuverability, and control.

- Wheels are the most appropriate solution for most applications
- Three wheels are sufficient to guarantee stability
- With more than three wheels an appropriate suspension is required
- Selection of wheels depends on the application

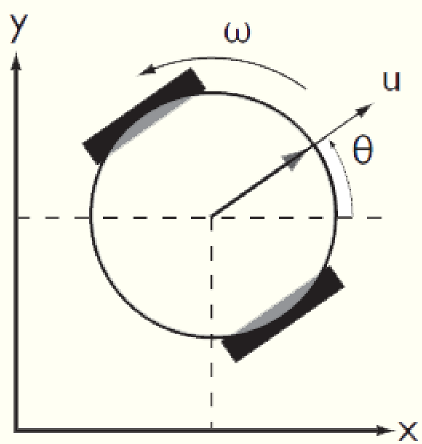


Degrees of Freedom

- Most actuators control a single degree of freedom (DOF)
  - a motor shaft controls one rotational DOF
  - a sliding part on a plotter controls one translational DOF

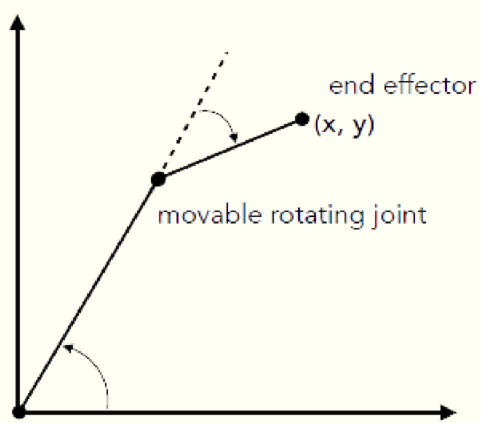
- Every robot has a specific number of DOF
- If there is an actuator for every DOF, then all DOF are controllable

DOF = ?



differential-drive robot

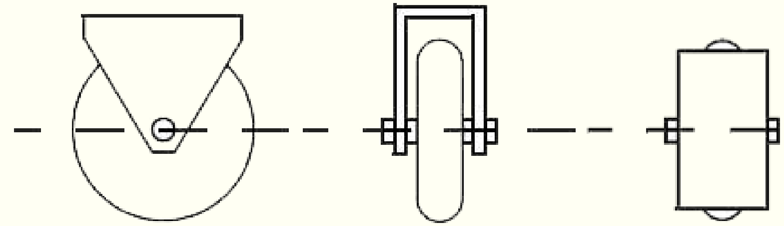
DOF = ?



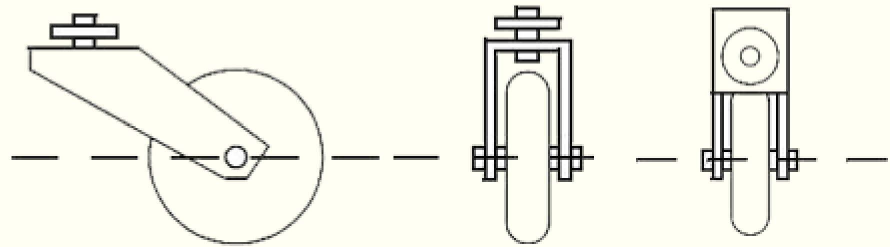
fixed rotating joint

The Four Basic Wheels Types

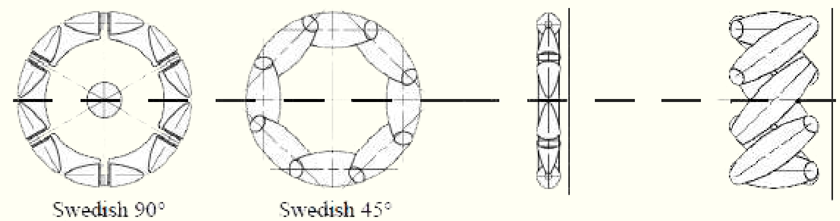
- **Standard wheel:** Two degrees of freedom; rotation around the (motorized) wheel axle and the contact point.



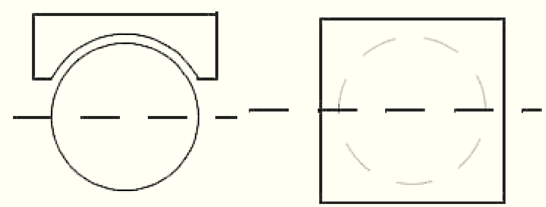
- **Castor wheel:** Three degrees of freedom; rotation around the wheel axle, the contact point and the castor axle.



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



- **Ball or spherical wheel:** Suspension technically not solved



Characteristics of Wheeled Robots and Vehicles

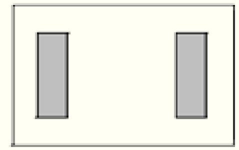
- **Stability** of a vehicle is be guaranteed with **3 wheels**
  - If center of gravity is within the triangle which is formed by the ground contact point of the wheels.

- Stability is improved by 4 and more wheel
  - however, these arrangements are hyper static and require a flexible suspension system.

- **Bigger wheels** allow to overcome **higher obstac**les
  - but they require higher torque or reductions in the gear box.
  - require high control effort
  - combining actuation and steering on one wheel makes the design complex and adds additional errors for odometry.

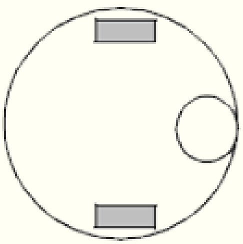
Different Arrangements of Wheels I

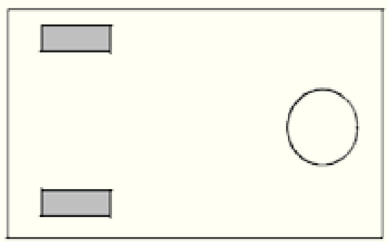
- Two wheels

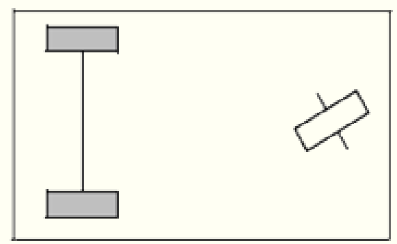


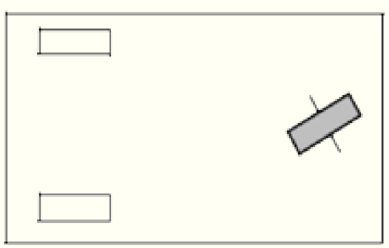
COG below axle

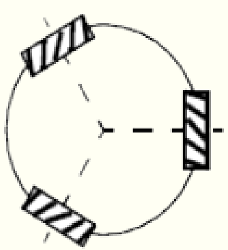
- Three wheels



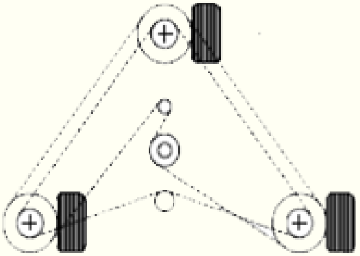






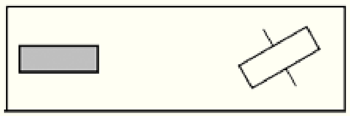
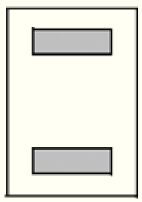
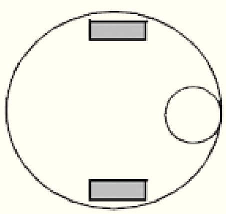
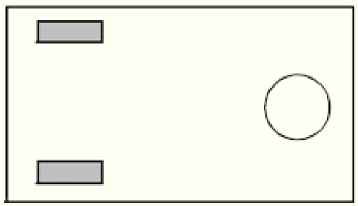


Omnidirectional Drive

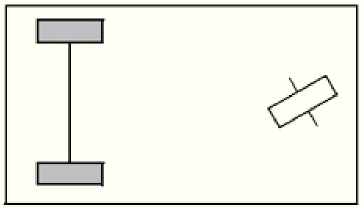
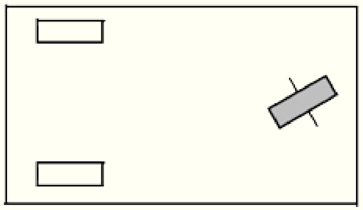
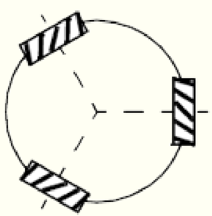
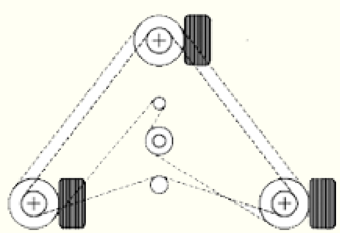


Synchro Drive

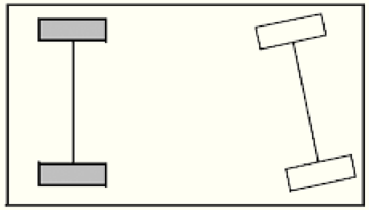
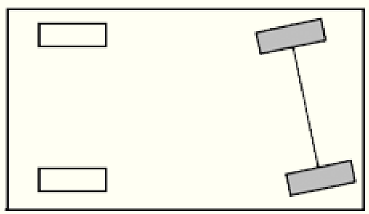
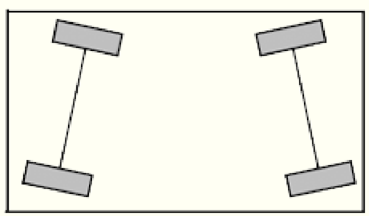
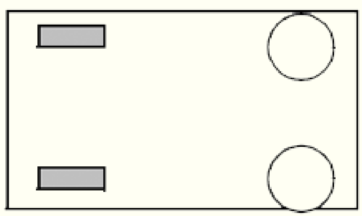
Wheel configurations for rolling vehicles

# of wheels	Arrangement	Description	Typical examples
2		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
3		Two-wheel centered differential drive with a third point of contact	Nomad Scout, smartRob EPFL
		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

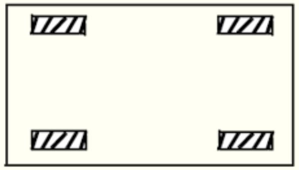
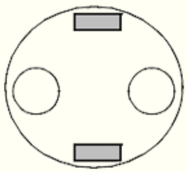
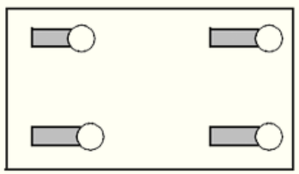
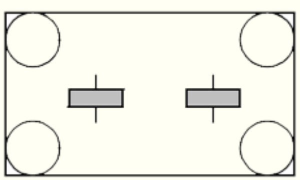
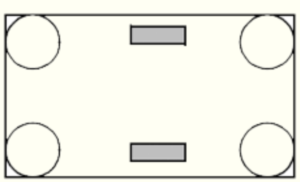
Wheel configurations for rolling vehicles

	Two connected traction wheels (differential) in rear, 1 steered free wheel in front	Piaggio minitrucks
	Two free wheels in rear, 1 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

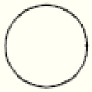
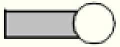
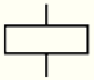
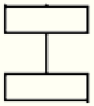
Wheel configurations for rolling vehicles

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
		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
		Four steered and motorized wheels	Four-wheel drive, four-wheel steering Hyperion (CMU)
		Two traction wheels (differential) in rear/front, 2 omnidirectional wheels in the front/rear	Charlie (DMT-EPFL)

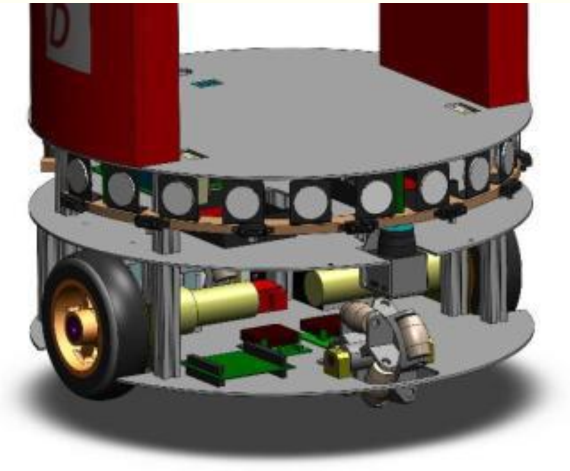
Wheel configurations for rolling vehicles

		Four omnidirectional wheels	Carnegie Mellon Uranus
		Two-wheel differential drive with 2 additional points of contact	EPFL Khepera, Hyperbot Chip
		Four motorized and steered castor wheels	Nomad XR4000
6		Two motorized and steered wheels aligned in center, 1 omnidirectional wheel at each corner	First
		Two traction wheels (differential) in center, 1 omnidirectional wheel at each corner	Terregator (Carnegie Mellon University)

Wheel configurations for rolling vehicles

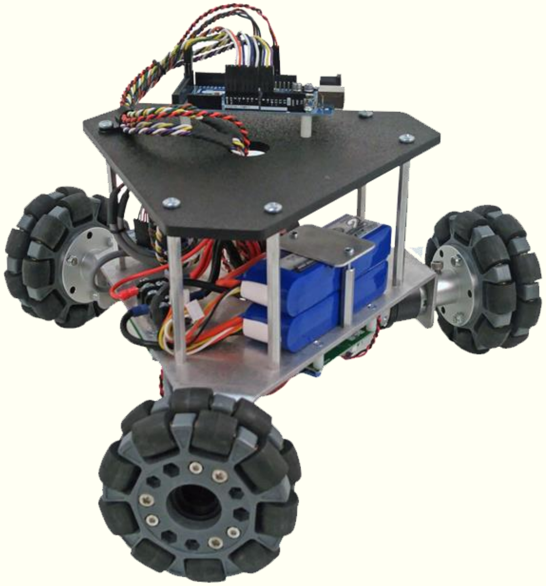
Icons for the each wheel type are as follows:	
	unpowered omnidirectional wheel (spherical, castor, Swedish);
	motorized Swedish wheel (Stanford wheel);
	unpowered standard wheel;
	motorized standard wheel;
	motorized and steered castor wheel;
	steered standard wheel;
	connected wheels.

Differential steering



- Here, two wheels are driven (but not steered) either forwards or backwards.
- A support (undriven) caster wheel is used for support.
- Two caster wheels can be used to keep symmetry:
  – added stability
  – axis of rotation at center of robot

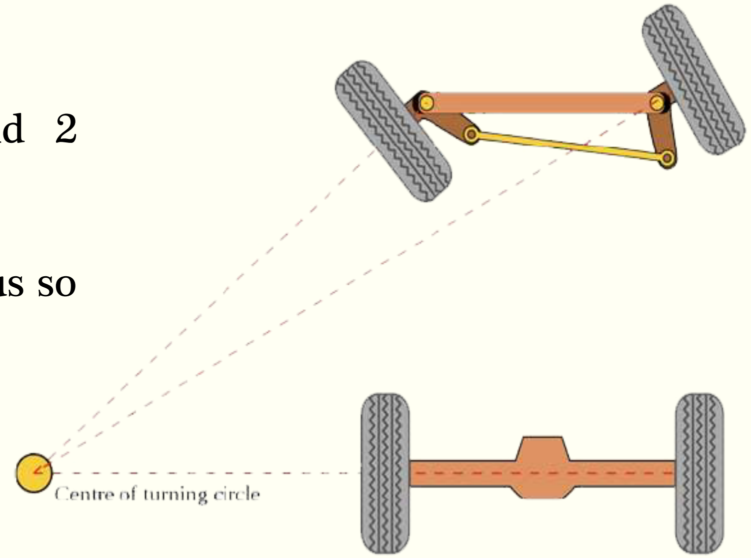
Omnidirectional



- 3 to 4 wheels (driven not steered) omnidirectional wheels.
- Relative rotation of each wheel determines translational and rotational speed of robot.

Ackerman steering

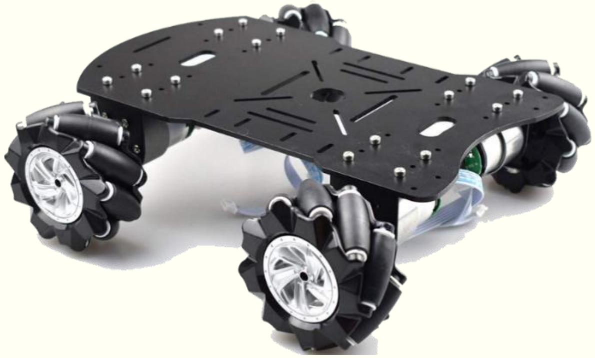
- Quad arrangement which two fixed wheels and 2 steered wheels (either pair or all 4 may be driven).
- When turning, the inner wheel is on a tighter radius so steering system should take account of this.



https://www.youtube.com/watch?v=bX3JQgb7GZk&t=2s

Mecanum

- Quad arrangement with all 4 wheels driven.
- Relative rotation of each wheel determines translational and rotational speed of robot.



https://www.youtube.com/watch?v=Ne09Y72zW_Y

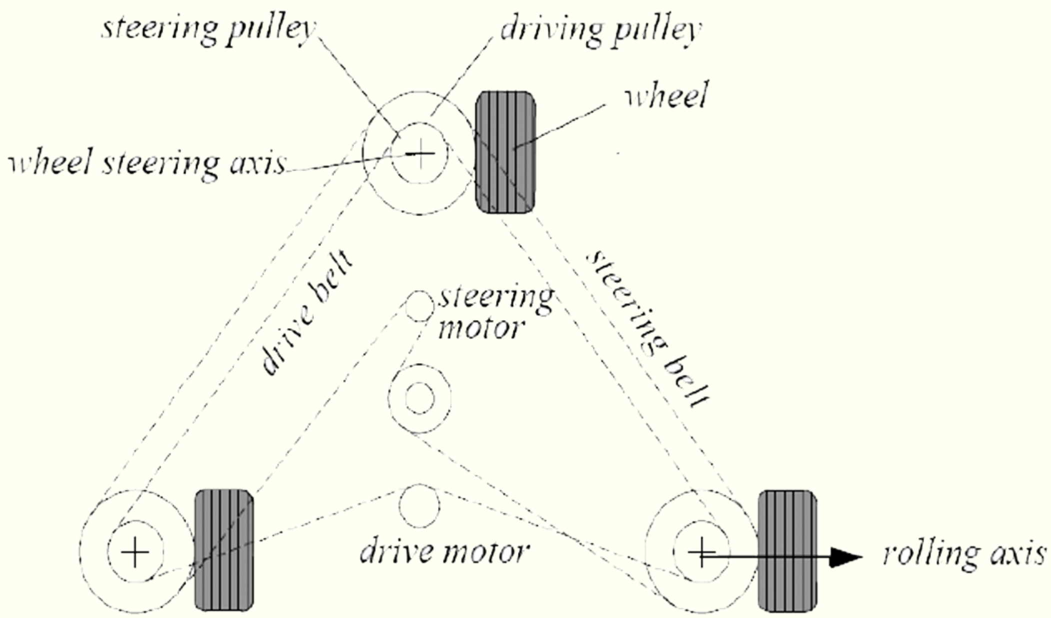
Synchro Drive system

- All wheels are actuated synchronously by one motor.
  - defines the speed of the vehicle

- All wheels steered synchronously by a second motor.
  - sets the heading of the vehicle

- The orientation in space of the robot frame will always remain the same
  - It is therefore not possible to control the orientation of the robot frame.

https://www.youtube.com/watch?v=nurCA5Q4_hw



Three aspects in wheeled Mobile robotics

Stability: the minimum number of wheels required for static stability is two. A two-wheel differential drive robot can achieve static stability if the center of mass is below the wheel axle.

