Sistemi Intelligenti Avanzati
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Università degli Studi di Milano

Introduction to Autonomous Mobile Robotics

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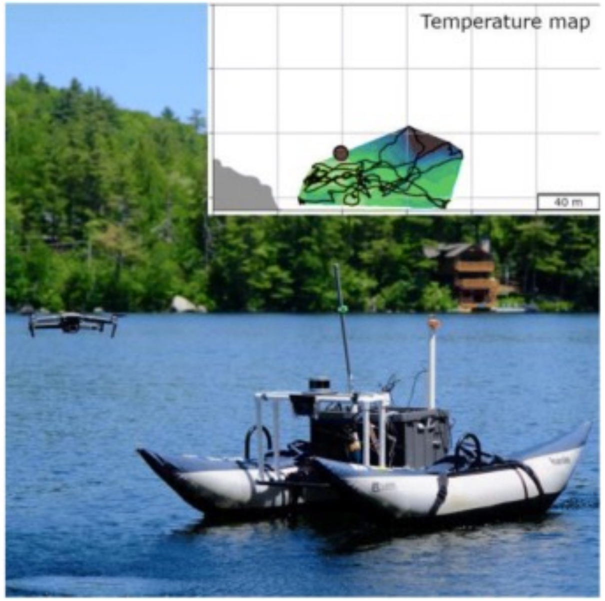
Autonomous mobile robots



What defines an autonomous mobile robot?

- Its architecture / configuration
  - Wheeled or legged
  - Humanoid
  - Fling – UAV, fixed wing
  - Water – ASV, underwater
  - …
- Its environment
  - Indoor (house, office, logistic, hospitals)
  - Outdoor (Field, marine, flying, space)
- Its tasks
  - Assistive / Collaborative (cleaning)
  - Patrolling / Surveillance
  - Urban Search and Rescue
- Its interaction with humans
  - Autonomous vs semi-autonomous
- Multi-robot

Autonomous mobile robots

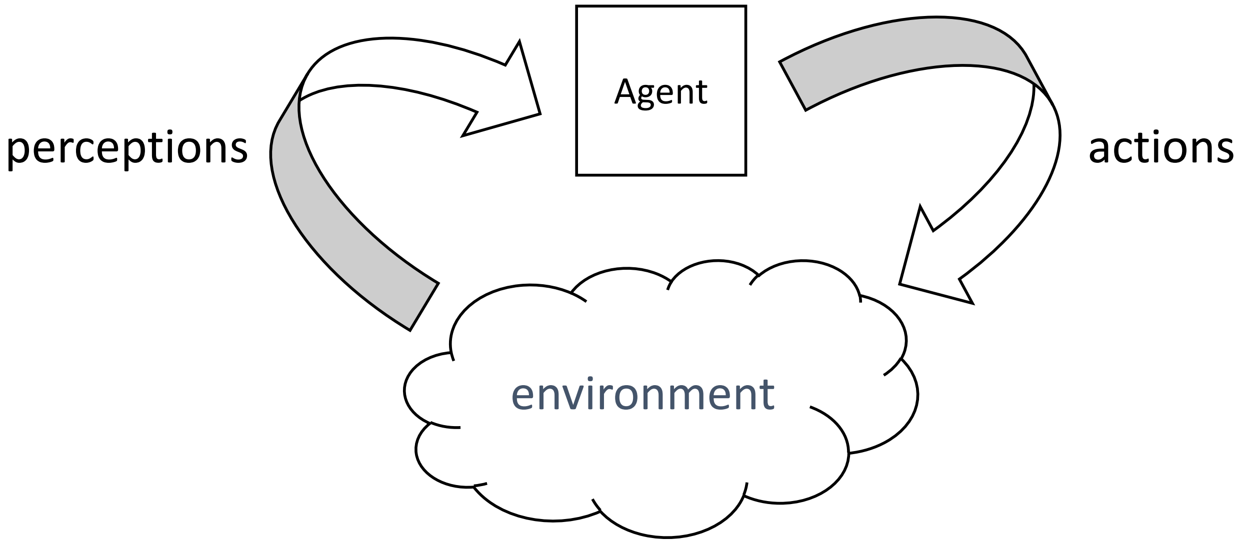
What is an autonomous mobile robot?

An agent that autonomously moves inside a given environment, to perform a given task