Note: Conventionally, static stability requires a minimum of three wheels, adding more wheels need to think about Suspension system for uneven terrain

Maneuverability :

A robot operating in a planar environment has 3 degrees of freedom which are (X, Y and theta)

• The ability to operate instantaneously in each of these degrees is determined by the direction a wheel can roll and whether it is steerable.

Controllability :

• Convert desired rotational and translational velocities to individual wheel commands
• Controlling the orientation of the mobile robot.

Degree of mobility: DOM (differentiable DOF)

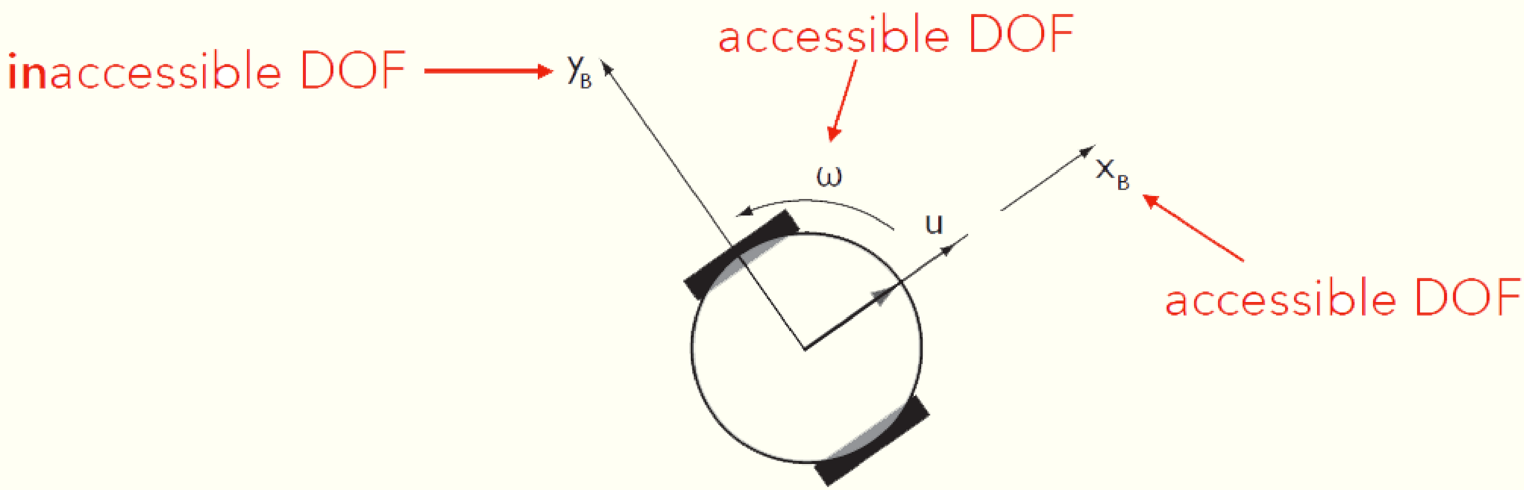
Degree of mobility (DOM): Number of DOF that can be directly accessed by the actuators
A robot in the plane has at most 3 DOMs (position and heading).

Holonomic motion:

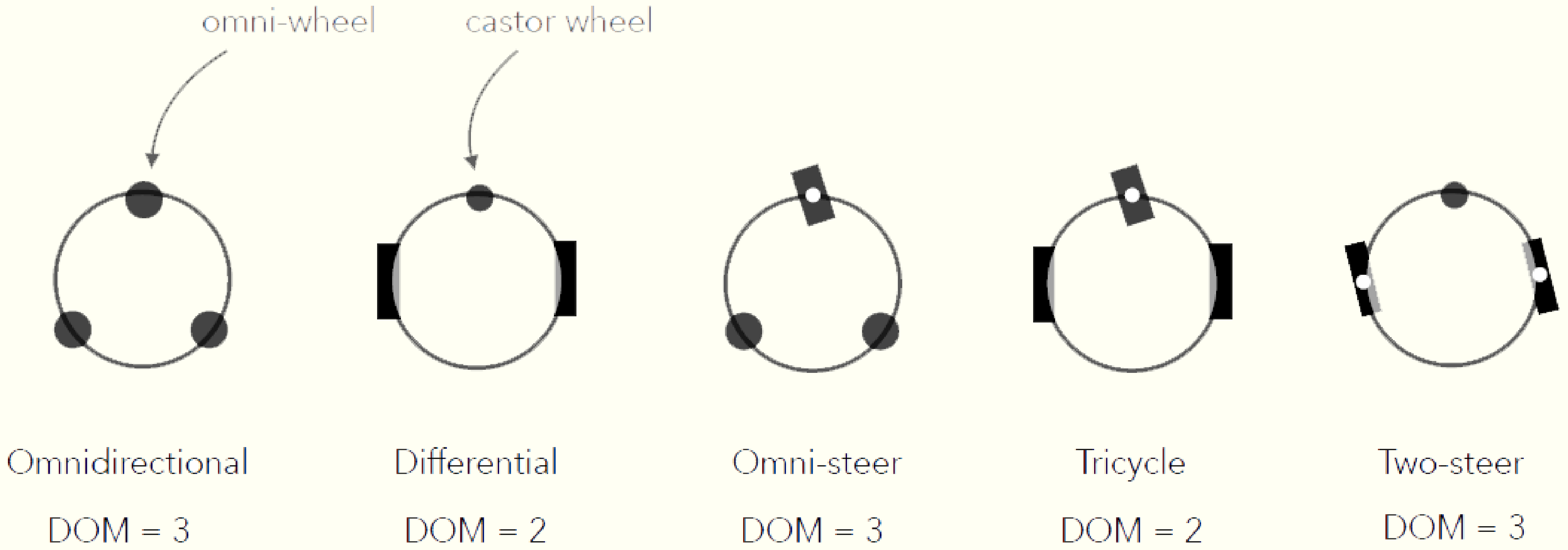
- **Holonomic robot:** When the number of DOF is equal to robot's DOM
- **Non-holonomic robot:** When the number of DOF is greater than robot's DOM
  When a robot's DOM it is larger than is DOF, the robot has 'redundant' actuation

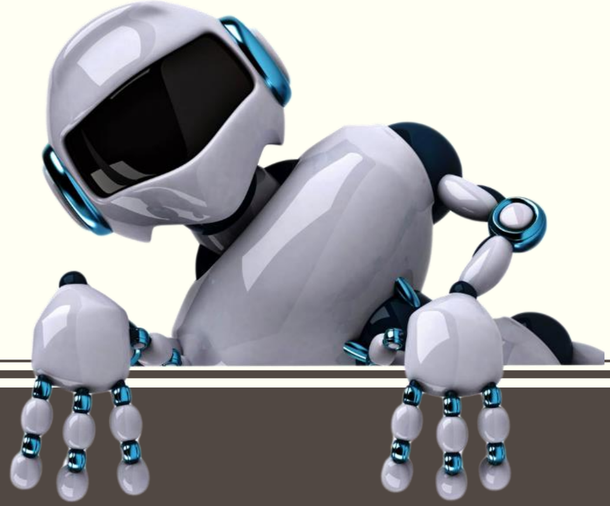
Differential-Drive Robot

Differential-drive robots can actuate left and right wheels (independently).



5 basic types of 3-wheel configurations:





THANK YOU FOR LISTENING

ANY QUESTIONS ?

3

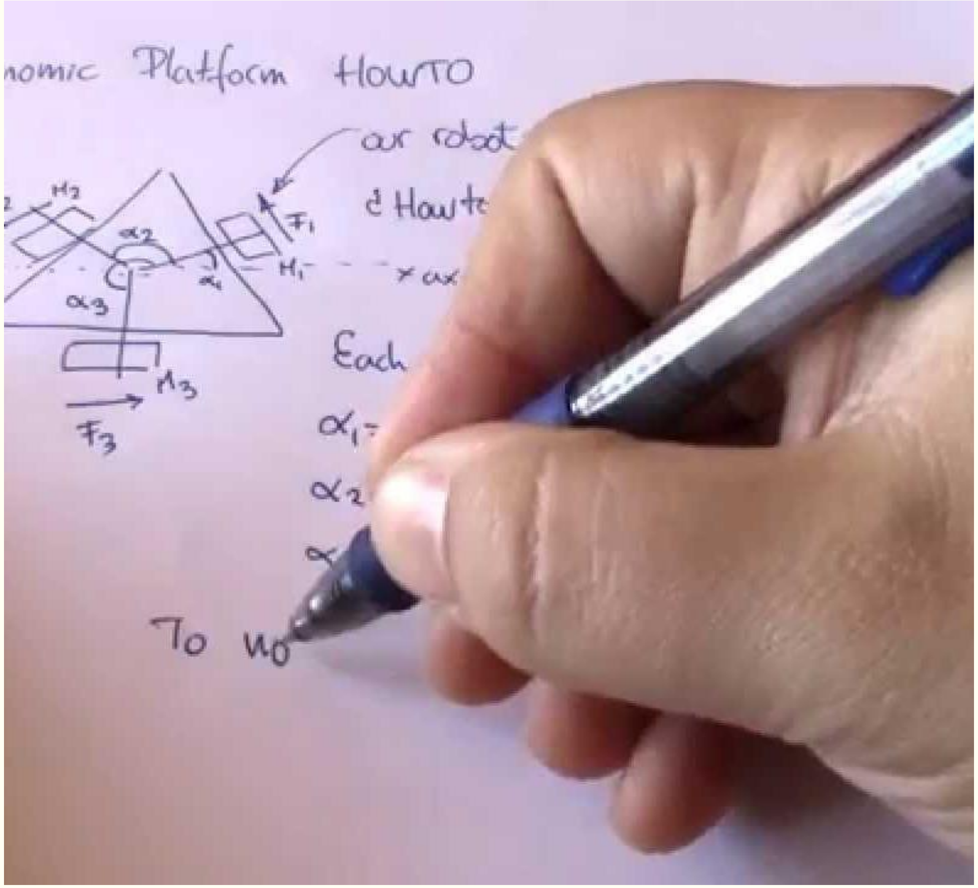
MOBILE ROBOT

DIFFERENTIAL MOBILE ROBOT

Lecturer:

Mohanad N. Noaman

Ninevah University
Electronics engineering college

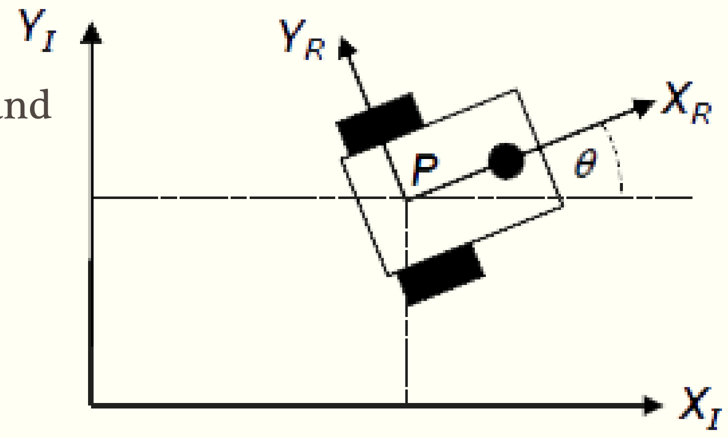


Modelling

- In order for a robot to follow a particular trajectory, we must drive the wheels at appropriate velocities.
- To know what velocities we require, we must determine a kinematic model of the robot.
- Using this model, we can then devise an appropriate control scheme to drive the robot along the required trajectory.

Coordinate frames

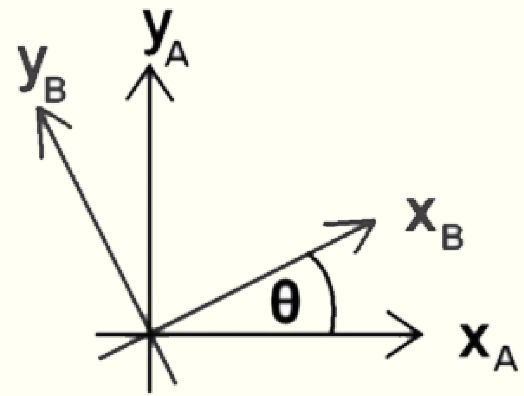
- We shall denote the global reference frame as *I* and the robot frame as *R*.
- Point **P** is mid-point of axle.



Transformation matrix

– We shall now have a look at transformation between two reference frames. Since we are only considering rotations about the $z-axis$, this simplifies the analysis.

– Consider the two coordinate systems A and B in which there is a rotation between them of angle θ.



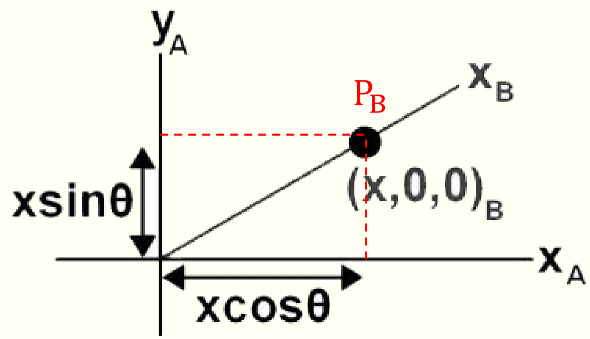
Rotation matrix

- Coordinate frame B is rotated by an angle θ to coordinate frame A.
- For a point in frame B, labelled P_B, what is the coordinates of this point with respect to frame A, labelled P_A?
- For this we need the rotation matrix ${}^{A}R_{B}$ to transform from frame B to A, i.e. $P_A = {}^{A}R_{B}P_B$. How do we calculate this?

$${}^{A}R_{B}$$

Rotation matrix

Consider $P_B = (x, 0, 0)$.
Drawing this we see from geometry that this corresponds to $P_A = (x\cos\theta, x\sin\theta, 0)$.

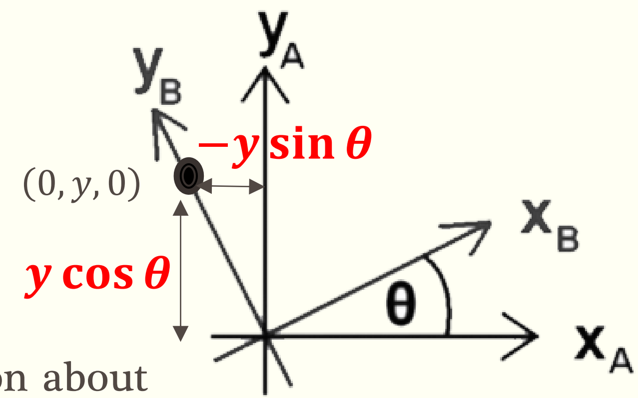


Thus, we know our rotation matrix looks something like:

$$\begin{bmatrix} x\cos\theta \\ x\sin\theta \\ 0 \end{bmatrix}_B = {}^{A}\begin{bmatrix} \cos\theta & ? & ? \\ \sin\theta & ? & ? \\ 0 & ? & ? \end{bmatrix}_B \begin{bmatrix} x \\ 0 \\ 0 \end{bmatrix}_B$$

Now considering point $P_B = (0, y, 0)$ we see $P_A = (-y\sin\theta, y\cos\theta, 0)$. Hence:

$$\begin{bmatrix} -y\sin\theta \\ y\cos\theta \\ 0 \end{bmatrix}_B = {}^{A}\begin{bmatrix} \cos\theta & -\sin\theta & ? \\ \sin\theta & \cos\theta & ? \\ 0 & 0 & ? \end{bmatrix}_B \begin{bmatrix} 0 \\ y \\ 0 \end{bmatrix}_B$$



A point $P_B = (0, 0, z)$ goes to $P_A = (0, 0, z)$, i.e. a rotation about θ doesn't affect z, hence:

$${}^{A}R_B = {}^{A}\begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}_B$$

Exercise

We have found rotation matrix for converting from a position defined in frame B to a position defined by frame A. However, what happens when we have a point defined in A and we want to express this in terms of frame B? Determine the appropriate matrices for these rotations.

Coordinate frames

- The robot's position is defined by: $\zeta_I = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}$
- We use the orthogonal rotation matrix:

$$R(\theta)^{-1} = \begin{bmatrix} cos\theta & sin\theta & 0 \\ -sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R(\theta) = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta & cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Transforming between frames:

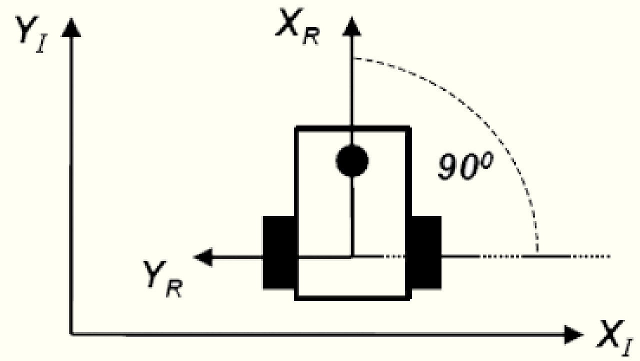
Given the two coordinate frames Zeta ζ_I (global frame) and Zeta ζ_R (robot frame), we can represent the robot velocity as:

$$\dot{\zeta}_R = R(\theta)^{-1} \dot{\zeta}_I$$

$$\dot{\zeta}_I = R(\theta)\, \dot{\zeta}_R$$

Example:

A robot has a global velocity of: $\dot{\zeta}_I = \begin{bmatrix} 0 \\ 1 \\ 3 \end{bmatrix}$



For the orientation shown, what is the velocity of the robot in the robot reference frame?

Solution:

Using the rotation matrix with $\theta = 90^\circ$

$$\dot{\zeta}_R = R(\theta)^{-1}\dot{\zeta}_I$$

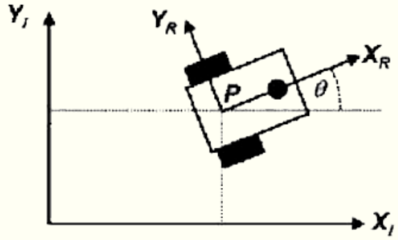
$$\dot{\zeta}_R = R(90^\circ)^{-1}\dot{\zeta}_I$$

$$= \begin{bmatrix} cos90^\circ & sin90^\circ & 0 \\ -sin90^\circ & cos90^\circ & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 3 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 3 \end{bmatrix}$$

Exercise

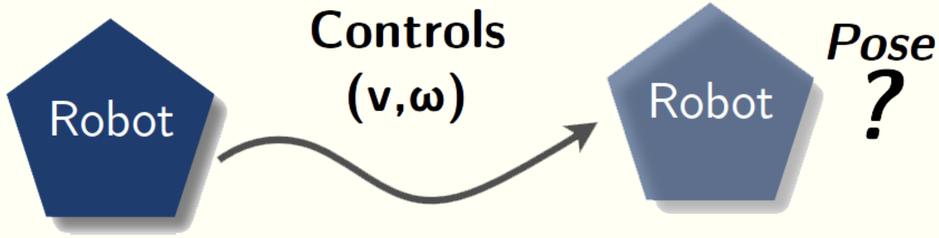
In the robot's frame of reference, its velocity is $(4, 0, -2)$.

For $\theta = 90^{\circ}$ what is the velocity in the global frame?

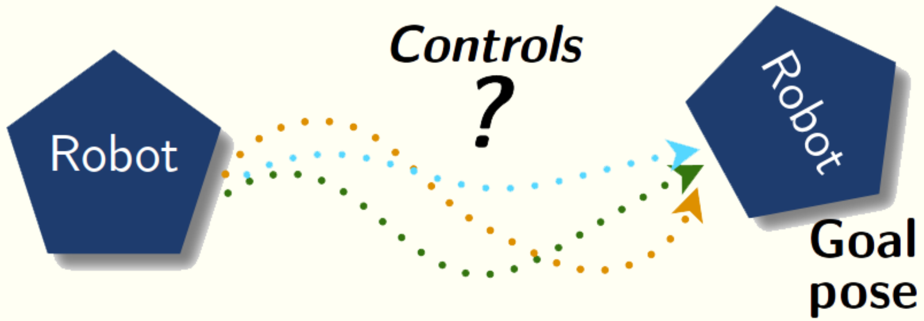


Kinematics

- **Forward** kinematics:
  - » Given the control parameters (e.g., wheel velocities), and the time of movement t, **find the pose** (x, y, θ) reached by the robots.

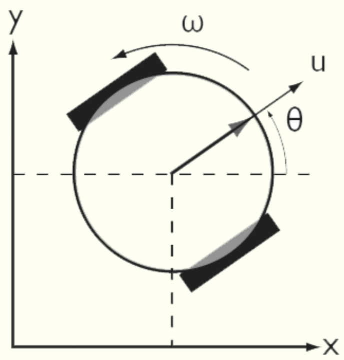


- **Inverse** kinematics:
  - » Given the final desired pose (x, y, θ), **find the control parameters** to move the robot there at a given time t.



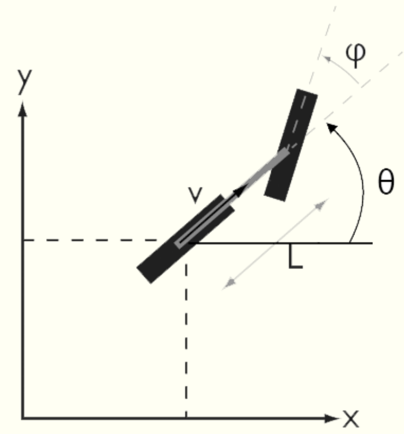
Forward Kinematics

- Differential equations describe robot motion
- How does robot state change over time as a function of control inputs?



$$\begin{cases} \dot{x} = u \cdot \cos\theta \\ \dot{y} = u \cdot \sin\theta \\ \dot{\theta} = \omega \end{cases}$$

differential-drive model
3 DOF (2 controllable)

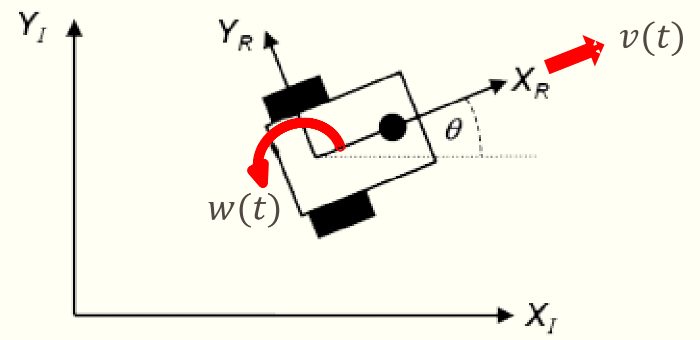


$$\begin{cases} \dot{x} = v \cdot \cos\theta \\ \dot{y} = v \cdot \sin\theta \\ \dot{\theta} = v \cdot \frac{\tan\phi}{L} \end{cases}$$

bicycle model
3 DOF (2 controllable)

Forward kinematic model

Consider the global velocity as a function of robot parameters.



Parameters

$$\dot{\zeta}_I = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = f(l,\ r,\ \theta,\ \dot{\varphi}_1, \dot{\varphi}_2)$$

$\dot{\varphi}_1, \dot{\varphi}_2$: the wheel's angular velocity.

r: the wheel radius.

l: is the center point-wheel distance.

$\dot{\zeta}_I$: the robot motion in the world frame.

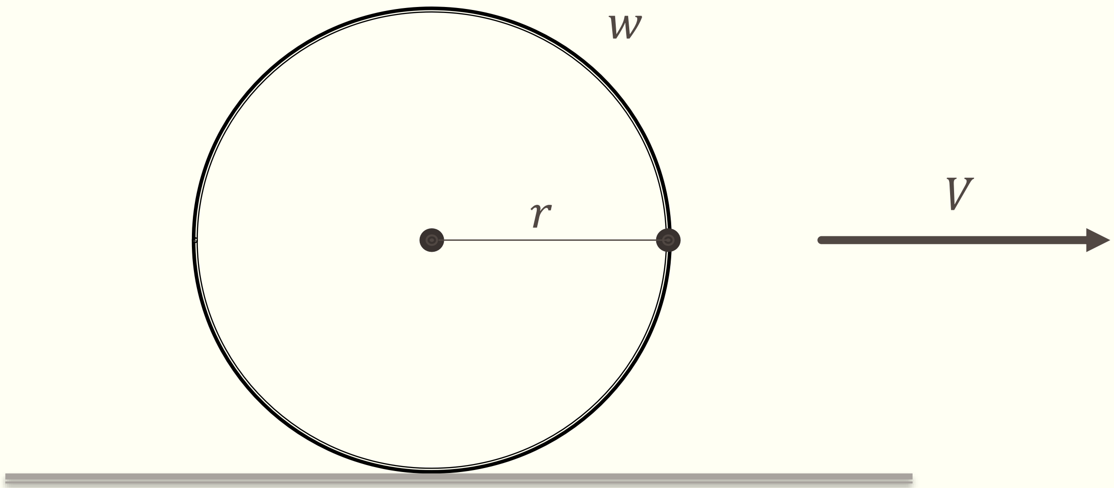
Forward kinematic model

$$V = \frac{D}{t}$$

When:

$$D = 2\pi r$$

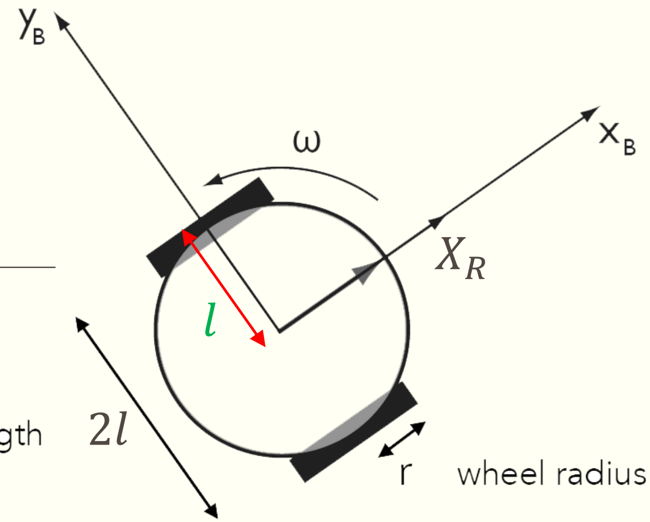
$$V = \frac{2\pi r}{t} = wr$$



Forward Kinematics

Actuators of differential-drive:

- Left wheel speed φ_1
- Right wheel speed φ_2



Forward velocity: $V_l = r\dot{\varphi}_1, V_r = r\dot{\varphi}_2$ (wheel linear velocity)

x - component

$$\dot{X}_R = \frac{V_l + V_r}{2} = \frac{1}{2} r\dot{\varphi}_1 + \frac{1}{2} r\dot{\varphi}_2$$

y - component

$$\dot{y}_R = 0$$

Motion:

$$\dot{x}_B = \dot{X}_R$$

$$\dot{y}_B = 0$$

$$\dot{\theta} = \omega$$

Rotational velocity:

- Consider only 1 wheel moving.
- Robot will pivot about stationary wheel with angular velocity:

$$\omega_1 = \frac{r\dot{\varphi}_1}{2l}$$

- A similar argument will apply to the other wheel (note rotation will be in the reverse direction):

$$\omega = \frac{r\dot{\varphi}_1}{2l} - \frac{r\dot{\varphi}_2}{2l}$$

Inverse kinematic model

It is now relatively easy to use this model to calculate the wheel velocities for a required global velocity:

$$\dot{\zeta}_I = R(\theta)\begin{bmatrix} \frac{1}{2}r\dot{\varphi}_1 + \frac{1}{2}r\dot{\varphi}_2 \\ 0 \\ \frac{r\dot{\varphi}_1}{2l} - \frac{r\dot{\varphi}_2}{2l} \end{bmatrix}$$

$$\begin{bmatrix} \frac{1}{2}r\dot{\varphi}_1 + \frac{1}{2}r\dot{\varphi}_2 \\ 0 \\ \frac{r\dot{\varphi}_1}{2l} - \frac{r\dot{\varphi}_2}{2l} \end{bmatrix} = R(\theta)^{-1}\dot{\zeta}_I$$

$$\dot{\zeta}_I = \frac{r}{2}R(\theta)\begin{bmatrix} 1 & 1 \\ 0 & 0 \\ \frac{1}{l} & -\frac{1}{l} \end{bmatrix}\begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{bmatrix}$$

Forward Kinematics

Right and left wheel velocities can be determined as

$$\omega \cdot (R + b/2) = v_R$$
$$\omega \cdot (R - b/2) = v_L$$

Solving these two equations for ω and R, while the latter is defined as the distance from ICR to the center of the robot

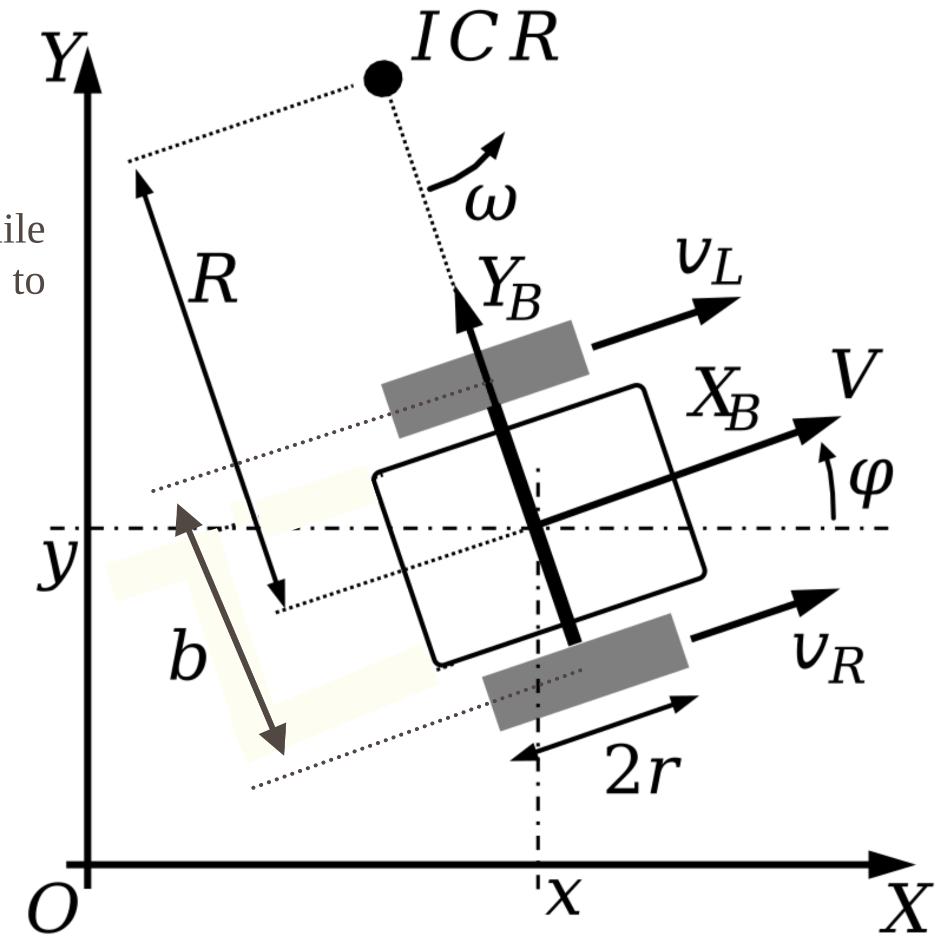
$$\omega = (v_R - v_L)/b$$
$$R = b/2 \cdot (v_R + v_L)/(v_R - v_L)$$

Using the equation for the angular velocity, the instantaneous velocity V of the point midway between the robot's wheels is given by

$$V = \omega \cdot R = \frac{v_R + v_L}{2}$$

The wheel tangential velocities can also be written as

$$v_L = r \cdot \omega_L$$
$$v_R = r \cdot \omega_R$$



HOMEWORK

For a differential drive robot with:

$\theta = \frac{\pi}{2} \quad r = 1 \quad l = 1$

and wheel angular velocities of:

$$\dot{\varphi}_1 = 4 \qquad \dot{\varphi}_2 = 2$$

what is the robot's global velocity?

For a differential drive robot with:

$\theta = 90^\circ \quad r = \frac{1}{4} \quad l = \frac{1}{2}$

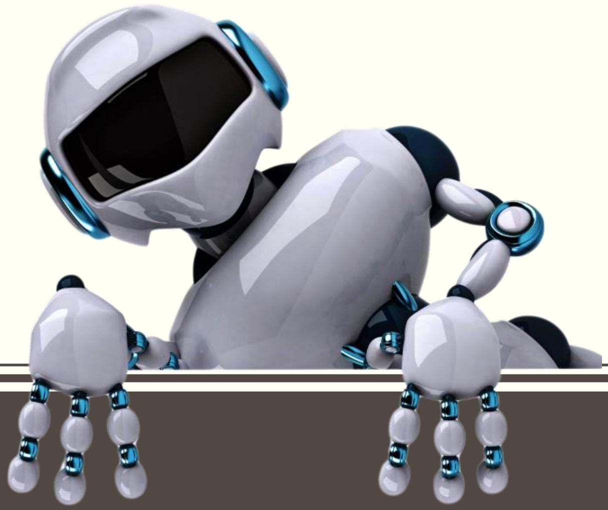
what wheel angular velocities are required to give a global velocity of:

$$v_x = 0, \qquad v_y = 3 \qquad \dot{\theta} = 1$$

Summary

- Wheel configuration predominantly depends on the application required.
- Analysis of a robot is usually performed within its own frame of reference. Determining the equivalent effect in the global frame is done through the utilization of rotation matrices.
- A kinematic model for the robot may be developed. This model may be used to determine global velocities (if wheel velocities are known) or determine what wheel velocities are required for specified global velocities.

In the next lecture, we will look at developing a kinematic model for wheel configurations in general.



THANK YOU FOR LISTENING

ANY QUESTIONS ?