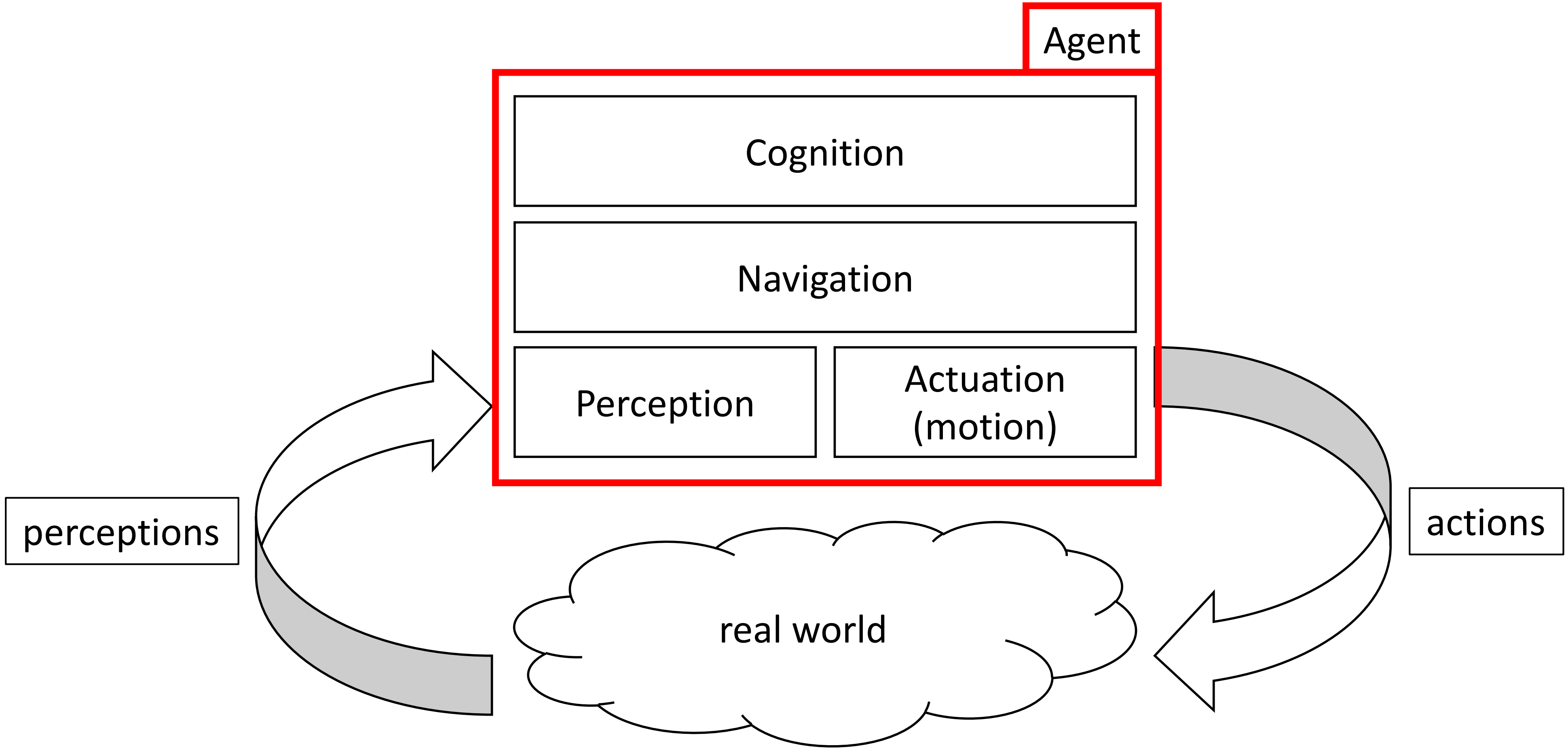
Robots as Agents

- *“[…] anything that can be viewed as perceiving its environment through sensors and acting upon that environment through actuators.” [Russel, Norvig 1995]*

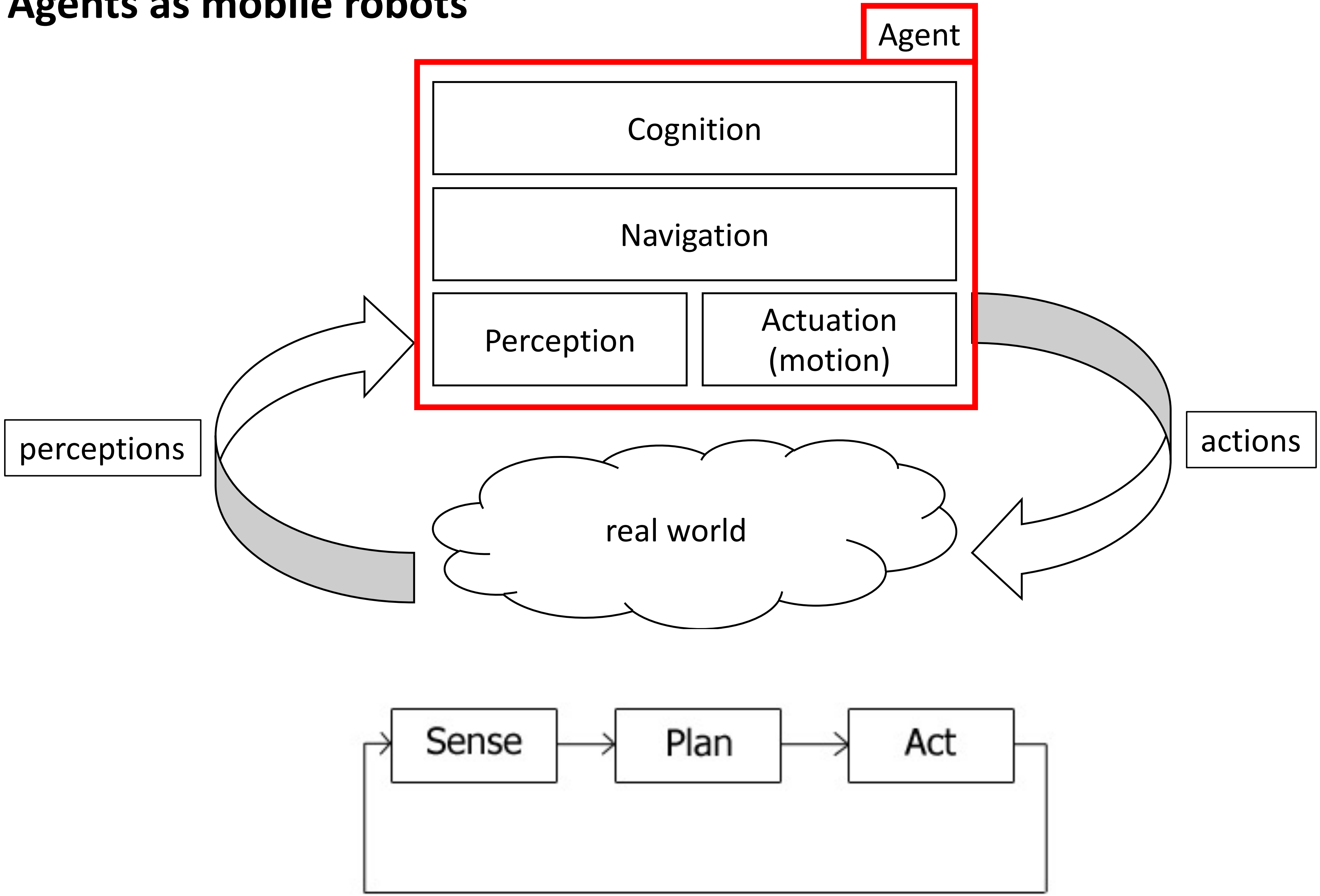
- *“[…] a computer system that is situated in some **environment**, and that is capable of **autonomous action** in this environment in order to meet its delegated objectives.“ [Wooldrige, 2009]*



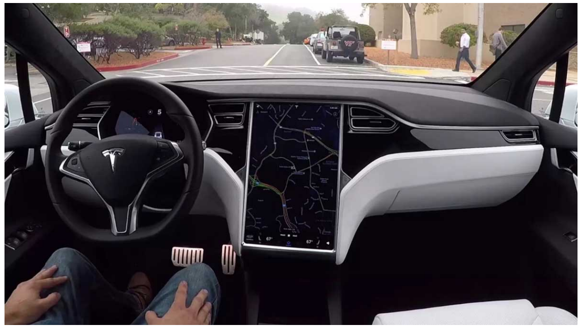
Agents as mobile robots



Agents as mobile robots

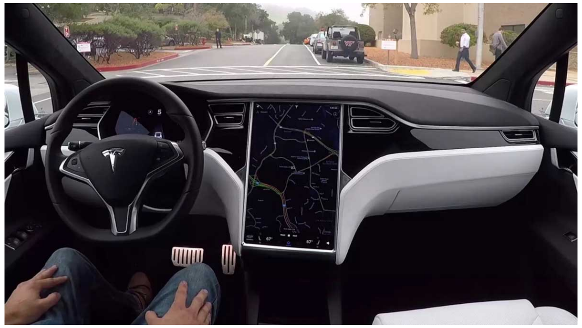


Environments and tasks



What we want robot to do? tedious, boring, hazardous, costly tasks that we do not want to do (or to help us in doing so)

Environments and tasks



What we currently have are robots that can perform repetitive simple tasks into controlled environments (e.g., industrial robots).