4

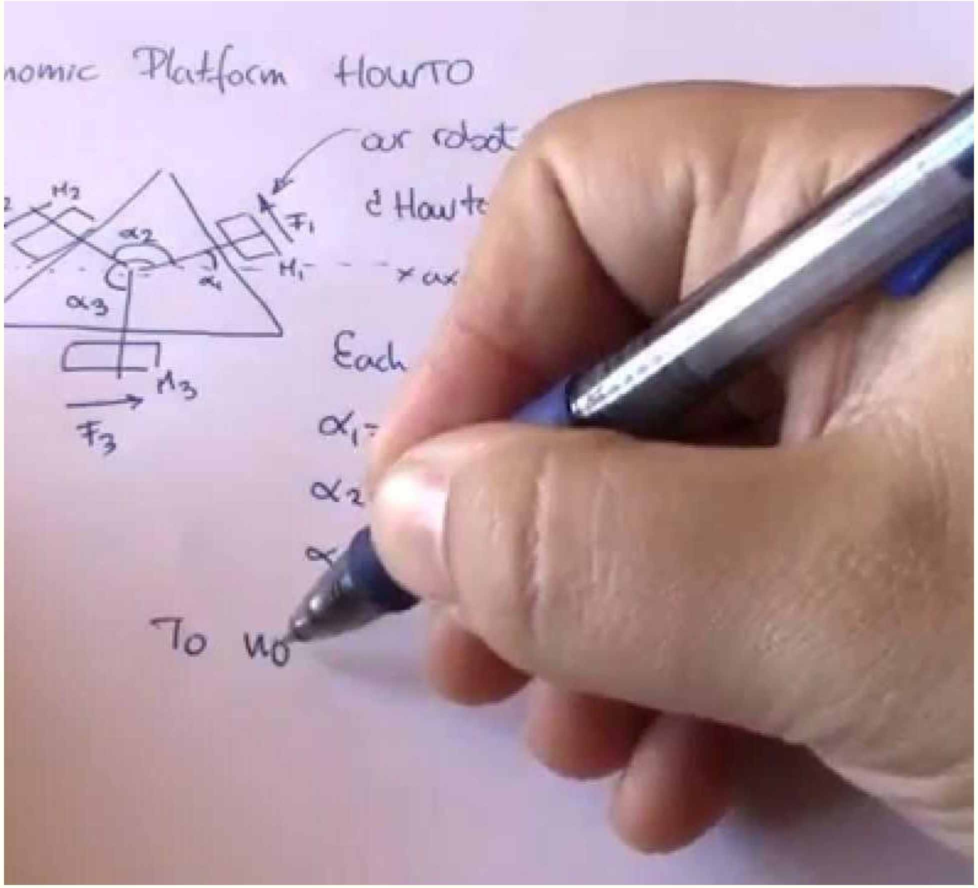
MOBILE ROBOT

Modelling II

Lecturer:

Mohanad N. Noaman

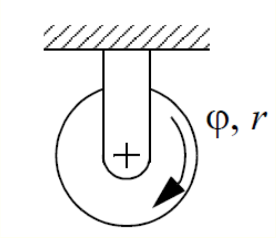
Ninevah University
Electronics engineering college

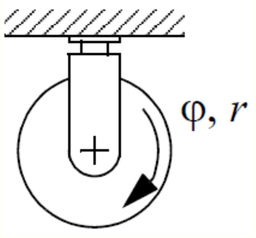


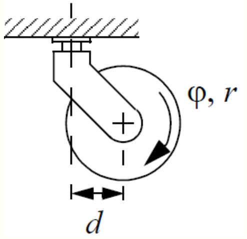
Wheel kinematic constraints

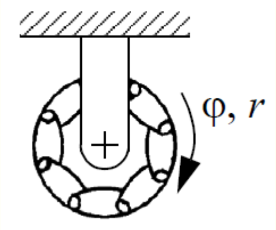
There are four basic wheel types:

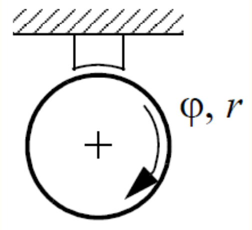
1. Fixed standard wheel
2. Steered standard wheel
3. Castor wheel
4. Swedish wheel
5. A spherical wheel





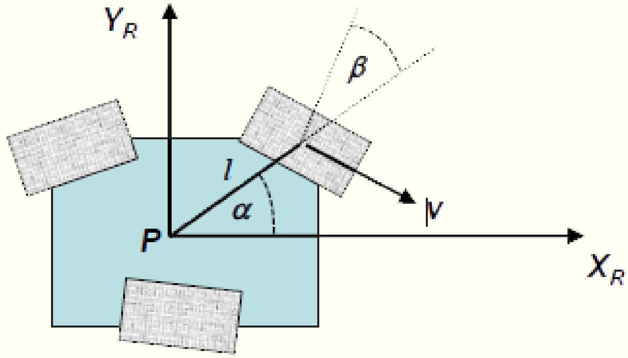




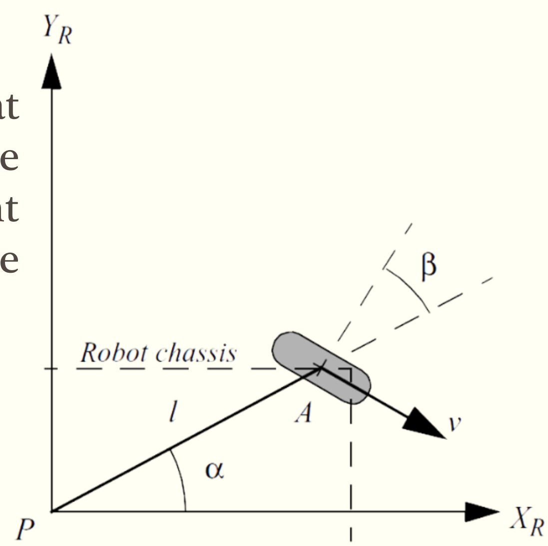


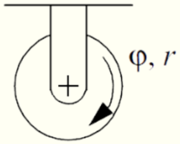
Wheel kinematic constraints: Fixed standard wheel

Consider a fixed wheel with respect to the robot coordinate frame.



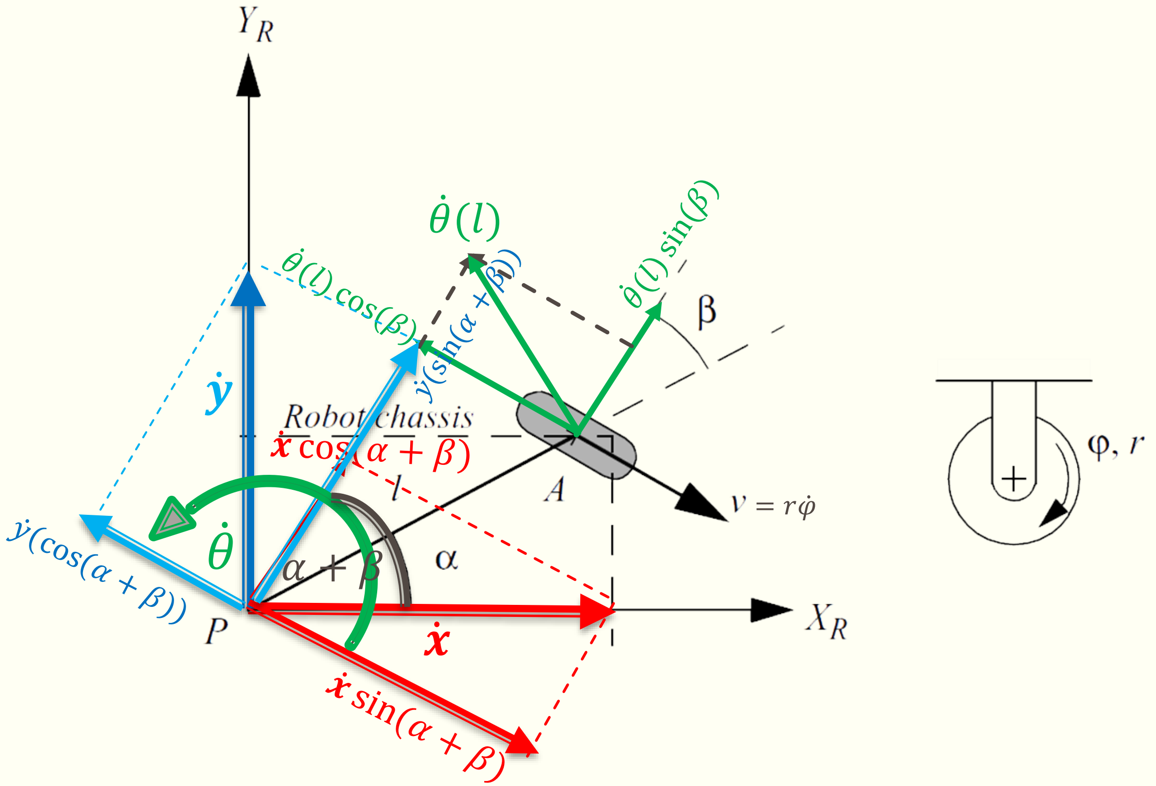
- No vertical axis of rotation for steering.
- Position of A is expressed in polar coordinates by distance l and angle α.
- α, β and l locate the wheel relative to the robot frame .
- The rolling constraint for this wheel enforces that all motion along the direction of the wheel plane must be accompanied by the appropriate amount of wheel spin so that there is pure rolling at the contact point.





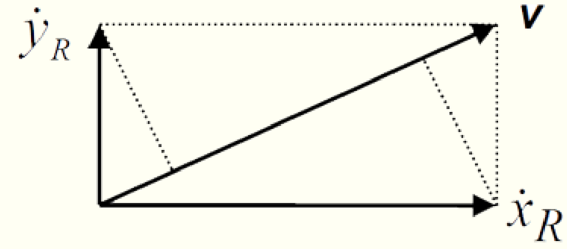
Fixed standard wheel constraints

- All velocities in the direction of wheel plain must be equal to the wheel velocity.
- All velocities components in perpendicular to the wheel plain must be equal zero that means there is no slipping laterally.



Velocity components

- Velocity of the wheels ($V_{1,2,....}$) gives the robot motion.
- We can think of this however that the robot's x, y and turning velocity contribute to the velocity of the wheel as shown below: (ω contribution not shown).
- Therefore can we determine wheel velocity v given the robot's velocity?

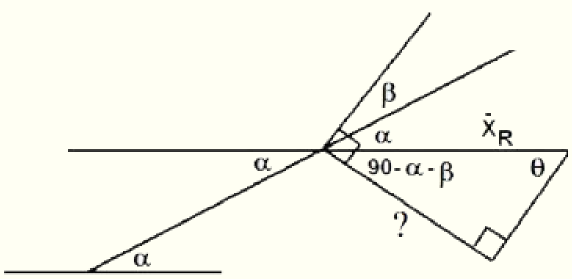


x - component

For a given $\dot{X}_R$, the component along the rolling plane of the wheel is:

$$\dot{X}_R \sin\theta$$

$$where\ \theta = 90 - (90 - \alpha - \beta)$$



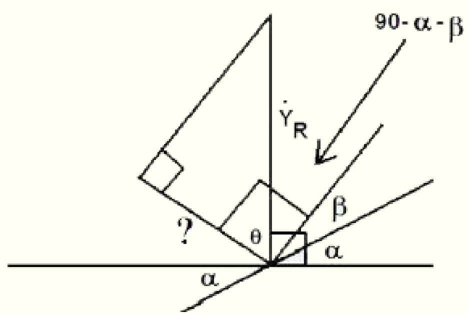
$$\dot{X}_R \sin(\alpha + \beta)$$

Y - component

For a given $\dot{Y}_R$, the component along the rolling plane of the wheel is:

$$-\dot{Y}_R \cos\theta$$

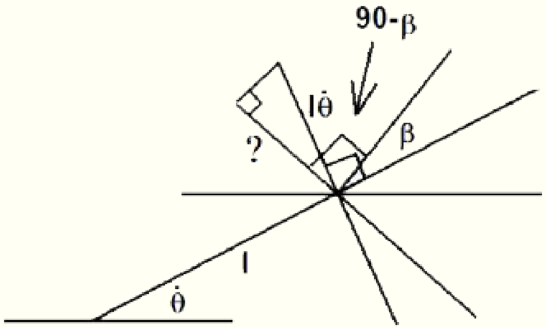
$$where\ \theta = 90 - (90 - \alpha - \beta)$$



$$-\dot{Y}_R \cos(\alpha + \beta)$$

θ - component

For a given $\dot{\theta}_R$, the component along the rolling plane of the wheel is:



$$-l\dot{\theta}\cos\beta$$

Wheel rolling components

- The wheel velocity must be:
  $= \dot{X}_R \sin(\alpha + \beta) - \dot{Y}_R \cos(\alpha + \beta) - l\dot{\theta} cos\beta$

- Writing in vector form, this is:

$$= [\sin(\alpha + \beta) \quad -\cos(\alpha + \beta) \quad -lcos\beta] \begin{bmatrix} \dot{X}_R \\ Y_R \\ \dot{\theta} \end{bmatrix}$$

- We can now express this in terms of our global velocity:

$$= [\sin(\alpha + \beta) \quad -\cos(\alpha + \beta) \quad -lcos\beta] \; R(\theta)\dot{\zeta}_I$$

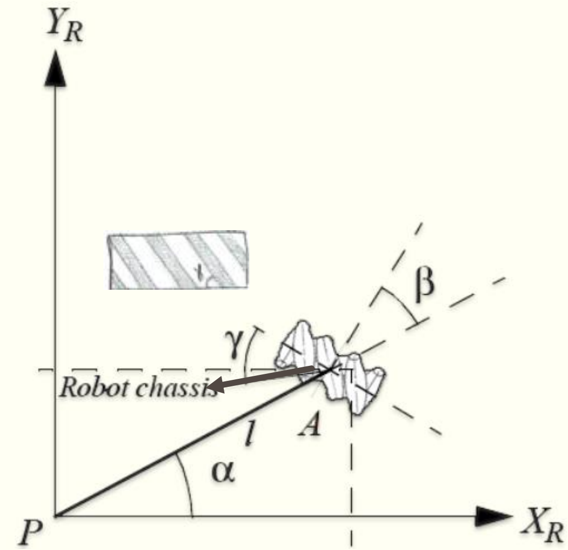
- As the wheel does not slip then we can write our rolling constraint for a standard wheel as:

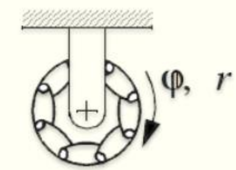
Rolling constraint: $[\sin(\alpha + \beta) \quad -\cos(\alpha + \beta) \quad -lcos\beta] \; R(\theta)\dot{\zeta}_I - r\dot{\varphi} = 0$

No sliding Constraint: $[cos(\alpha+\beta) \quad \sin(\alpha+\beta) \quad lsin(\beta)] \; \dot{\zeta}_R = 0$ Because $V = 0$

Omnidirectional wheel

- The geometry and constraint equations are similar to the standard wheel analysis with the added parameter of γ, the offset of the rotation axis of the rollers compared with the wheel circumference.





Robot kinematic constraints

We can combine the wheel constraints for all wheels on the robot into a single equation:

$$J_1(\beta_s)R(\theta)\dot{\zeta}_I - J_2\dot{\varphi} = 0$$

where:

$$[\sin(\alpha+\beta+\gamma) \quad -\cos(\alpha+\beta+\gamma) \quad -l\cos(\beta+\gamma)]\ R(\theta)\dot{\zeta}_I - r\dot{\varphi}\cos\gamma = 0$$

Rolling

$$[\cos(\alpha+\beta+\gamma) \quad \sin(\alpha+\beta+\gamma) \quad l\sin(\beta+\gamma)]R(\theta)\dot{\zeta}_I - r\dot{\varphi}\sin\gamma - r_{sw}\dot{\varphi}_{sw} = 0$$

Sliding: Slide motion

Where $\dot{\varphi}_{sw}$ is the angular velocity of the small rollers.

Robot kinematic constraints

- $J_1(\beta_s)$ denotes the projections along each wheel plane.

$$J_1(\beta_s) = \begin{bmatrix} J_{1f} \\ J_{1s}(\beta_s) \end{bmatrix} = \begin{bmatrix} \sin(\alpha_1 + \beta_1) & -\cos(\alpha_1 + \beta_1) & -l\cos\beta_1 \\ \sin(\alpha_2 + \beta_2) & -\cos(\alpha_2 + \beta_2) & -l\cos\beta_2 \\ & \cdot & \\ & \cdot & \\ & \cdot & \\ \sin(\alpha_t + \beta_t) & -\cos(\alpha_t + \beta_t) & -l\cos\beta_t \end{bmatrix}$$

Note that this can be split into fixed and steerable cases.

- J_2 is a diagonal matrix $(N \times N)$ with values corresponding to the wheel radii, i.e.

$$\begin{bmatrix} r_1 & 0 & \ldots \\ 0 & r_2 & \ldots \\ \ldots & \ldots & \ldots \end{bmatrix}$$

- $\dot{\varphi}(t)$ is a vector $(N \times 1)$ containing the wheel angular velocities, i.e. $\dot{\varphi}(t) = \begin{bmatrix} \dot{\varphi}_f(t) \\ \dot{\varphi}_s(t) \end{bmatrix} = \begin{bmatrix} \dot{\varphi}_1(t) \\ \dot{\varphi}_2(t) \\ \ldots \\ \dot{\varphi}_3(t) \\ \ldots \end{bmatrix}$

Note that this can be split into fixed and steerable cases.

Robot kinematic constraints

- We can apply a similar combining for the **no-slip constraints**, i.e.

$$C_1(\beta_s)R(\theta)\dot{\zeta}_I = 0$$

Where:

$$C_1(\beta_s) = \begin{bmatrix} C_{1f} \\ C_{1s}(\beta_s) \end{bmatrix} = \begin{bmatrix} \cos(\alpha_1 + \beta_1) & \sin(\alpha_1 + \beta_1) & l sin\beta_1 \\ \cos(\alpha_2 + \beta_2) & \sin(\alpha_2 + \beta_2) & l sin\beta_2 \\ & . & \\ & . & \\ & . & \\ \cos(\alpha_t + \beta_t) & \sin(\alpha_t + \beta_t) & l sin\beta_t \end{bmatrix}$$

Example 1: A differential drive robot

- We can combine the constraint equations to give:

$$\begin{bmatrix} J_1(\beta_s) \\ C_1(\beta_s) \end{bmatrix} R(\theta)\dot{\zeta}_I = \begin{bmatrix} J_2\dot{\varphi} \\ 0 \end{bmatrix}$$

- We will consider the two (powered) standard wheels, the 3rd wheel is unpowered and omnidirectional so we can ignore this in our analysis.

Consider:

Left wheel:

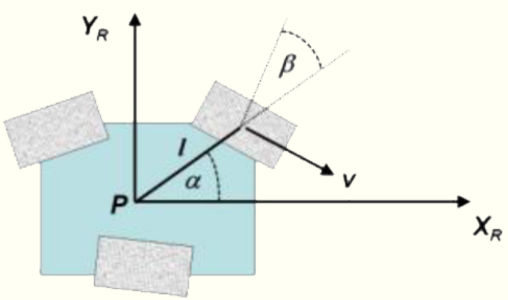
$$\alpha = \frac{\pi}{2}$$

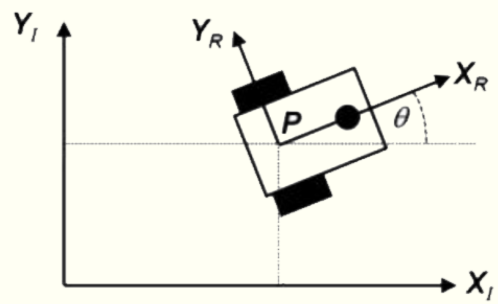
$$\beta = 0$$

Right wheel

$$\alpha = -\frac{\pi}{2}$$

$\beta = \pi$ (to ensure **V** is in X_R direction)





- Substituting in values gives:

$$\begin{matrix} \text{RW} \\ \text{LW} \\ \text{RW or LW} \end{matrix} \quad \begin{bmatrix} \sin(\alpha+\beta) & -\cos(\alpha+\beta) & -l\cos\beta \\ \sin(\alpha+\beta) & -\cos(\alpha+\beta) & -l\cos\beta \\ \cos(\alpha+\beta) & \sin(\alpha+\beta) & l\sin(\beta) \end{bmatrix} R(\theta)\dot{\zeta}_I = \begin{bmatrix} J_2\dot{\varphi} \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & l \\ 1 & 0 & -l \\ 0 & 1 & 0 \end{bmatrix} R(\theta)\dot{\zeta}_I = \begin{bmatrix} J_2\dot{\varphi} \\ 0 \end{bmatrix}$$

Therefore our robot velocity in the global frame is:

$$\dot{\zeta}_I = R(\theta)^{-1} \begin{bmatrix} 1 & 0 & l \\ 1 & 0 & -l \\ 0 & 1 & 0 \end{bmatrix}^{-1} \begin{bmatrix} J_2\dot{\varphi} \\ 0 \end{bmatrix}$$

$$= R(\theta)^{-1} \begin{bmatrix} 1/2 & 1/2 & 0 \\ 0 & 0 & 1 \\ 1/2l & -1/2l & 0 \end{bmatrix} \begin{bmatrix} J_2\dot{\varphi} \\ 0 \end{bmatrix}$$

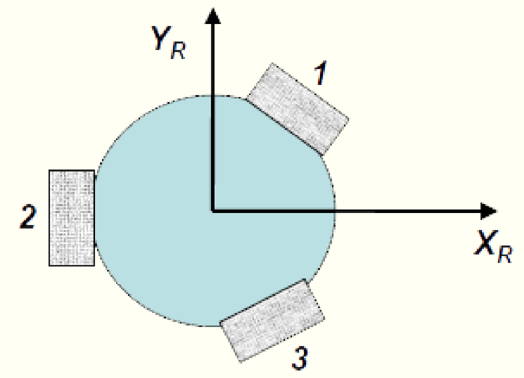
Exercise

Show that this is the same equation as we previously determined for our forward kinematic model, i.e.

$$\dot{\zeta}_I = R(\theta)^{-1} \begin{bmatrix} \frac{1}{2} r\dot{\varphi}_1 + \frac{1}{2} r\dot{\varphi}_2 \\ 0 \\ \frac{r\dot{\varphi}_1}{2l} - \frac{r\dot{\varphi}_2}{2l} \end{bmatrix}$$

Example 2: An omnidirectional drive robot

- Consider a robot composed of $\mathbf{3} \times \mathbf{90}°$ wheels placed at $\mathbf{120}°$ from one another.



- Our reference point will be the center of the robot.
- Wheel 2 will be parallel to Y_R.
- We consider the motion in terms of the rolling constraints for our 3 driven wheels:

$$J_{1f}(\beta_s)R(\theta)\dot{\zeta}_I = J_2\dot{\varphi}$$

or re-arranging to give:

$$\dot{\zeta}_I = R(\theta)^{-1}J_{1f}(\beta_s)^{-1}\ J_2\dot{\varphi}$$

- Geometry gives:

$\alpha_1 = \frac{\pi}{3},\ \alpha_2 = \pi, \qquad \alpha_3 = -\frac{\pi}{3}$

$\beta = 0$ (as all wheels are perpendicular to the circumference)

$\gamma = 0$

$$J_{1f} = \begin{bmatrix} \sin(\frac{\pi}{3}) & -\cos(\frac{\pi}{3}) & -l \\ 0 & \cos(\frac{\pi}{3}) & -l \\ \sin(-\frac{\pi}{3}) & -\cos(-\frac{\pi}{3}) & -l \end{bmatrix} = \begin{bmatrix} \sqrt{3}/2 & -1/2 & -l \\ 0 & 1 & -l \\ -\sqrt{3}/2 & -1/2 & -l \end{bmatrix}$$

Giving:

$$\dot{\zeta}_I = R(\theta)^{-1}\begin{bmatrix} \frac{1}{\sqrt{3}} & 0 & -\frac{1}{\sqrt{3}} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3}l & -\frac{1}{3}l & -\frac{1}{3}l \end{bmatrix} J_2\dot{\varphi}$$

Exercise

For this omnidirectional drive robot with a wheel radius of 1 cm, robot diameter of 2 cm and θ of 0°:

– a) What is the global velocity of the robot given wheel velocities of $(2,3,1)\ rad/s$?

– b) What wheel velocities are required to give a global velocity of $\dot{\zeta}_I = (\sqrt{3},2,1)\ cm/s$?

Manoeuvrability

- Now we have derive the kinematic model for any robot, we can formally define the manoeuvrability of a robot.
- This is defined in 2 parts:
  - Degree of mobility: $\boldsymbol{\delta_m} = \mathbf{3} - \boldsymbol{rank}[\boldsymbol{C_1}(\boldsymbol{\beta_s})]$
  - Degree of steerability: $\boldsymbol{\delta_s} = \boldsymbol{rank}[\boldsymbol{C_{1s}}(\boldsymbol{\beta_s})]$
- Our definition for manoeuvrability becomes:

$$\boldsymbol{\delta_M} = \boldsymbol{\delta_m} + \boldsymbol{\delta_s}$$

For our differential drive robot:

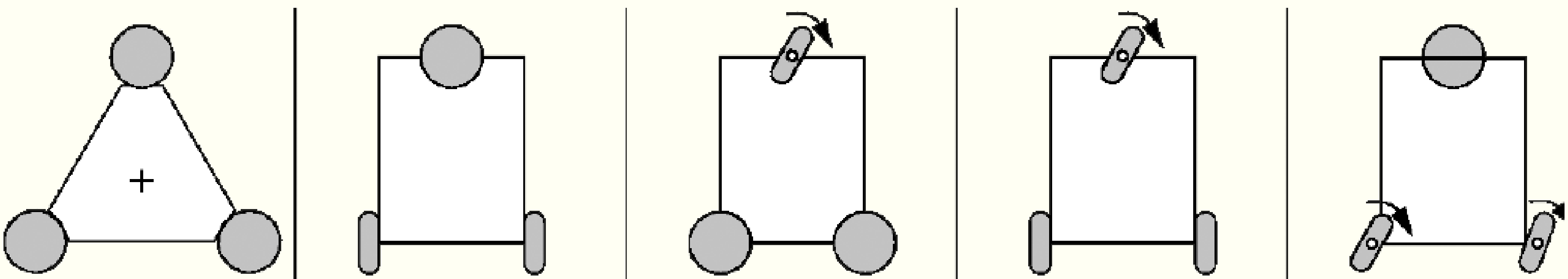
- Degree of mobility: $\boldsymbol{\delta_m} = \mathbf{3} - \boldsymbol{rank}[\boldsymbol{C_1}(\boldsymbol{\beta_s})]$ $where$ $\boldsymbol{rank}[\boldsymbol{C_1}(\boldsymbol{\beta_s})] = 1$ so $\boldsymbol{\delta_m} = 2$.
- Degree of steerability: $\boldsymbol{\delta_s} = \boldsymbol{rank}[\boldsymbol{C_{1s}}(\boldsymbol{\beta_s})]$ $where$ $\boldsymbol{rank}[\boldsymbol{C_{1s}}(\boldsymbol{\beta_s})] = 0$ so $\boldsymbol{\delta_s} = 0$.
- Degree of manoeuvrability $\boldsymbol{\delta_M} = 2$.

Manoeuvrability

- Now we have derive the kinematic model for any robot, we can formally define the manoeuvrability of a robot.

- This is defined in 2 parts:
  - Degree of mobility: $\boldsymbol{\delta_m = 3 - rank[C_1(\beta_s)]}$
  - Degree of steerability: $\boldsymbol{\delta_s = rank[C_{1s}(\beta_s)]}$
- Our definition for manoeuvrability becomes:

$$\boldsymbol{\delta_M = \delta_m + \delta_s}$$

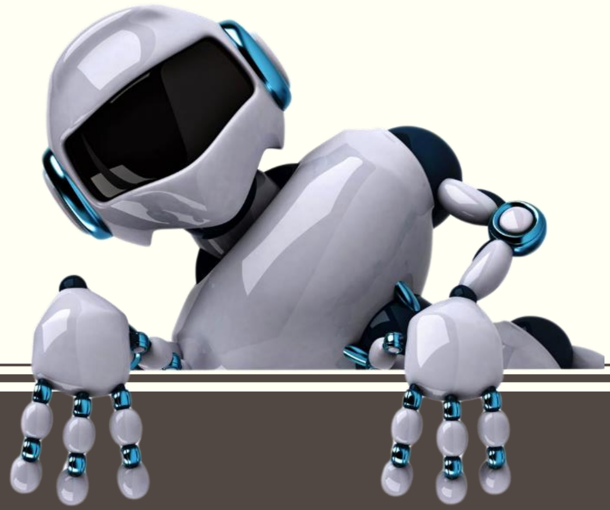


Omnidirectional	Differential	Omni-steer	Tricycle	Two-Steer
$\delta_M = 3$	$\delta_M = 2$	$\delta_M = 3$	$\delta_M = 2$	$\delta_M = 3$
$\delta_m = 3$	$\delta_m = 2$	$\delta_m = 2$	$\delta_m = 1$	$\delta_m = 1$
$\delta_s = 0$	$\delta_s = 0$	$\delta_s = 1$	$\delta_s = 1$	$\delta_s = 2$

Summary

- By considering the constraints under which a wheel can operate, a kinematic model for the robot may be developed.
- From this general model, a kinematic model for two of the commonest wheel configurations (differential drive and omnidirectional) was derived.
- This model may also be used to determine robot manoeuvrability.
- Open or closed loop control may be implemented for trajectory planning.

In the next lecture, we will look at the sensors required for robot autonomy.



THANK YOU FOR LISTENING

ANY QUESTIONS ?

5

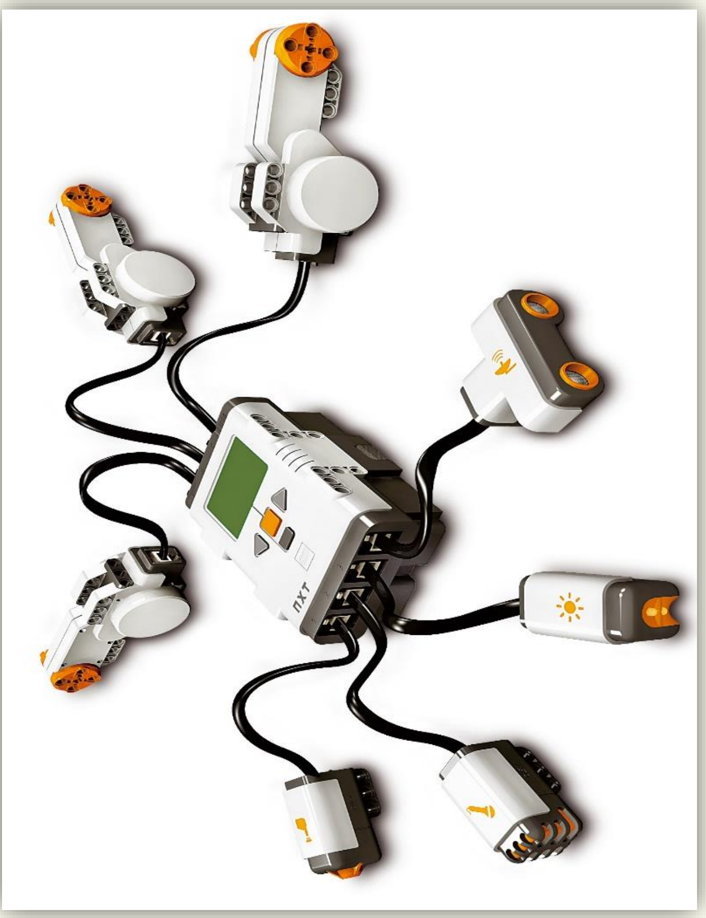
MOBILE ROBOT

Sensors

Lecturer:

Mohanad N. Noaman

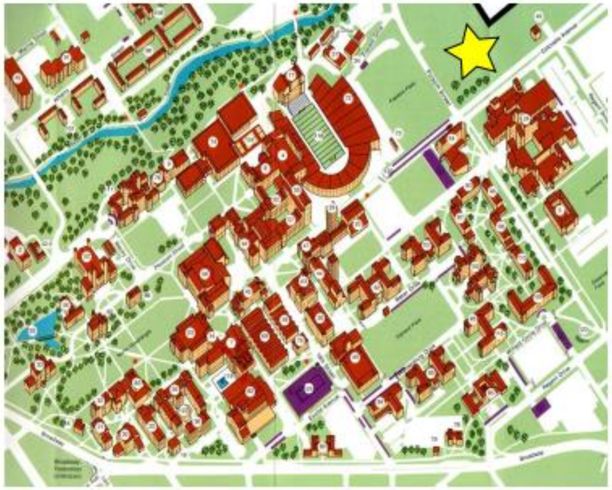
Ninevah University
Electronics engineering college



Where am I?

Localization (State estimation)

Reference system
Map



Where am I going?

Representation
+
Mapping

How do I get there?

Planning (Deliberative)
Motion Control (Feedback)
Behaviors (Reactive)

Obstacle avoidance

Sensors

Reference: Carnegie Mellon University

Introduction

- For autonomy, the robot must be able to measure internal parameters and also sense a potentially dynamic environment.
- Sensors are used for:
  - measuring position / motion.
  - locating objects.
  - avoiding collisions.
  - measuring interactions.

  (either anticipated or unexpected)
- A single sensor can provide only a limited amount of information about the environment therefore a robot depends on a wide range of sensors.
- However combining information from several sensors (sensor fusion) is problematic because:
  - different features dominate (i.e. visible, thermal) making alignment difficult.
  - different points of view, fields of view.
  - different time base (not a problem for static objects).
  - noise complicates process.

Classification of Sensors

The robot can measure its **local / global position** and/or **movement**, as well as the **presence of objects** or **useful landmarks** through the use of *internal* and/or *external* sensing actions:

Sensing direction

- ***Proprioceptive sensors:*** measure values internally to the system (robot). Examples are: motor speed, wheel load, heading of the robot, battery status
- ***Exteroceptive sensors:*** gather information from the robot environment, such as distance to objects, intensity of the ambient light, radio signals

Sensing modality

- ***Passive sensors:*** Measure energy coming from the environment
- ***Active sensors:*** Emit their proper energy and measure the reaction, potentially more effective but depends on the characteristics of the environment

Reference: Carnegie Mellon University

General Classification

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers	EC	P
	Optical barriers	EC	A
	Noncontact proximity sensors	EC	A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders	PC	P
	Potentiometers	PC	P
	Synchros, resolvers	PC	A
	Optical encoders	PC	A
	Magnetic encoders	PC	A
	Inductive encoders	PC	A
	Capacitive encoders	PC	A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass	EC	P
	Gyroscopes	PC	P
	Inclinometers	EC	A/P

A, active; P, passive; *P*/A, passive/active; PC, proprioceptive; EC, exteroceptive.

General Classification

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)	Reflectivity sensors Ultrasonic sensor Laser rangefinder Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound	EC EC	A A
Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

A, active; P, passive; *P*/A, passive/active; PC, proprioceptive; EC, exteroceptive.

Characterizing Sensor Performance

Range

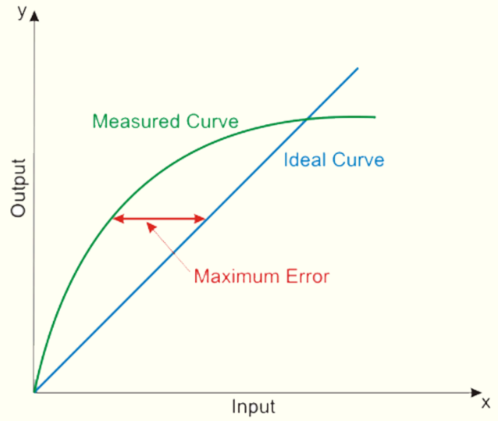
- It is the minimum and maximum value of physical variable that the sensor can sense or measure. For example, a Resistance Temperature Detector (RTD) for the measurement of temperature has a range of -200° to 800°C.

Resolution

- minimum difference that can be measured between two values (for digital sensors it is usually related to the A/D conversion)
- It is the minimum change in input that can be sensed by the sensor.

Linearity

- Linearity is the maximum deviation between the measured values of a sensor from ideal curve.



Characterizing Sensor Performance

Bandwidth or Frequency

- the speed with which a sensor can provide a stream of readings.
- usually there is an upper limit depending on the sensor and the sampling rate.
- one has also to consider phase (delay) of the signal.

Sensitivity

- Ratio of output change to input change dy/dx
- e.g., magnitude of change of the output of a visual sensor in relation to a change in the illumination

Accuracy

- The error in measurement is specified in terms of accuracy. It is defined as the difference between measured value and true value. It is defined in terms of % of full scale or % of reading.

$$\left(accuracy = 1 - \frac{|m - v|}{v} \right)$$

error ($|m - v|$)

m = measured value
v = true value

Characterizing Sensor Performance

Repeatability:

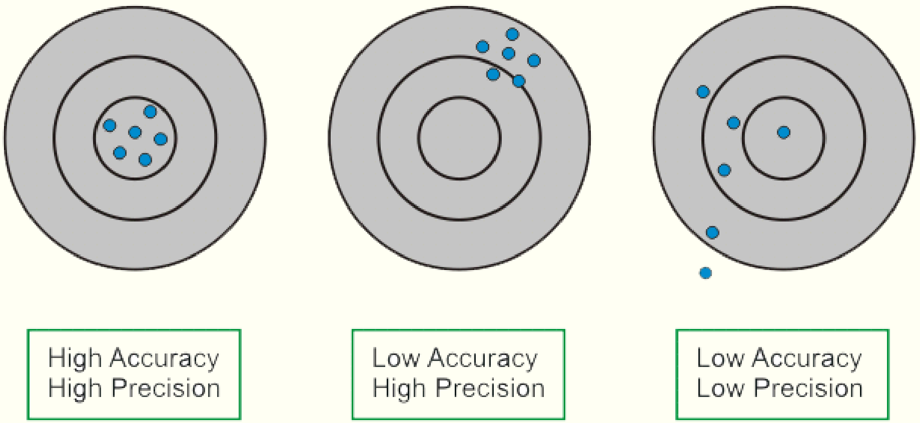
- It is defined as the ability of sensor to produce the same output every time when the same input is applied and all the physical and measurement conditions kept the same including the operator, instrument, ambient conditions etc.

Reproducibility:

- It is defined as the ability of sensor to produce the same output when same input is applied.

Precision:

- It is defined as the closeness among a set of values. It is different from accuracy.