What we want is a sci-fi general AI robot capable of interacting with us and adapt to new challenges and tasks

Environments and tasks for robots

Despite costs (still quite high) manipulators are “commonly” used in manufacturing, but for performing repetitive and preprogrammed tasks…

Environments and tasks for robots

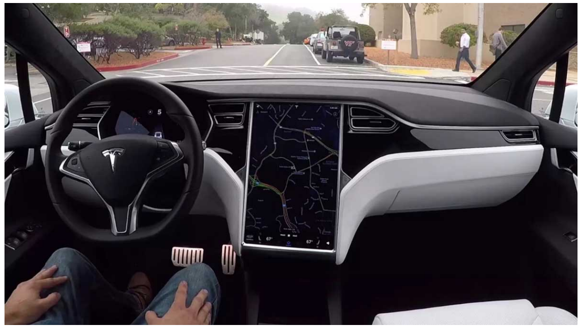
Despite costs (still quite high) manipulators are “commonly” used in manufacturing, but for performing repetitive and preprogrammed tasks…

…however their generalization to different settings (e.g. logistics, small manufacturing, …)

Environments and tasks for robots

Domestic robots are slowly becoming a common item in our homes, but even in this case they have limited abilities and they can perform only simple tasks (vacuum cleaners, lawnmowers, …)

Environments and tasks for robots



Autonomous driving cars are “almost” here, however:

- Driving in roads is a problem that is “easy” to be modeled
- How to do the last mile towards *really* having autonomous road vehicles is still unknown
  (a lot of effort, and money, since 2010, no results)

Environments and tasks for robots

Broadly speaking: if we simplify the environment enough, and we simplify the robot’s tasks enough, we can *have* autonomous robots…

…but there are still major limitations that prevents the widespread adoption of such machines.

(on the other side, general AI sci-fi robots are still sci-fi)

Limitations of Autonomous Robots

An agent that autonomously moves inside a given environment, to perform a given task

The major limitations of modern robots are due to the fact that robots need to make *decisions* to adapt their behaviour to the *environment* towards reaching theirs *tasks*…so where is the limitations?

- *Embodiment* = is it related to limitation in the robot HW?
- *Cognition* = is it related to limitation in the robot reasoning / SW?

What is missing to Autonomous Robots

[Pieter Abbeel, 2008]

Limitations of Autonomous Robots

An agent that autonomously moves inside a given environment, to perform a given task

It seems that, while we still have major limitations in terms of robots' actuation (wheels, arms, grippers) sensorial perception (sensors), and computational power (CPU/GPU,Memory) , the main limitation is still related to their cognition level, i.e., how to make decisions.

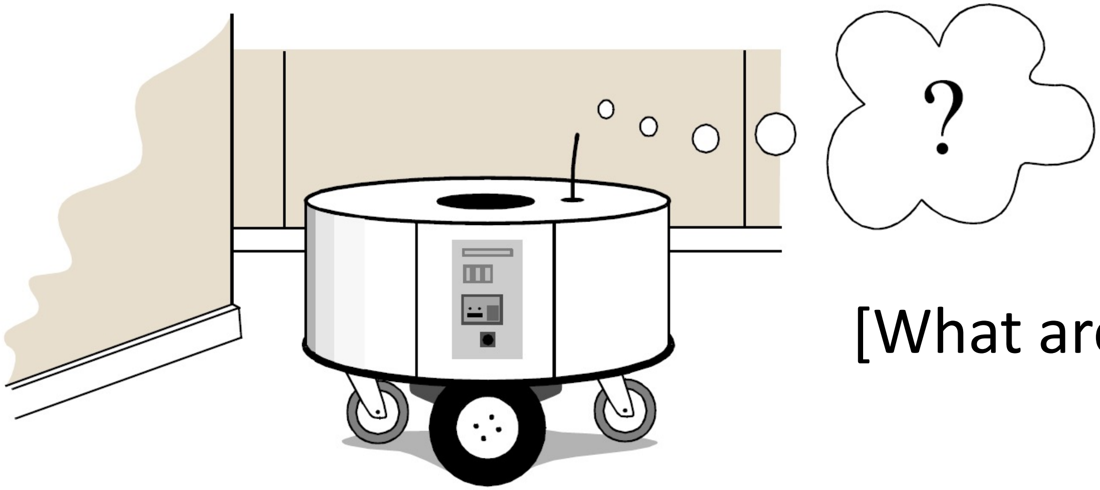
Limitations of Autonomous Robots

An agent that autonomously moves inside a given environment, to perform a given task

If we have to pick one major issues about modern autonomous robots, the main one is *perception*, as it involves the *interpretation* of sensed data in a meaningful way.

Thus, *mobility* is a critical aspects as depends on perception and interpretation (while, manipulators, have less strict requirements)

Towards Autonomous Robots



An autonomous mobile robot needs to solve different concurrent tasks

Towards Autonomous Robots

[Where am I?]

[Where to go next?]

[How do I go there?]

[How to accomplish this task?]

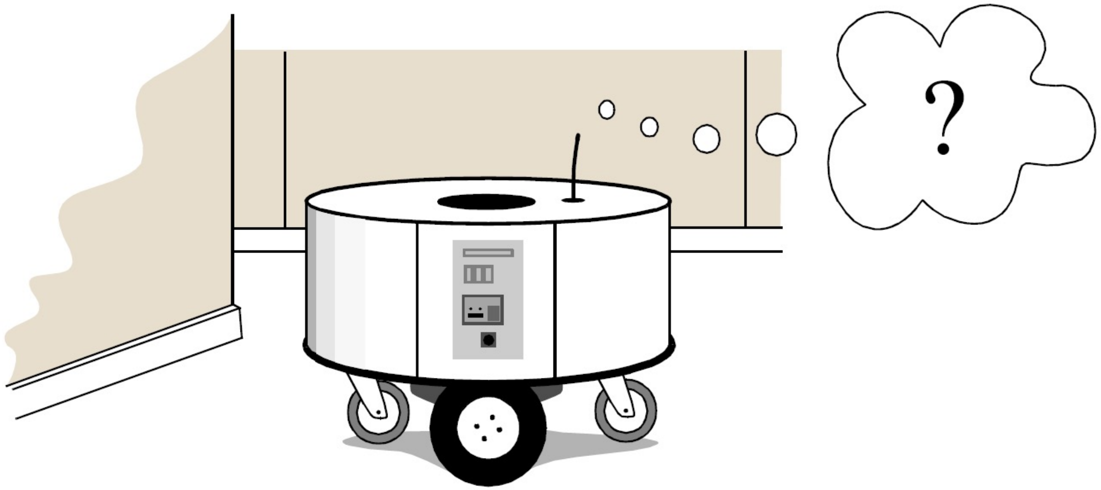
[What task is next?]

[What plan to do all my tasks for today?]

[What are my tasks?]