Dead reckoning

- **Odometry sensors:** Motor Encoders, to measure wheels, rotors, helices ... rotation
- **Inertial sensors** (measure forces, non-inertial effects): Gyroscope, Accelerometer
- **Heading / orientation sensors:** Compass, Inclinometer

Proprioceptive sensors

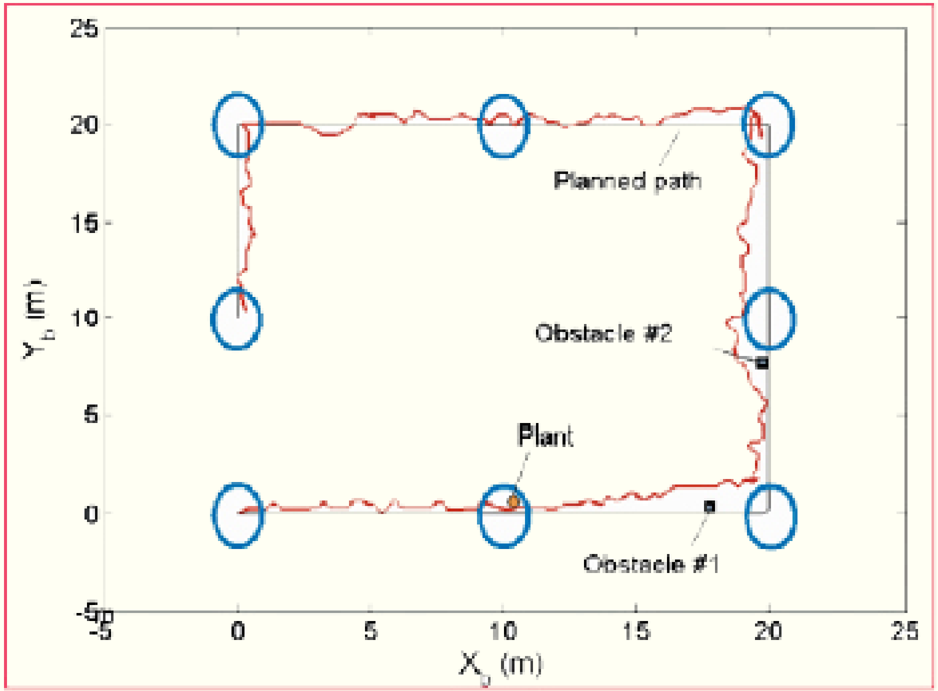
Reference: Carnegie Mellon University

Dead reckoning

- One of the fundamental problems for mobile robots is measuring **absolute motion**.

- This can be done internally with sensors however errors rapidly accumulate and therefore they are only used on short time scales.

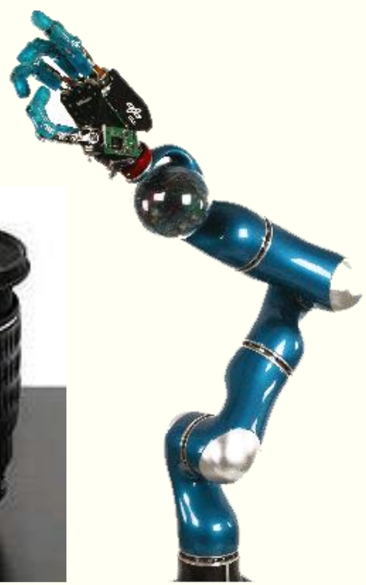
- The two options available are:
  - wheel encoders (optical encoders)
  - inertial navigation system (accelerometers and gyroscopes)

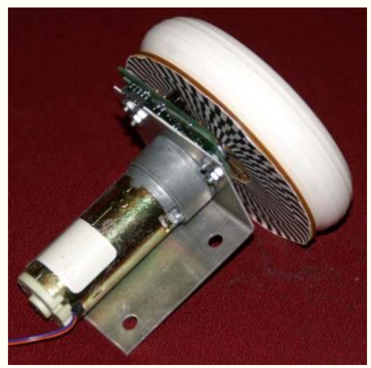


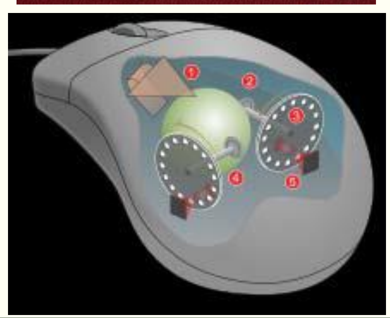
Optical encoder

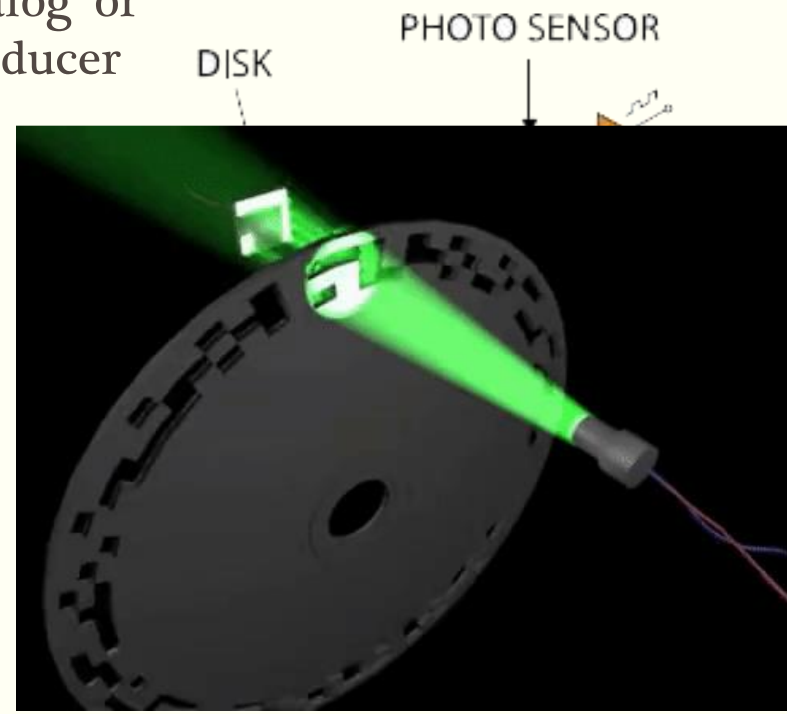
- In an optical encoder, slots in the disk allow a beam of light to pass through it at certain angular positions.
- As the disk rotates, pulses are counted to determine the angular displacement.

So, it is an electro-mechanical device that converts linear or angular position of a shaft to an analog or digital signal, making it an linear/angular transducer







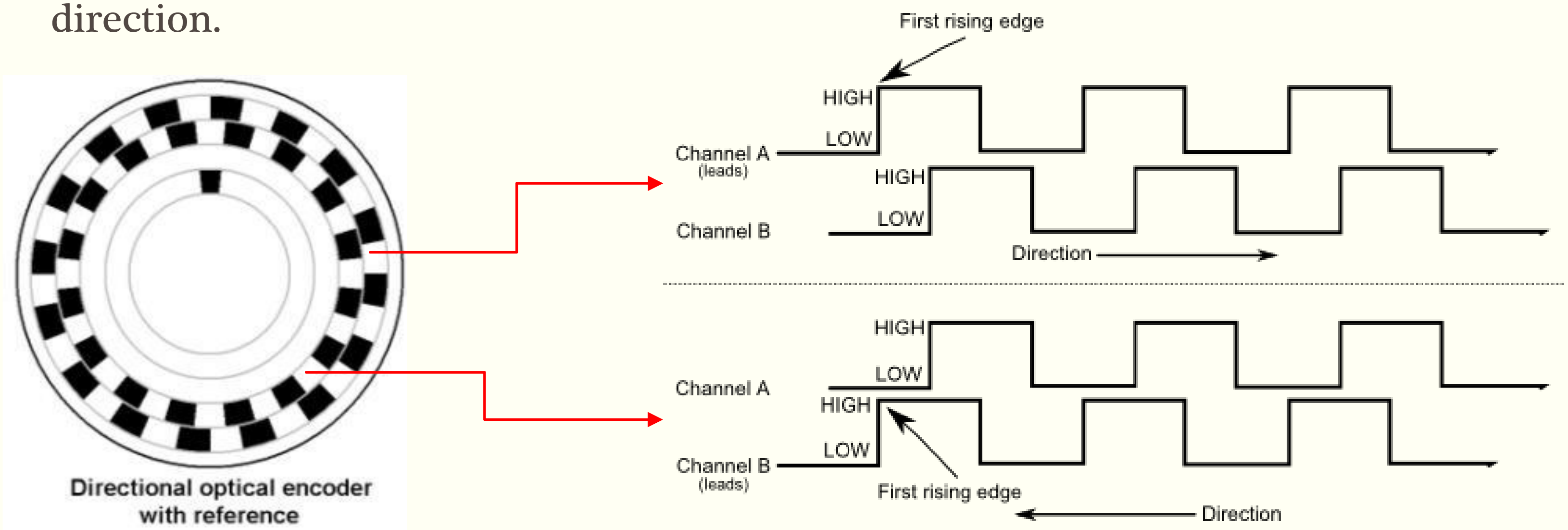


Optical encoder

- **measure position** or speed of the wheels or steering
- **integrate wheel movements** to get an estimate of the position -> odometry
- optical encoders are proprioceptive sensors
- typical resolutions: **64 - 2048** increments per revolution.

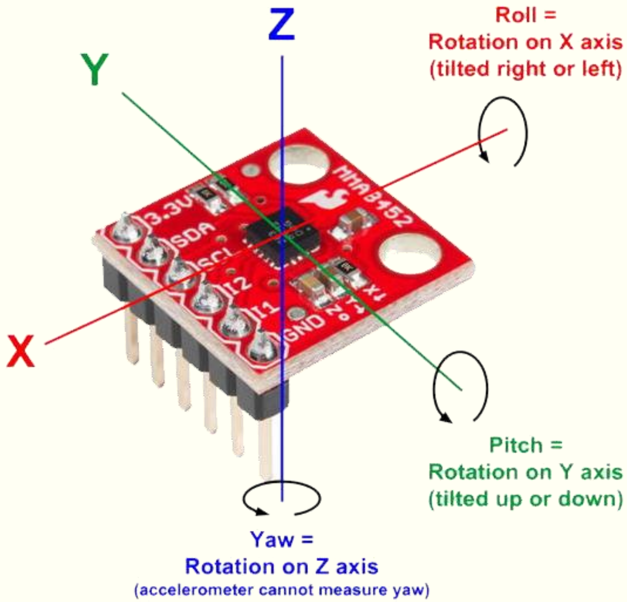
Two types:

- **regular:** counts the number of transitions but cannot tell the direction of motion.
- **quadrature:** uses two sensors in quadrature-phase shift. The ordering of which wave produces a rising edge first tells the direction of motion. Additionally, resolution is 4 times bigger. A second track can be used (offset by 90°) to determine rotation direction.

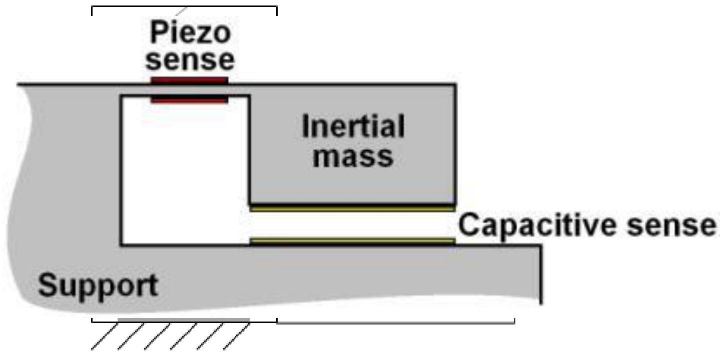


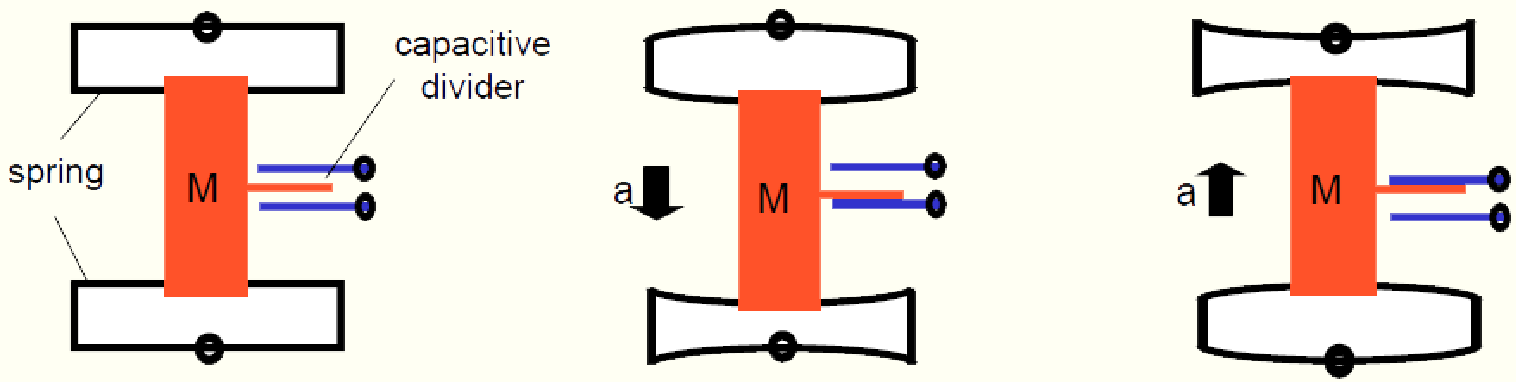
Accelerometer

- An accelerometer is essentially an inertial mass on a spring.
- The measurement of movement of this inertial mass, here either by piezo resistive or capacitive, leads to an output voltage proportional to acceleration.
- A double integration of the measurement gives displacement.



- The noise floor of an accelerometer is defined in g/$\sqrt{\text{Hz}}$.
- The signal conditioning electronics for an accelerometer is a low pass filter (practically done with a capacitor).
- This defines the operational bandwidth
  - the higher the capacitor value, the lower the filter cut-off and the lower the noise floor however this then limits how quickly the accelerometer will respond.



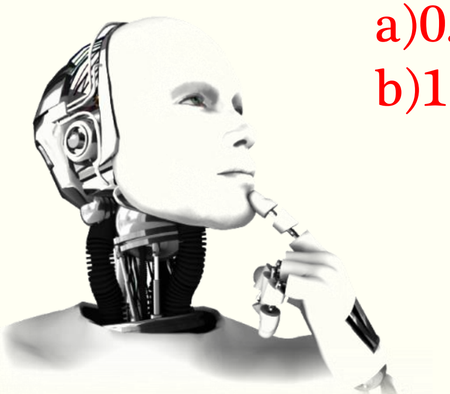


Exercise

The noise floor of an **ADXL330** is around $300\mu sg/\sqrt{\text{Hz}}$. What is the noise level if you wish to make a measurement every:

a)0.1 s

b)10 ms



Gyroscope

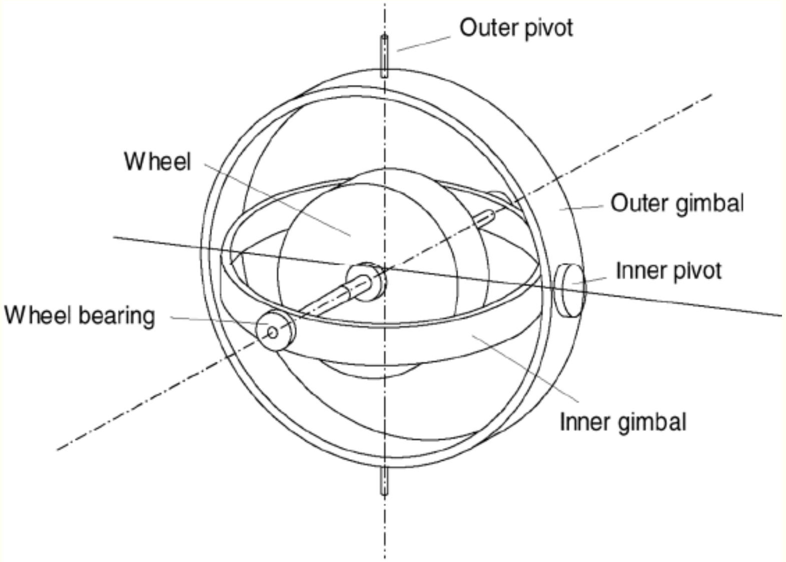
Concept:

- Inertial properties of a fast spinning rotor
- Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.

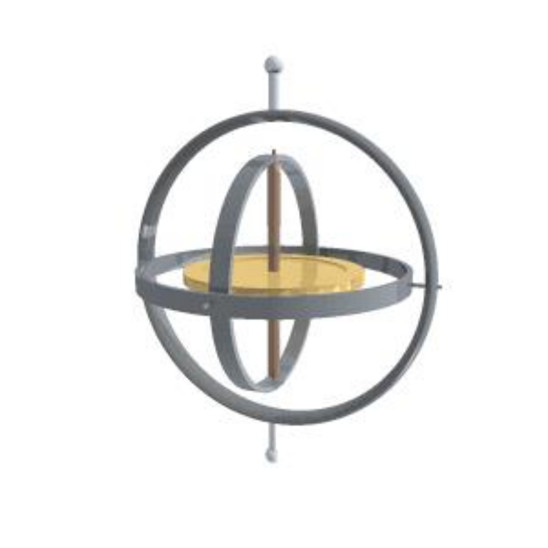
No torque can be transmitted from the outer pivot to the wheel axis

- spinning axis will therefore be space-stable
- however friction in the axes bearings will introduce torque and so drift ->precession

Quality: 0.1° in 6 hours (a high quality mech. gyro costs up to 100,000 $)

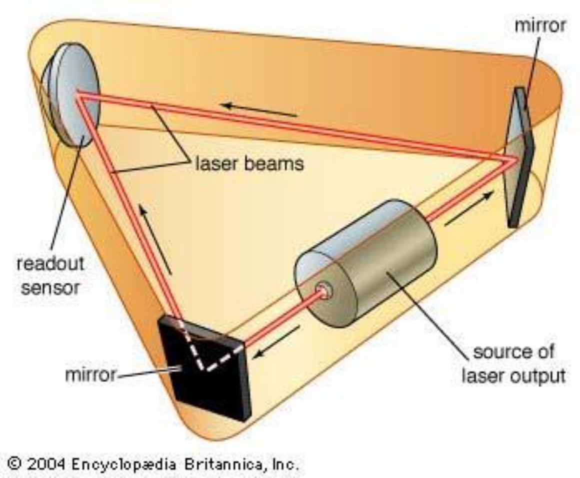


Mechanical Gyroscope



Optical Gyroscopes

- **Optical gyroscopes** (The Sagnac effect)
  - Angular speed (heading) sensors using two monochromic light (or laser) beams from the same source.
  - One is traveling in a fiber clockwise, the other counterclockwise around a cylinder.
- **Laser beam traveling in direction opposite to the rotation**
  - slightly shorter path.
  - phase shift of the two beams is proportional to the angular velocity Ω of the cylinder.
  - In order to measure the phase shift, coil consists of as much as 5Km optical fiber.



New solid-state optical gyroscopes based on the same principle are build using microfabrication technology.