[What's my battery status?]

[What is that?]



Divide et impera: divide robot functionalities in sub-problems, organize them at different level of abstraction, solve them separately, integrate

Towards Autonomous Robots

[Where am I?] → [What's my battery status?] → [What is that?] →

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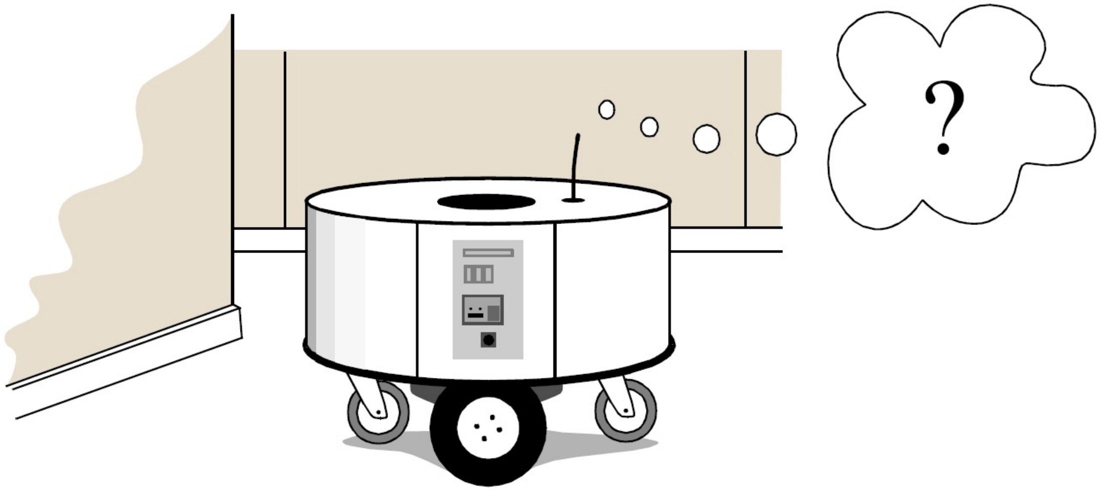

Adapt the execution to environmental changes, unexpected events, make robust solutions (e.g., self-driving cars)

Towards Autonomous Robots

[Where am I?]

[Where to go next?]

[How do I go there?]

Navigation and mapping and their subproblems:

Motion, mapping, localization, path planning, path execution

[How to accomplish this task?]

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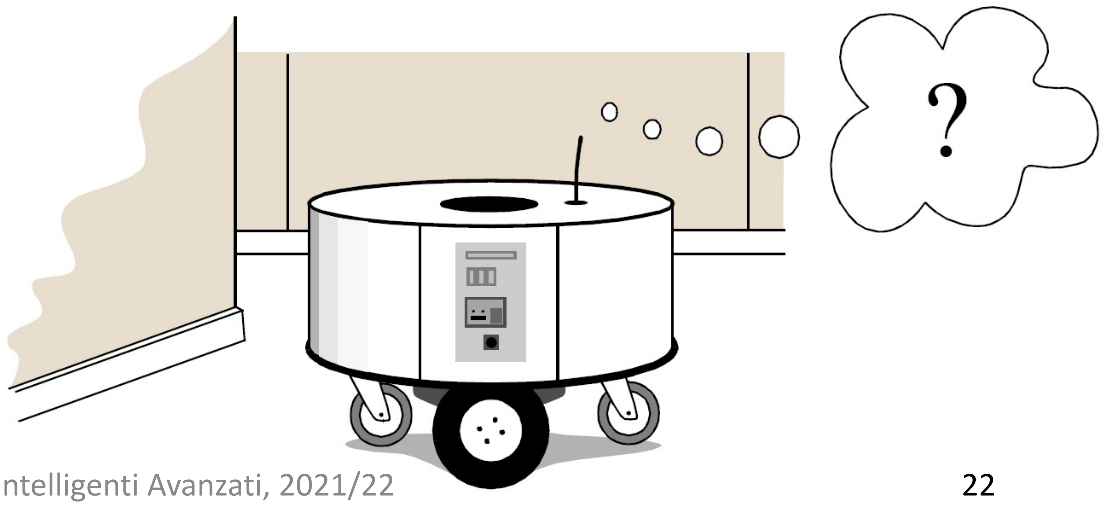

Towards Autonomous Robots

[Where am I?]

[Where to go next?]

[How do I go there?]

[How to accomplish this task?]

Task-related problems: manipulation, grasping, human-robot interaction, cleaning, patrolling, …

[What task is next?]

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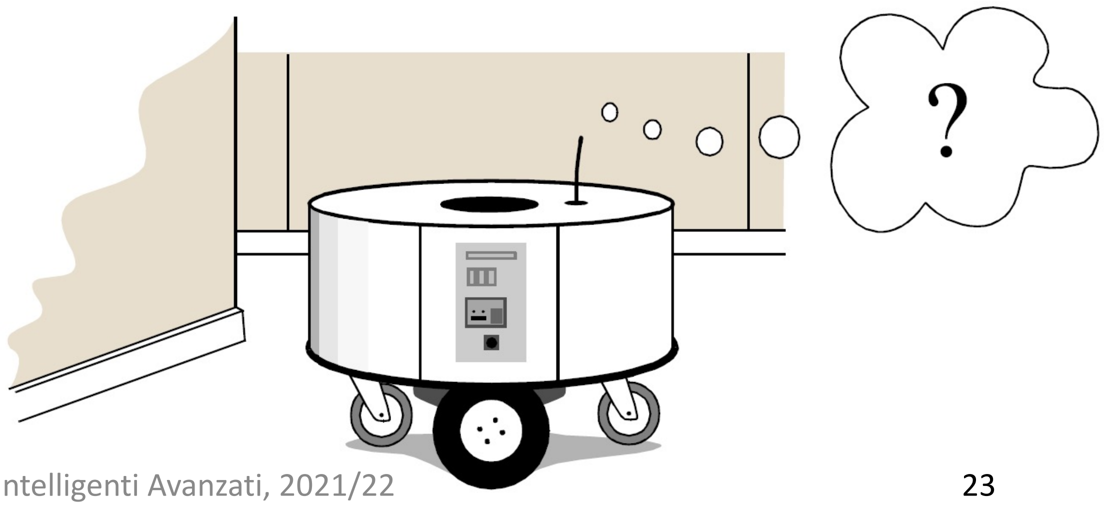

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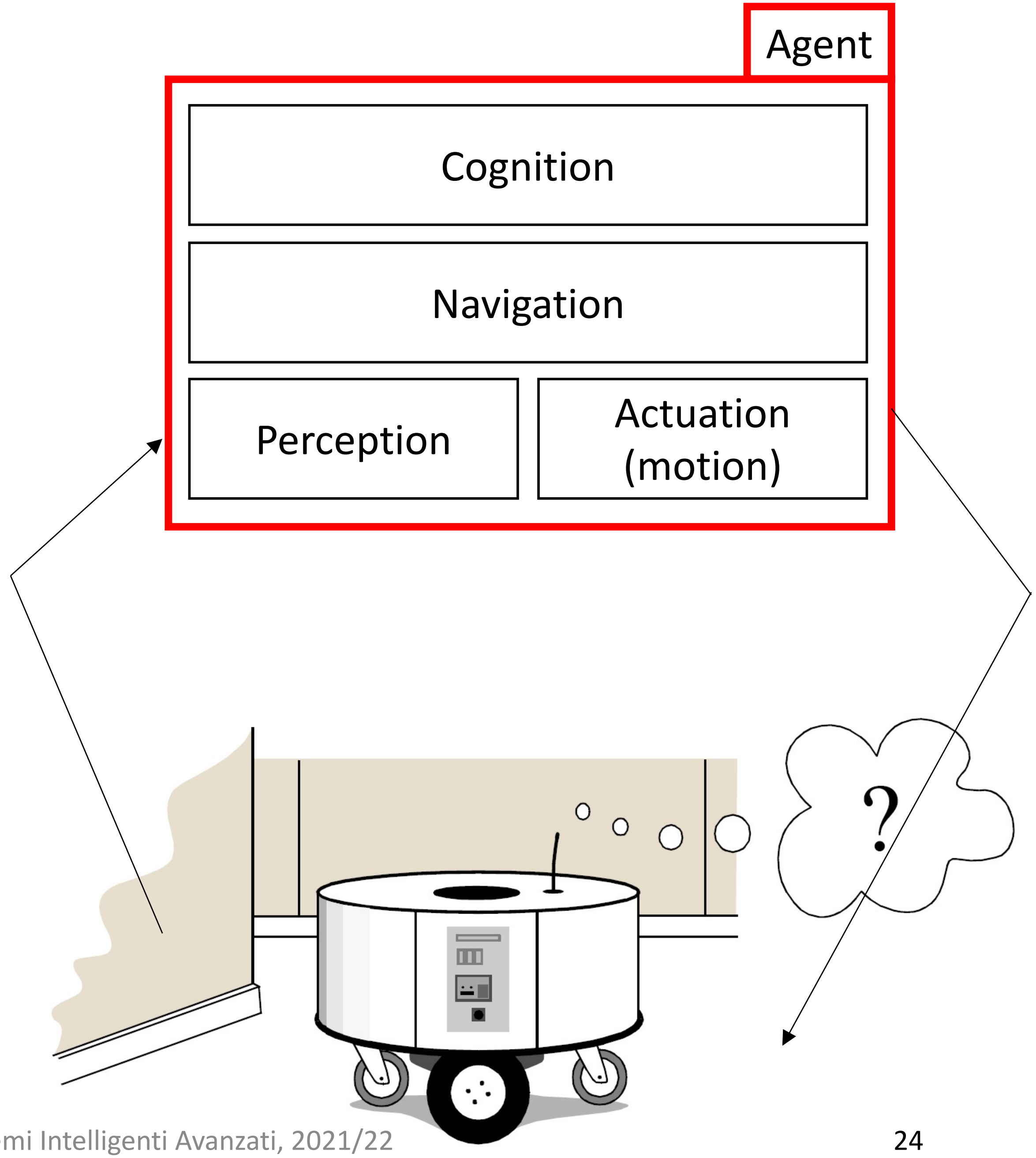

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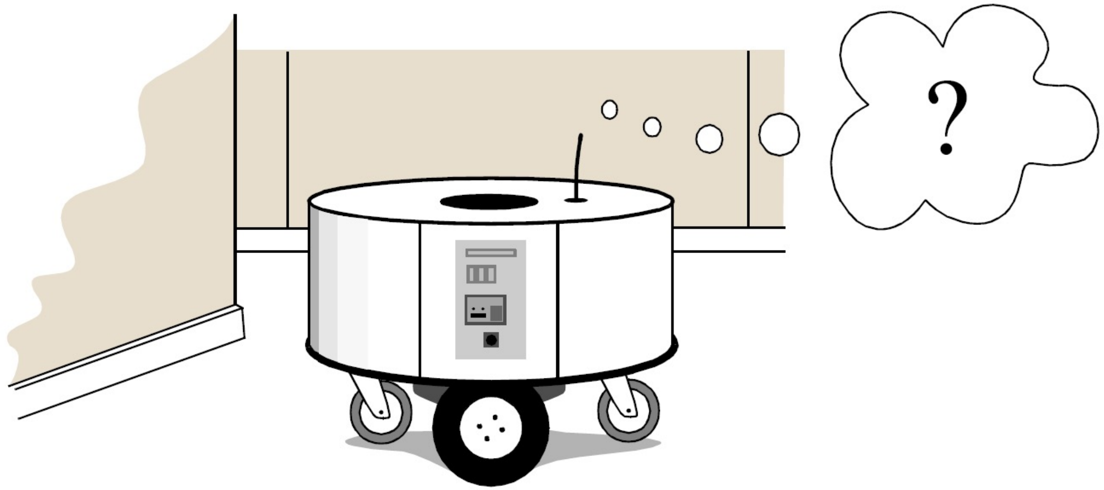
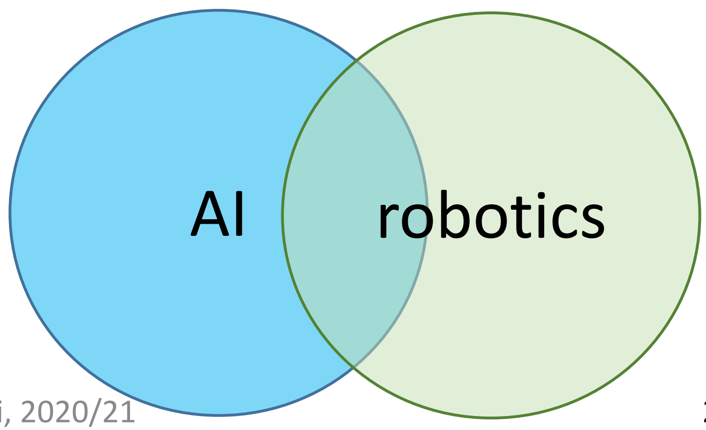


Planning problems, AI for robotics



Different robots, different level of complexity

[Kunze et al., 2018]

SURVEYED AI-ENABLED LONG-TERM AUTONOMY ROBOT SYSTEMS.