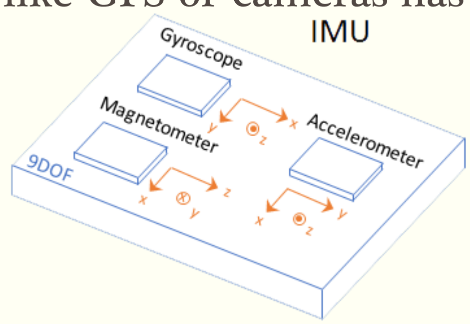
Inertial Measurement Unit (IMU)

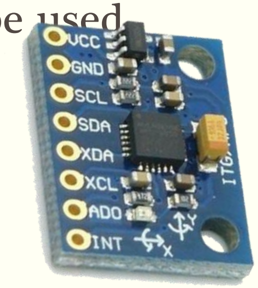
- **An inertial measurement unit (IMU)** is a device that uses measurement systems such as gyroscopes and accelerometers to estimate the relative position (**x, y, z**), orientation (**roll, pitch, yaw**), velocity, and acceleration of a moving vehicle.

- In order to estimate motion, the gravity vector must be subtracted. Furthermore, initial velocity has to be known.

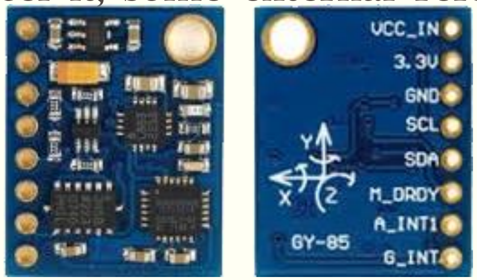
- **IMUs are extremely sensitive to measurement errors** in gyroscopes and accelerometers: **drift in the gyroscope** unavoidably undermines the estimation of the vehicle orientation relative to gravity, which results in incorrect cancellation of the gravity vector. Additionally observe that, because the **accelerometer data is integrated twice to obtain the position**, any residual gravity vector results in a quadratic error in position.

- After long period of operation, all IMUs drift. To cancel it, some external reference like GPS or cameras has to be used.



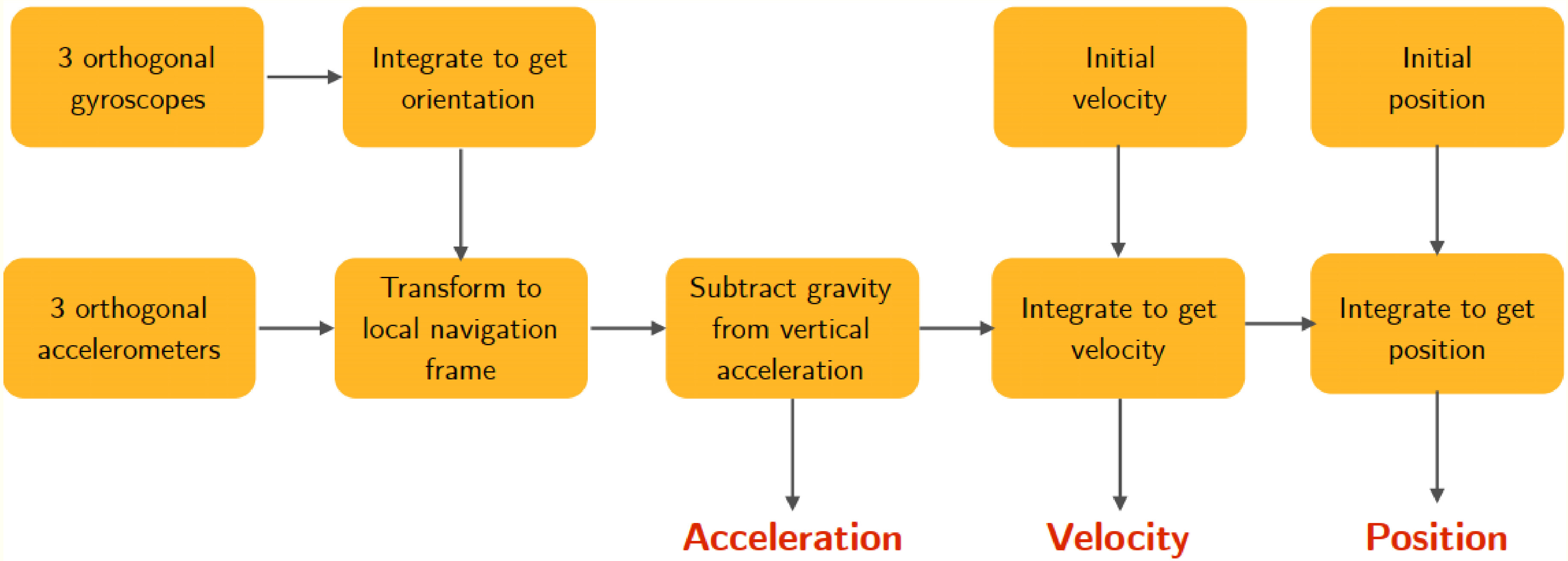


MPU-6050



GY-85

Inertial Measurement Unit (IMU)



Reference: Carnegie Mellon University

Problems with dead reckoning

- Optical encoders can be fitted to robot axles and the corresponding transform matrices then used to determine position.
  – In practice, wheel slip (spin and skid) both contribute to significant errors.

- Accelerometers and gyroscopes may be used.
  – In practice, noise is a problem with zeroing errors integrating to large errors rapidly.

- Although it may be practical to use these sensors for mobile robots over small distances, the errors accumulate to unacceptable magnitude.

Problems with dead reckoning

	Accelerometer Bias Error		Horizontal Position Error [m]			
Grade	[mg]		1s	10s	60s	1hr
Navigation	0.025		0.13 mm	12 mm	0.44 m	1.6 km
Tactical	0.3		1.5 mm	150 mm	5.3 m	19 km
Industrial	3		15 mm	1.5 m	53 m	190 km
Automotive	125		620 mm	60 m	2.2 km	7900 km

Accelerometer Misalignment		Horizontal Position Error [m]			
[mg]		1s	10s	60s	1hr
0.05°		4.3 mm	0.43 m	15 m	57 km
0.1°		8.6 mm	0.86 m	31 m	110 km
0.5°		43 mm	4.3 m	150 m	570 km
1°		86 mm	8.6 m	310 m	1100 km

	Gyro Angle Random Walk (ARW)		Horizontal Position Error [m]			
Grade	[deg/√hr]		1s	10s	60s	1hr
Navigation	0.002		0.01 mm	0.1 mm	1.3 mm	620 m
Tactical	0.07		0.1 mm	3.2 mm	46 m	22 km
Industrial	3		10 mm	0.23 m	3.3 m	1500 km
Automotive	5		20 mm	0.45 m	6.6 m	3100 km

Reference: Carnegie Mellon University

Possible solutions

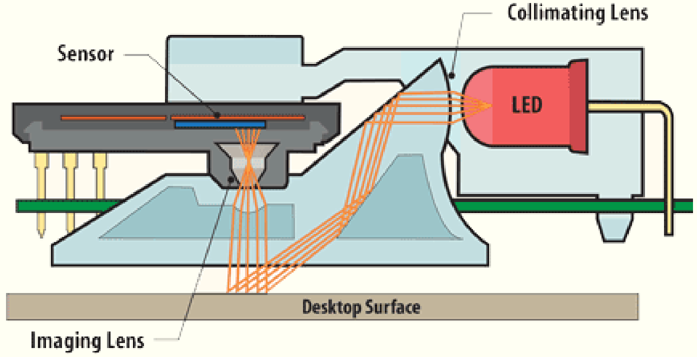
- Dead reckoning is proprioceptive(internal sensing) and used for short term navigation requirements.
- Exteroceptive sensing is required to support this and give acceptable accuracy over longer distances.
- Options include:
  - optical mice
  - compass
  - artificial beacons
  - landmarks (will be covered later)

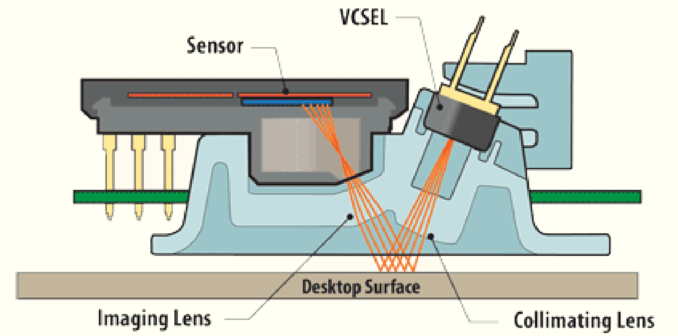
- **Visual landmarks** (lighthouses, stars, natural landmarks)
- **Ground radio beacons** (UWB or WiFi anchors, RFID markers)
- **Satellite radio beacons** (GPS)

Exteroceptive sensors

Optical mice

- Use pattern tracking to monitor motion.
- Two mice required to measure translation and rotation.
- Potential problems with working distance.

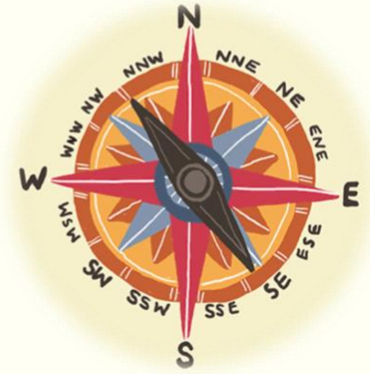




Reading

"Understanding optical mice," Avago Technologies
http://www.avagotech.com/docs/AV02-1265EN
"The optical mouse for indoor mobile robot odometry measurement," Palacin et al, Sensors and Actuators A126(2006) 141-147Image

Compass

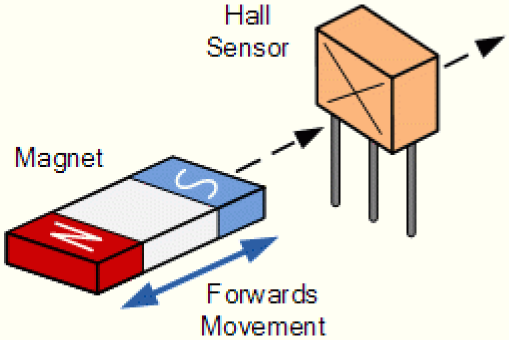


- **Used since before 2000 B.C.**
  when Chinese suspended a piece of natural magnetite from a silk thread and used it to guide a chariot over land.

- **Magnetic field on earth**
  absolute measure for orientation (even birds use it for migrations (2001 discovery))

- **Large variety of solutions to measure magnetic/true north**
  - mechanical magnetic compass
  - Gyrocompass
  - direct measure of the magnetic field (Hall-effect, magneto-resistive sensors)

- **Major drawback of magnetic solutions**
  - easily disturbed by magnetic objects or other sources
  - bandwidth limitations (0.5 Hz) and susceptible to vibrations
  - not suitable for indoor environments for absolute orientation



Hall effect compass

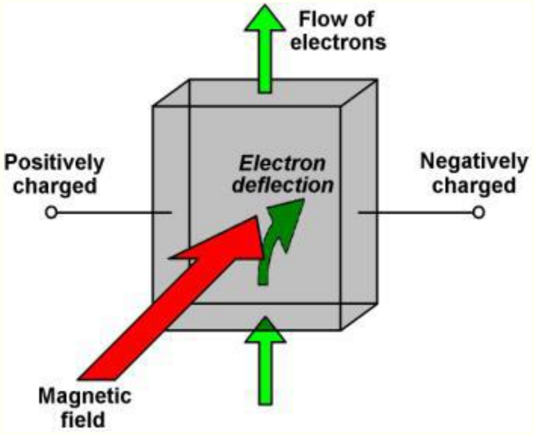
If a magnetic field, B, is placed across a current, I, flowing through a conductor, a potential difference is set up.

- The potential generated is proportional to the magnetic field:

$$V = K_H \frac{BI}{t}$$

- By using two of these arranged orthogonally, north is given by:

$$\tan\theta = \frac{V_x}{V_y}$$



The Hall effect

Compass calibration

The calibration procedure for a compass is to rotate it by 3600and determine the required scaling parameters.

– In practice, two complete rotations are required to account for acceleration and deceleration.

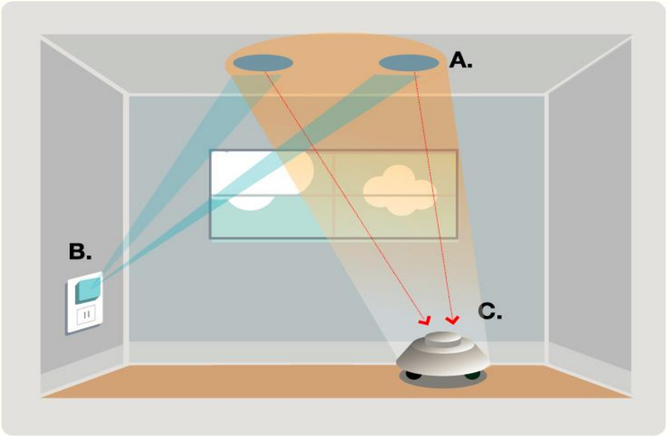
Reading –details of such a calibration procedure is given in:
"Application of Electronic Compass for Mobile Robot in an Indoor Environment" Vladimir et al, IEEE International Conference on Robotics and Automation, Roma 2007.

Artificial beacons

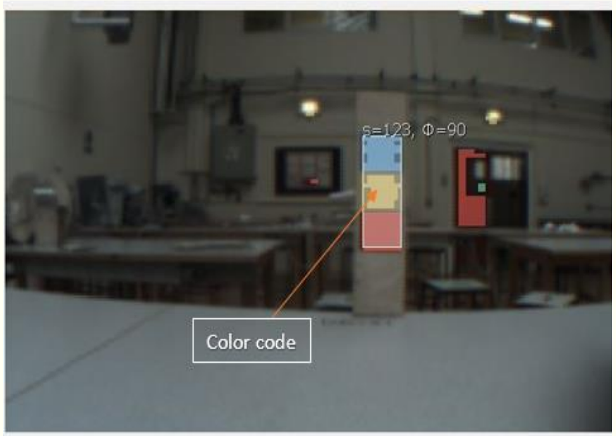
- **The environment may be modified to provide points of reference for the robot. So, beacon are signaling guiding devices with a precisely known position**

- **Beacons may be:**
  - passive, i.e. painted markings
  - active, i.e. I.R. beacons

- **Examples include:**
  - smart tags (passive or active)
  - GPS (outdoor), WiFi(indoor)



Spot light beacon

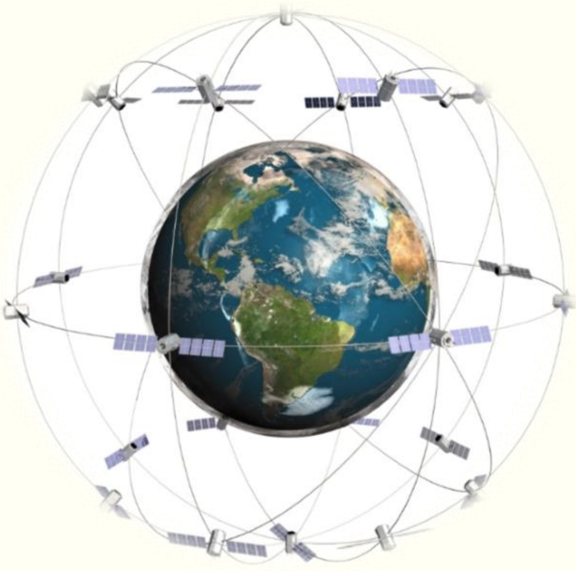


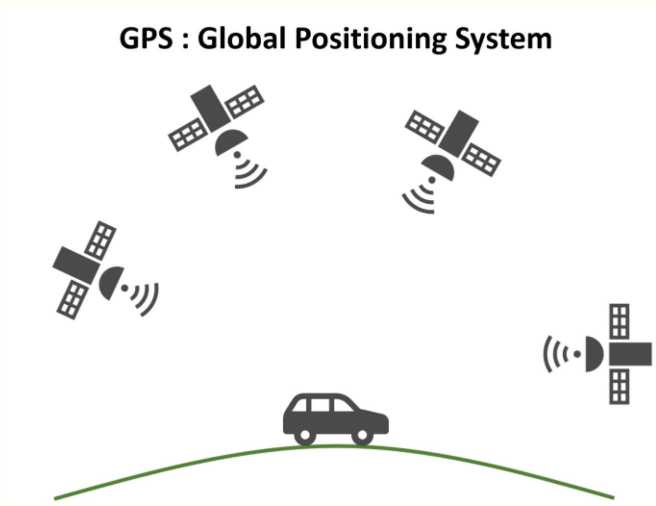
Color code beacon

Global positioning satellites (GPS)

The Global Positioning System (GPS) is a space-based Global navigation satellite system that provides location and time information.

- 32 satellites send out a high frequency signal (~1 GHz) containing satellite position and timing information.
- Signal is synchronized with atomic clocks on the satellites.
- A GPS receiver picks up this signal and uses its internal clock to convert this timing information into the distance to the satellite.
- The receiver"s clock is a crystal oscillator (relatively inaccurate) and must be updated from the satellites to remain accurate.
- The distance information is then used to calculate the position of the receiver using trilateration.



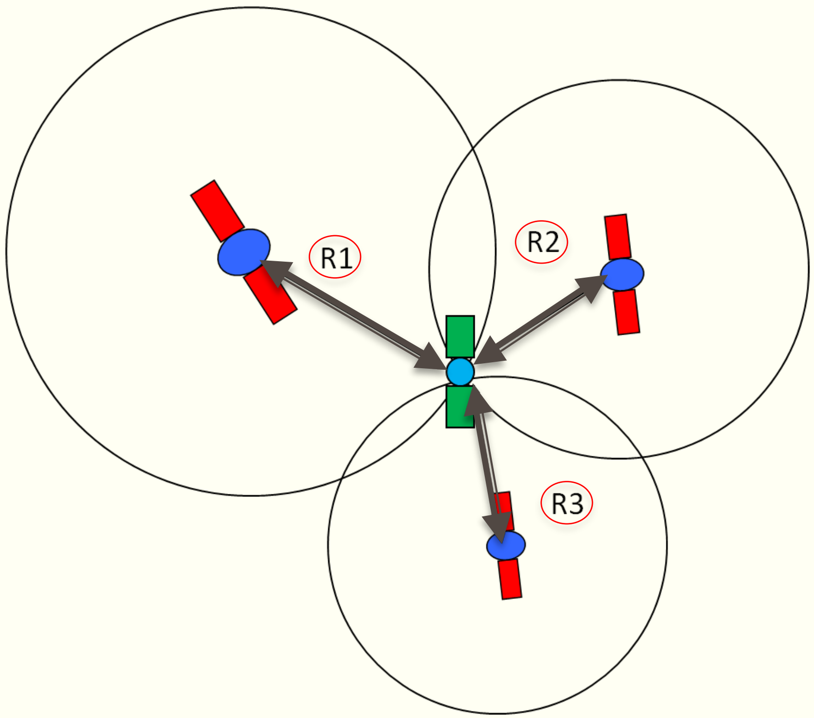


GPS for robotics?