Domain	Environment Variability	Task Diversity	Semantics	Dynamics	Partial Observability	Cost & Criticality	Interaction & Cooperation	Level of Autonomy	Duration	Navigation & Mapping	Perception	KR & Reasoning	Planning	Interaction	Learning	System
Space	L	L	L	L	H	H	L	M	Years	○	●	–	●	○	–	Opportunity [9], [10]
									Years	○	●	–	●	○	–	IPEX [11]
Marine	M	L	L	M	H	H	L	H	Days	○	●	○	●	–	○	AUVs [12], [13]
									Months	○	○	–	○	–	–	Gliders [14]
Air	M	M	M	H	H	H	M	M	Days	○	●	○	○	–	–	AtlantikFlyer [15]
Field	H	M	L	M	H	M	M	M	Days	●	●	○	–	○	○	VT&R2 [16]
									Years	●	●	○	–	–	○	BearNav [17], [18]
Road	M	L	M	H	M	H	M	L	Days	○	●	●	○	–	○	VaMP [19]
									Days	○	●	○	○	–	○	ARGO [20]
									Months	○	●	○	○	–	○	PANS [21]
									Months	○	●	○	○	–	○	VIAC [22]
Service	H	H	H	L	H	L	H	M	Days	●	○	○	●	●	○	Rhino [23]
									Days	●	○	○	●	●	○	Minerva [24]
									Days	●	○	○	○	●	○	Willow Garage [25]
									Months	●	●	●	●	●	●	STRANDS [26]
									Years	●	●	●	●	●	●	CoBot [27]

Legend: L *low*, M *medium*, H *high*, – *not integrated*, ○ *partially integrated*, ● *fully integrated*

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Autonomous Robots at large

Mechanics

Kinematics

Control Theory

Signal Processing

Information Theory

Probability Theory

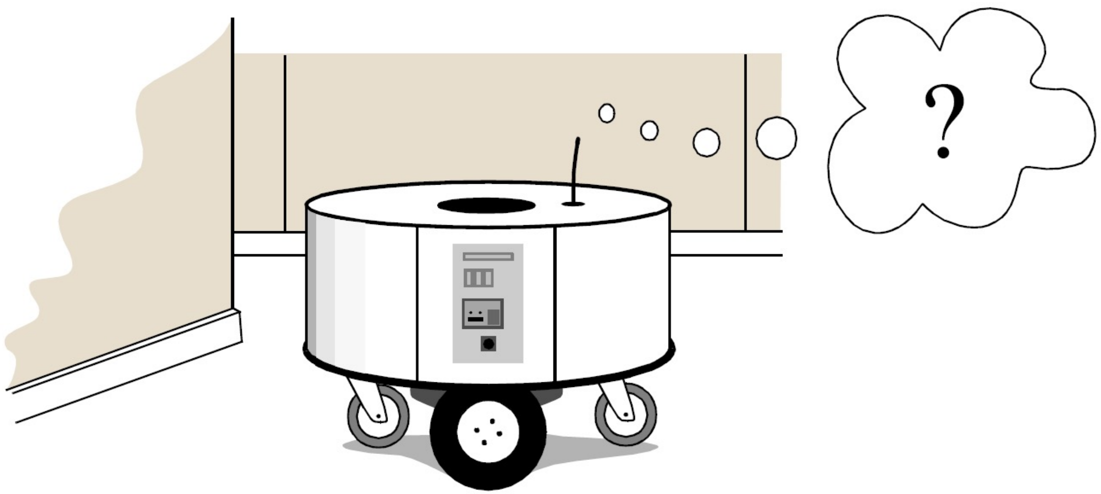
Artificial Intelligence

Computer Vision

Multi Agent Systems

Multiple perspectives and fields involved, from HW to SW

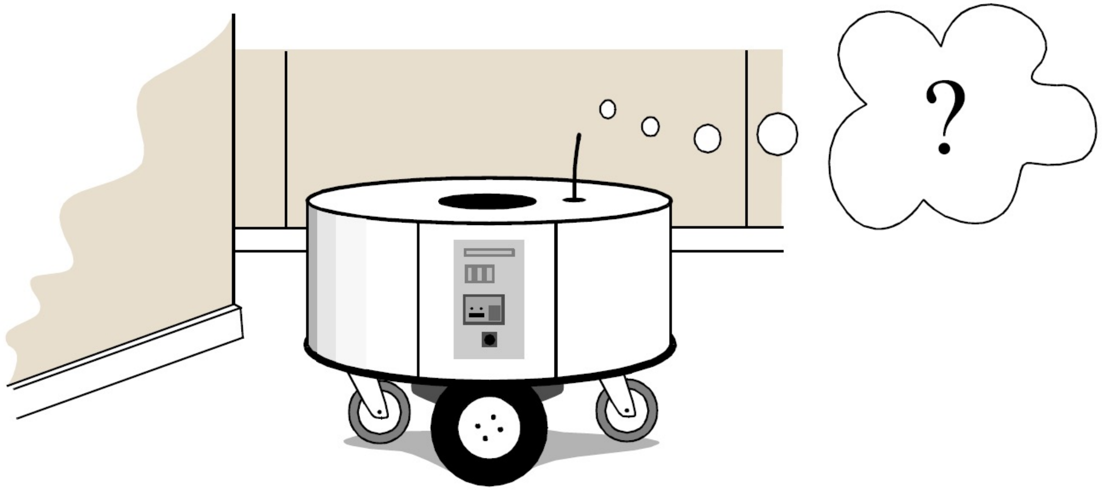
There is no single solution on how to address this problem (robotics is still a young field)



Outline

Overview of core concepts:

- Robot Motion
- Perception
- Localization and Mapping
- Navigation



Assumption: let's talk about the simplest type of mobile robots, wheeled ground vehicles

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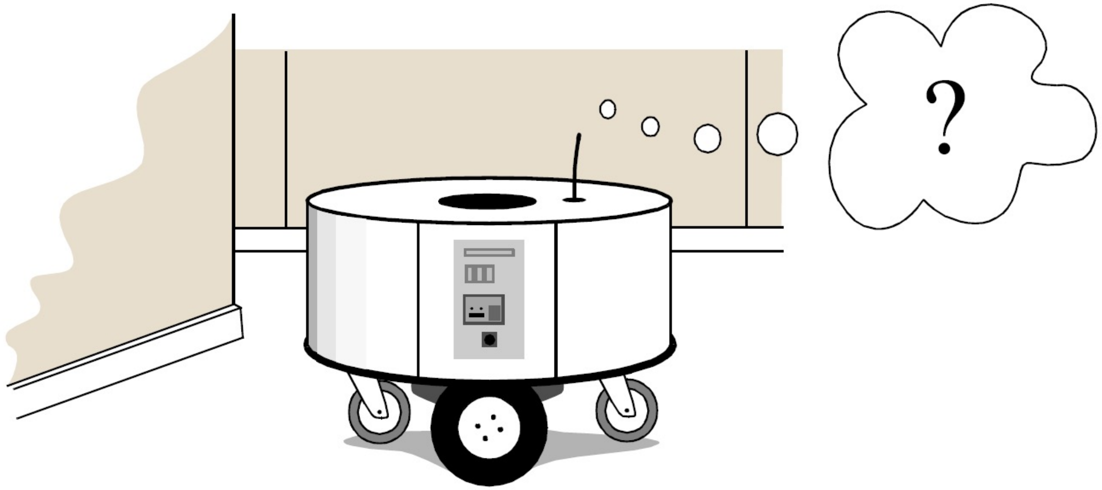