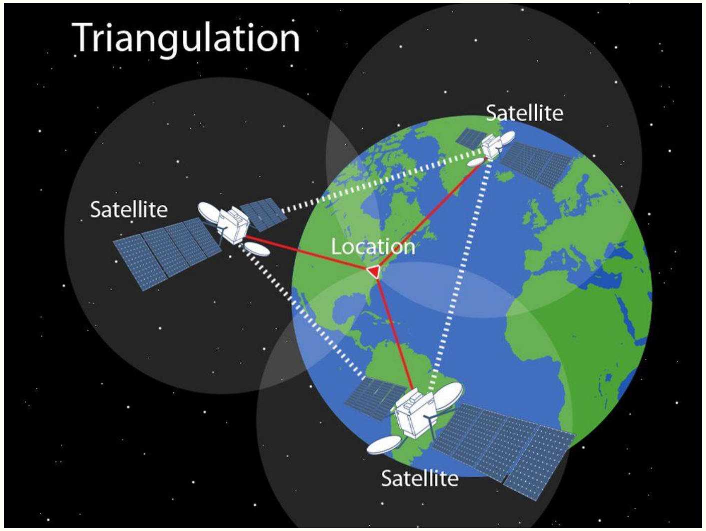
- **Suitable for:**
  - UAVs
  - in an open environment
  - in a city (limited use)
- **Unsuitable for:**
  - within a building
  - extra-terrestrial exploration

Trilateration

- Imagine a 2D surface with a satellite (of known position) transmitting a signal.
- After calculating the distance to that satellite you know you are located on the circumference of a circle away from the satellite.
- By applying the same argument to two other satellites then a point is defined at which you must be located.



$$d^2 = x^2 + y^2$$



In 3 dimensions

- In 3D you require 4 satellites:
  - 1st identifies a sphere
  - 2nd reduces this to a circle
  - 3rd reduces this to 2 points
  - 4th identifies unique point
- If you know your altitude, a minimum of 3 is required as the Earth's surface provides the 4th reference point.
- However the more satellites that are being measured, the more accurate the reading.

Accuracy of GPS

- By considering the speed at which the electronics can process the signal, this equates to an accuracy of ~1m.
- However errors add to this accuracy limit:
  - Atmospheric (ionosphere and troposphere) –variable speed of light causing errors of ~ 5m.
  - Ephemeris (satellite position) ~ 3m
  - Clock drift (even after relativistic correction) ~ 2m
  - Multipath errors (reflections) ~ 1m
- Differential GPS (measurement relative to a known position) reduces this error.

Active Ranging

Active ranging

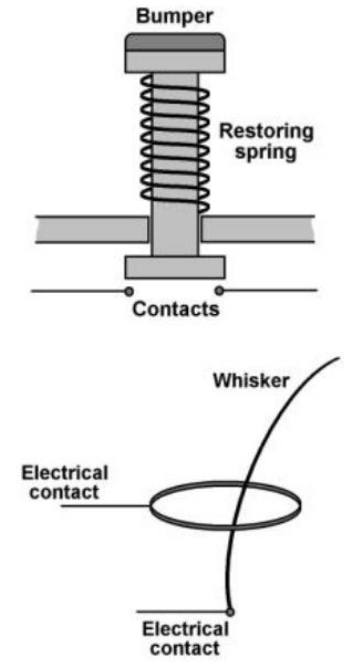
- A robot must know where it is to function correctly hence the importance of navigation (dead reckoning, beacons, etc).
- However, due to the dynamic nature of the environment, an equally important objective for the robot is to be able to sense objects around it.
- Maps provide information about the static environment but what about:
  - objects that have been moved
  - people
  - other robots

Tactile sensors

- A tactile sensor is essentially a „zero distance" range sensor.
- It is commonly used in mobile robotics as a „fail-safe" measurement that an object is too close and the robot must stop.

Note that tactile sensors are also used for manipulating objects, for example a robot hand picking up an egg.

Tactile sensors: Touch



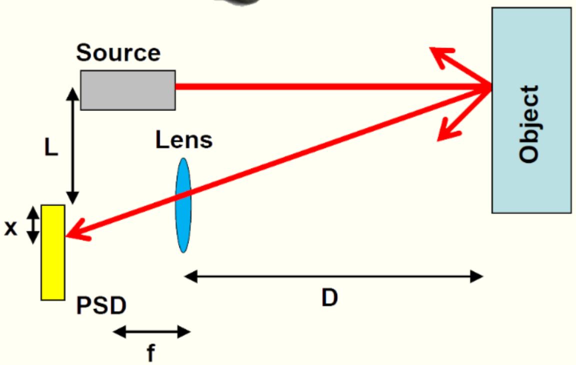
- The simplest type of sensor for obstacle avoidance is a simply switch (with mechanical compliance):
  - this can be fairly robust such as a bumper.
  - or more sensitive such as a whisker which has the ability to flex.
- In either case, when contact is made a circuit closes thereby detecting contact.

Infrared sensors

- Used for proximity detection
- An infrared beam is sent out, two options for detection:
  - intensity of reflected light (dependent on object reflectivity)
  - position sensitive photodetector(PSD)

$$D = \frac{fL}{x}$$

Sharp GP2D 120



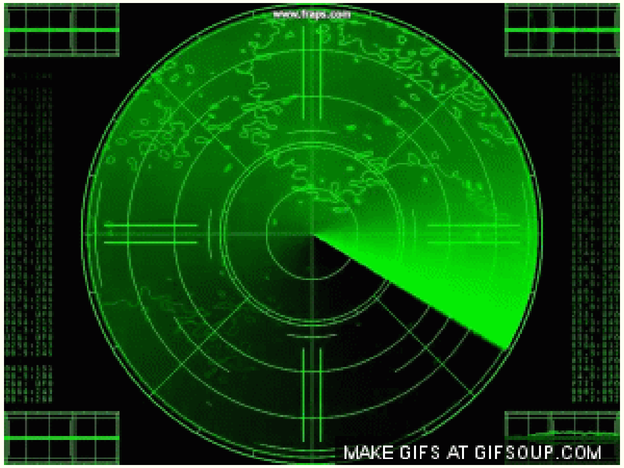
Time of flight measurements

- For this we can use **sonar** or **lidar**.
- Sonar uses sound, lidar uses EM radiation
- There are 3 major differences in sound to EM:
  - sound requires a medium, light will travel through a vacuum
  - sound is slower (≈330 ms^{-1}compared with $3 \times 10^8 ms^{-1}$)
  - sound has a longer wavelength (50 KHz ≈ 6.872 mm compared with, for example, 632 nm for red light)
    - specular reflection (mirror like) when roughness is less than the wavelength (man-made environments)
    - diffuse reflection when roughness is greater than wavelength (natural environments)

Ultrasonic echolocation *(SONAR –SOund Navigation And Ranging)*

Operational Principle:

An ultrasonic pulse is generated by a piezoelectric emitter, reflected by an object in its path, and sensed by a piezo-electric receiver. Based on the speed of sound in air and the elapsed time from emission to reception, the distance between the sensor and the object is easily calculated.

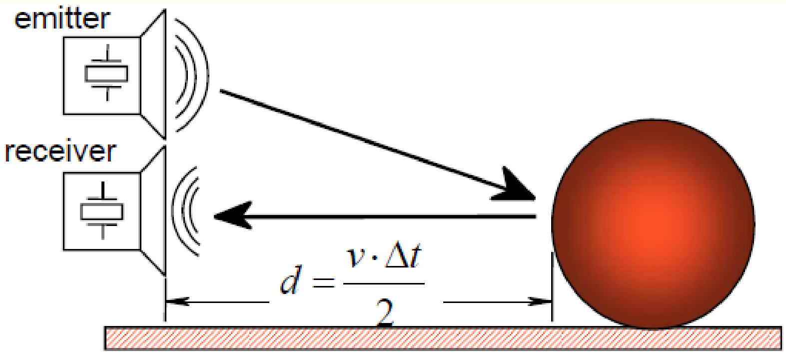


Main Characteristics:

- Precision influenced by angle to object (as illustrated on the next slide)
- Useful in ranges from several cm to several meters
- Typically relatively inexpensive

Applications:

- Distance measurement (also for transparent surfaces)
- Collision detection



Ultrasonic sensors

- Several frequencies are required:
  - some frequencies may be absorbed by the object material
  - others destructively interfere with one another for particular object geometries.
- Time for the first echo to be measured is used to measure the range.

- Range between 12 cm up to 5 m
- Resolution of ~ 2 cm
- Accuracy 98% relative error 2%

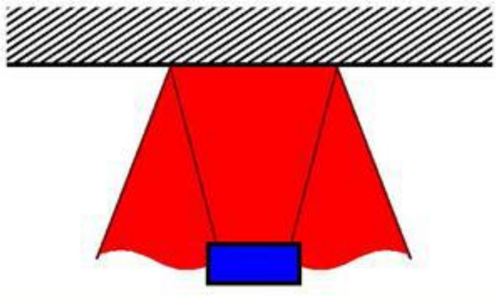
- Two configurations are possible:
  - a separate transmitter and receiver.
  - a single sensor for actuation and detection.

  - Daventech
  - Polaroid (SensComp)
  - MaxSonar

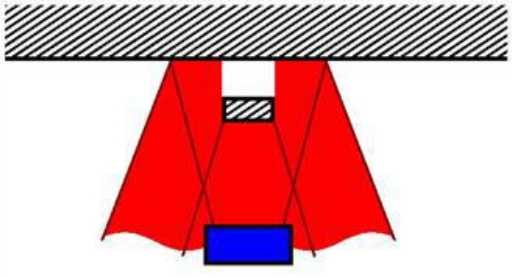
MaxSonar Polaroid (SensComp) Daventech

Accuracy of ultrasonic sensors

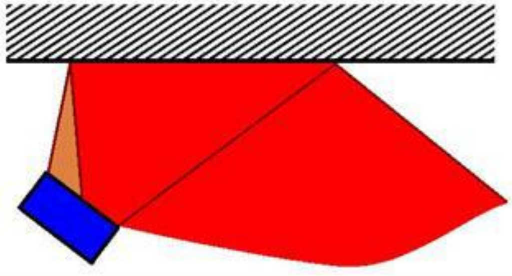
- Under ideal operation, the ultrasonic sensor will give an accurate range measurement for the direction it is pointing.



- For small obstructions, the range to the obstruction is accurate but lateral resolution is lost.
  - To overcome this a narrow beam can be used but this makes full coverage more difficult.

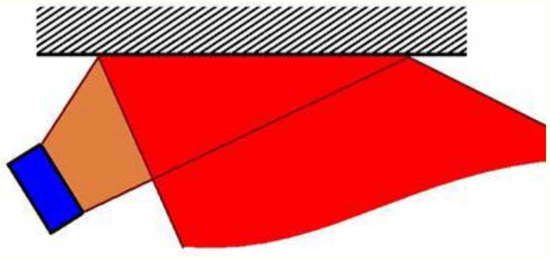


- If the first echo is received from the edge of the beam profile, the “straight ahead” range is underestimated.

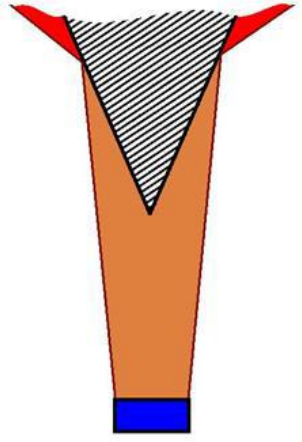


Accuracy of ultrasonic sensors

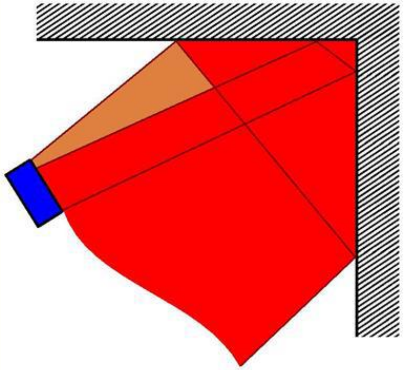
- At glancing angles, no echo is returned and so it appears that there is no object / wall there.



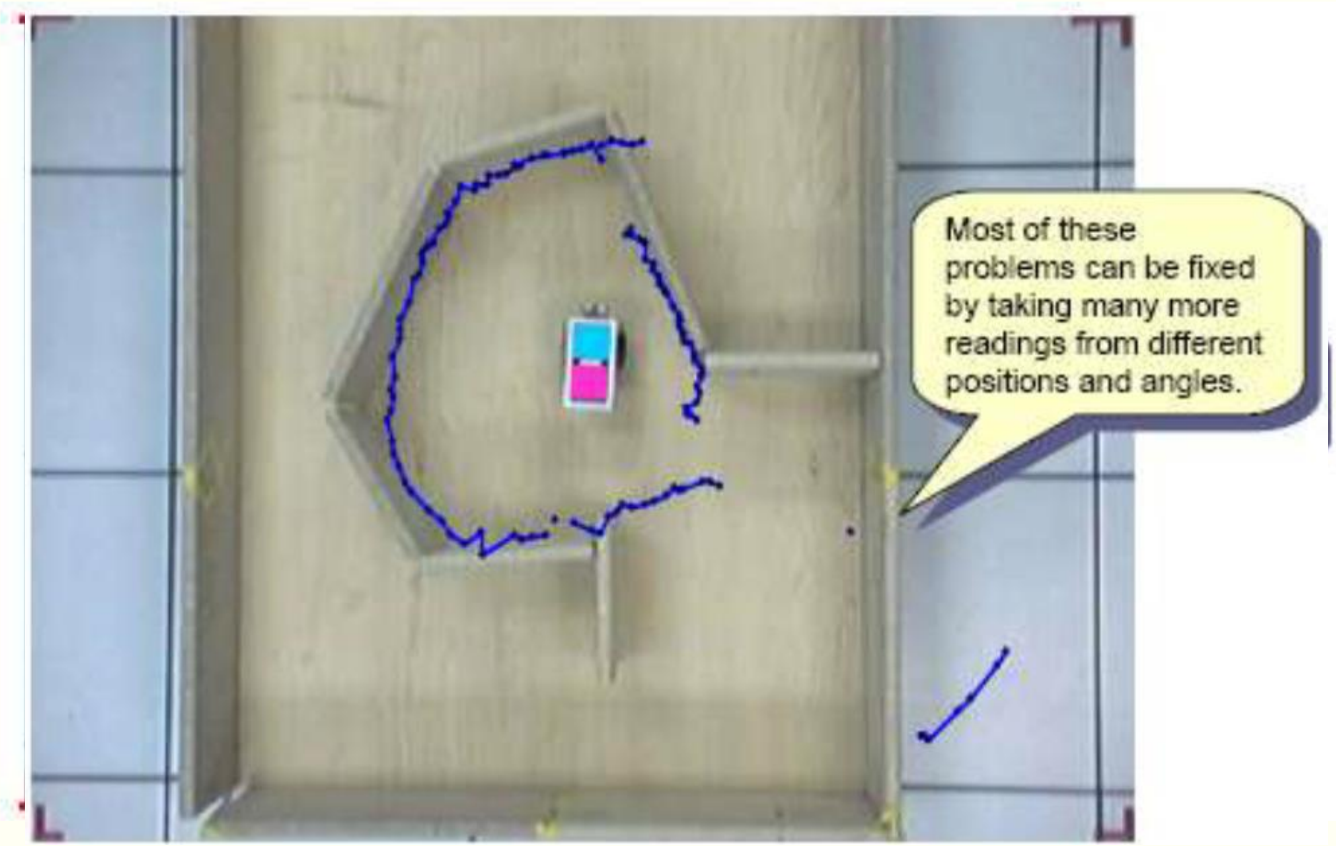
- Similar to the last case, no signal is returned and so this corner is not detected.
  - In practice, the corner will be a curve which will probably produce a faint but detectable return signal.



- At corners, multiple reflections of the beam may occur before it returns to the receiver thereby resulting in an overestimation of range.



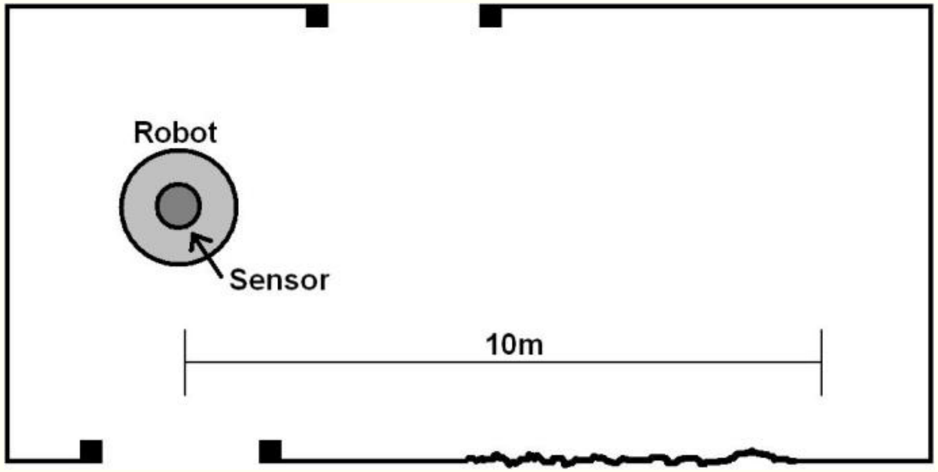
Ultrasonic Range Sensors: Mapping Example



Blue [illegible] position
ranges to [illegible] (x, y) [illegible] environment.

Exercise

The mobile robot shown overleaf has a top mounted rotating ultrasonic sensor giving it a 360° sensor range. The sensor has a beam angle of 30° and range of 10m. By considering what errors are possible with an ultrasonic sensor, sketch what you'd expect the robot's perception of the environment to be.



LIDAR *(LIght Distancing And Ranging)*

- As the wavelength of light is small, this allows for better focusing of the beam and therefore greater spatial resolution than ultra sonics.

- However the speed of light is much greater than of sound and to measure time of flight of a light pulse would require extremely fast electronics.

- In LIDAR, an intensity modulated beam is used instead and the phase shift of this modulation on the returned signal is used to calculate distance.

- A working range of $10m$ gives us a round trip distance of $20m$.
- Set this as our intensity modulation wavelength.
- This corresponds to a modulation frequency of:

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8}{20} = 15\ MHz$$

- For a phase measurement resolution of 10 then that corresponds to an accuracy of $20\ /\ 360\ =\ 6cm$.

Note that we can only measure phase shifts up to 360°.

LIDAR *(LIght Distancing And Ranging)*

- As LIDAR systems utilize a point of light, they must be scanned to obtain the required fields of view.

Note: Transparent objects, i.e. glass doors, windows, etc, is a major problem for LIDAR systems.