Assumption: let's talk about the simplest type of mobile robots, wheeled ground vehicles

Robot Motion

Locomotion

Wheels

Configuration

Kinematics

Robot Wheels

1

2

3

4

Four main types of wheels:

1. Standard wheel - 2 DOF - rotation around the wheel axle
2. Castor wheel – 2 DOF – rotation around the steering joint
3. Mecanum wheel (Swedish or Omni Wheel) – 3DOF –
   rotation around wheel axle, rollers, contact point, 45° or 90°
4. Ball or Spherical Wheel

Mecanum wheel = omnidirectional

Wheel Configuration

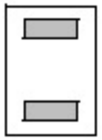
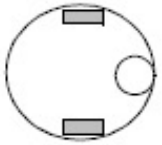
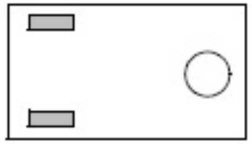
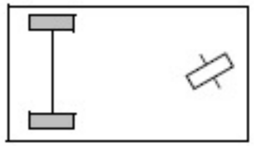
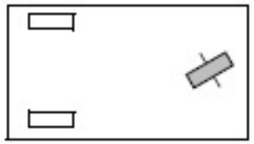
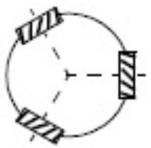
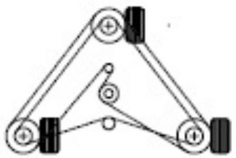
- How many wheels? 2,4,6,8?
- How many axes?
- What type of wheels?

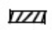
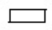
Targets:

- Stability = robot does not fall → 2 wheels minimum, 3+ for “robust” solutions
- Maneuverability = do we have motion constraints? (e.g., car in parallel parking)
- Controllability = how difficult is to control movement?

Usually, maneuverability and controllability are inversely correlated

Wheel Configuration

# 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
		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

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.

From Siegwart,Introduction to Autonomous Mobile Robots, MIT Press 2004

Wheel Configuration

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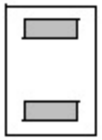
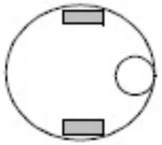
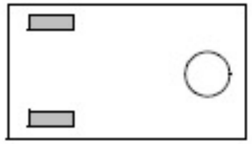
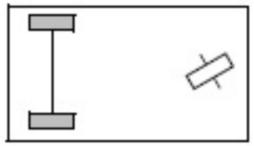
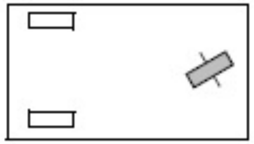
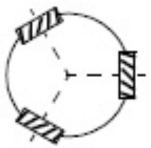
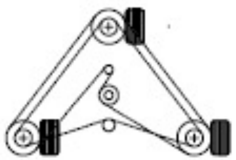
		Two-wheel differential drive with the center of mass (COM) below the axle	Cye personal robot
3		Two-wheel centered differential drive with a third point of contact	Nomad Scout, smartRob EPFL
		Two independently driven wheels in the rear/front, 1 unpowered omnidirectional wheel in the front/rear	Many indoor robots, including the EPFL robots Pygmalion and Alice
		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

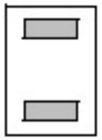
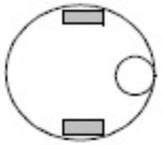
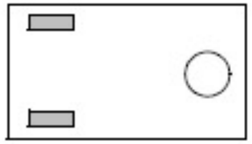
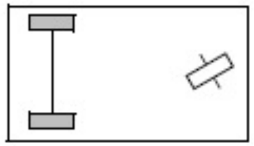
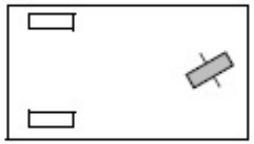
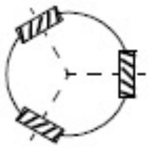
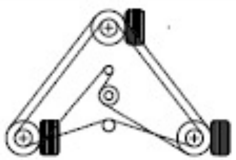
Icons for the each wheel type are as follows:	
	unpowered omnidirectional wheel (spherical, castor, Swedish);
	motorized Swedish wheel (Stanford wheel);
	unpowered standard wheel;
	motorized standard wheel;
	motorized and steered castor wheel;
	steered standard wheel;
	connected wheels.

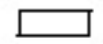
Popular configurations:

- Limited number of wheels
- Limited motors
- Simple

From Siegwart,Introduction to Autonomous Mobile Robots, MIT Press 2004

Wheel Configuration

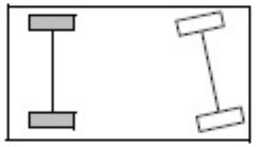
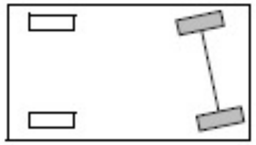
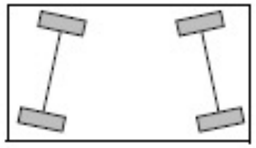
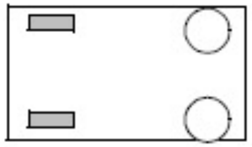
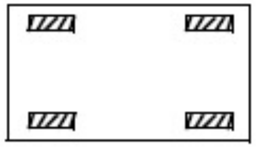
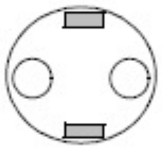
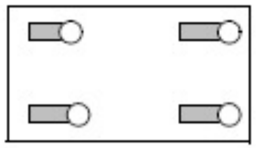
# of wheels	Arrangement	Description	Typical examples
2		One steering wheel in the front, one traction wheel in the rear	Bicycle, motorcycle
		Two-wheel differential drive with the center of mass (COM) below the axle	Cye personal robot
3		Two-wheel centered differential drive with a third point of contact	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
		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

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.

Omnidirectional with 3 motors and a simple architecture

From Siegwart,Introduction to Autonomous Mobile Robots, MIT Press 2004

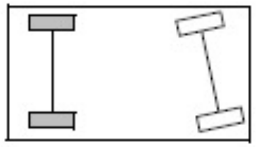
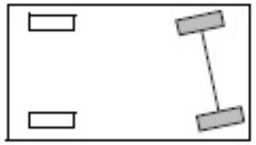
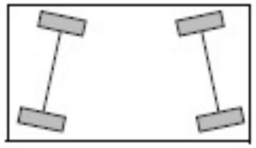
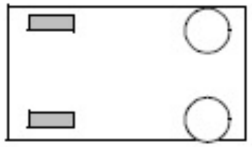
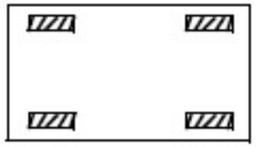
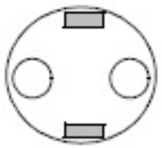
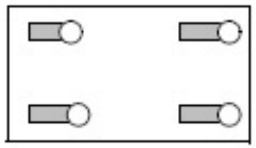
Wheel Configuration

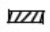
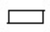
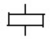
# of wheels	Arrangement	Description	Typical examples
4		Two motorized wheels in the rear, 2 steered wheels in the front; steering has to be different for the 2 wheels to avoid slipping/skidding.	Car with rear-wheel drive
		Two motorized and steered wheels in the front, 2 free wheels in the rear; steering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

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.

From [Siegwart, Introduction to Autonomous Mobile Robots]

Wheel Configuration

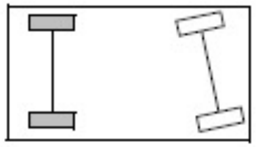
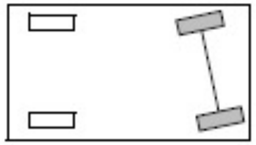
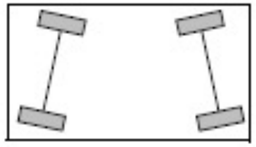
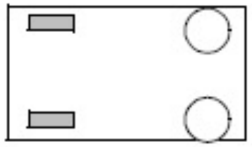
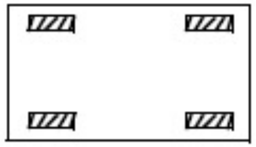
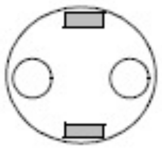
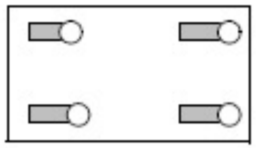
# of wheels	Arrangement	Description	Typical examples
4		Two motorized wheels in the rear, 2 steered wheels in the front; steering has to be different for the 2 wheels to avoid slipping/skidding.	Car with rear-wheel drive
		Two motorized and steered wheels in the front, 2 free wheels in the rear; steering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

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.

Car configuration – parallel parking

From [Siegwart, Introduction to Autonomous Mobile Robots]

Wheel Configuration

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

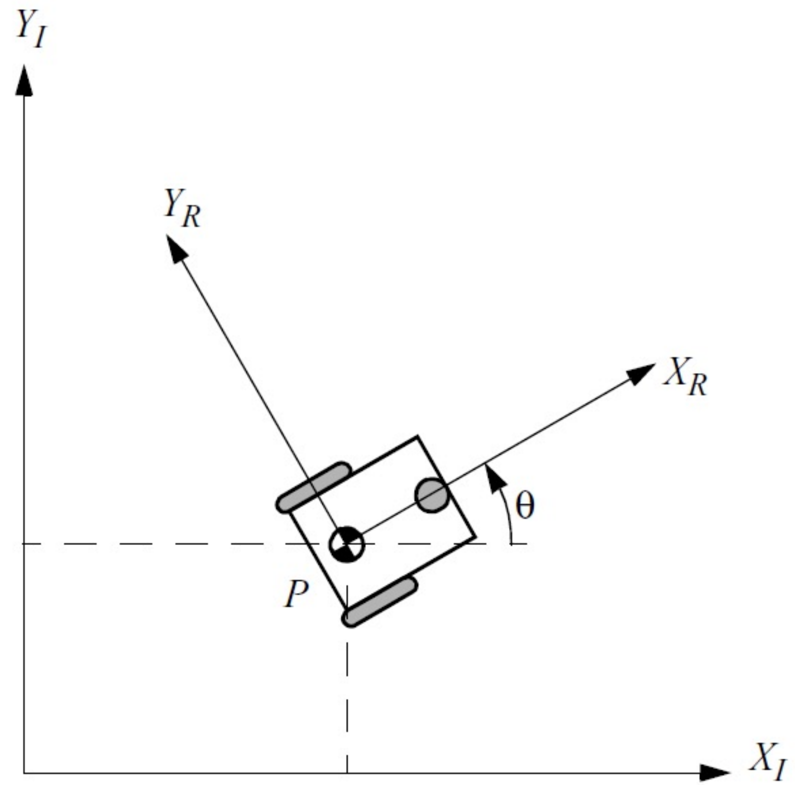
Icons for the each wheel type are as follows:	
	unpowered omnidirectional wheel (spherical, castor, Swedish);
	motorized Swedish wheel (Stanford wheel);
	unpowered standard wheel;
	motorized standard wheel;
	motorized and steered castor wheel;
	steered standard wheel;
	connected wheels.

Omnidirectional – 4 wheels

From [Siegwart, Introduction to Autonomous Mobile Robots]

Kinematics

- Describe how a mechanical system behaves, is needed to create control software for the robot
- Kinematic Model of the robot and Constraints
  - Representing the robot position and the robot movement in a global and local reference frame



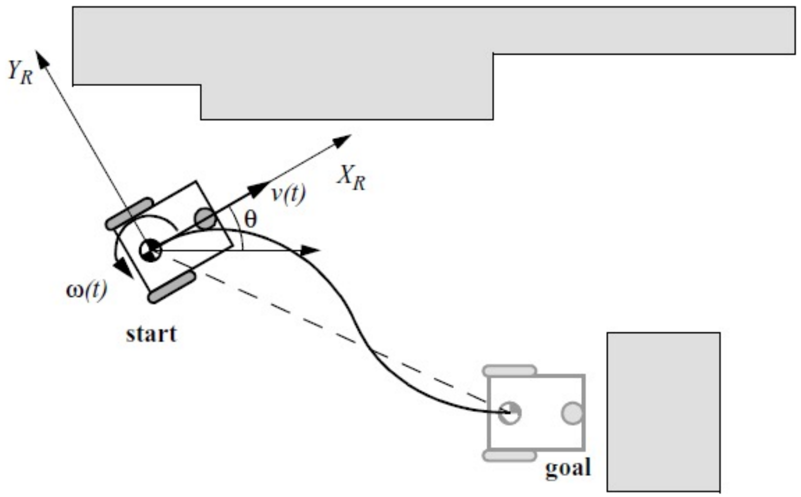
The robot pose is expressed as

$$[x, y, \theta]$$

in the global reference frame

Kinematics

- Forward Kinematics computes the robot speed in the global reference frame given the spinning speed of each wheel
- Inverse Kinematics compute the robot actuators parameters to reach a given configuration
- Each wheel configuration results into a set of constraints



Usually, robot DDOF are considered: Differential Degrees of Freedom (that are equal to the degree of mobility of the robot)

$$DDOF \leq \delta_m \leq DOF$$

Sistemi Intelligenti Avanzati
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Introduction to Autonomous Mobile Robotics #2

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