BASICS of MOBILE ROBOTICS 1
Components of a Mobile Robot

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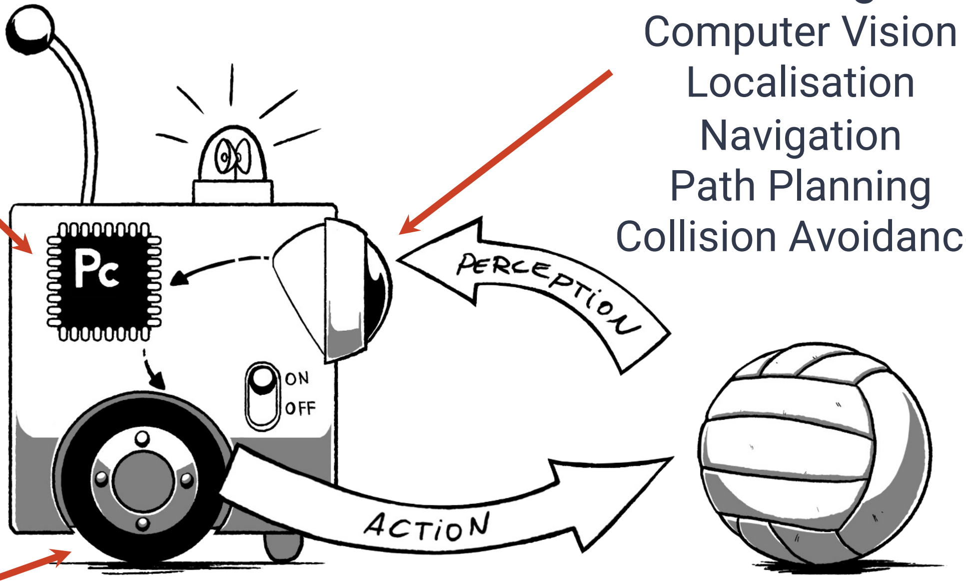
Overview of the Components of a Mobile Robot

System Integration



Processors
Embedded electronics
Architectures
Communication
Programming
Real-time Control

Sensors Integration
Computer Vision
Localisation
Navigation
Path Planning
Collision Avoidance

Mechanics
Actuators
Energy
Locomotion

credits : Thymio MOOC

Mechanics - Locomotion Control

Is a difficult and unsolved problem :

Locomotion and movement are due to **complex interactions between the controller, the body, and the environment.** Requires solving multiple complex computational challenges:

- good coordination of multiple DOFs,
- dealing with uncertainties,
- keeping balance,
- adapting to terrain/environment,
- adapting to changing body properties, …

Challenge for mechanics, actuation, energy, sensing, control, ... This is still not properly solved in robotics, and still not properly understood in animals

Mechanics – Trade Offs

	What	Characteristics	Implications
Stability	Not falling over.	Static stability does not require any motion to maintain balance, as opposed to dynamic stability.	Static stability is guaranteed with 3 wheels. More wheels increases dynamic stability, but these should be free to avoid impacting maneuverability as these systems are hyperstatic and require a flexible suspension system.
Controllability	Ease-precision in converting motor commands into rotational and translational velocities.	Useful for accurate steering and dead reckoning (i.e. estimation of one’s position based on previous positions).	Inverse correlation between controllability and maneuverability. • **cars have good controllability but poor maneuverability** • **omnidirectional robots using Swedish wheels have good maneuverability but poor controllability** (due to uncertainty in steering and speed).
Maneuverability	Ability to change direction.	Omnidirectional drive offers the highest maneuverability (ability to move at any time in any direction on the ground plane).	

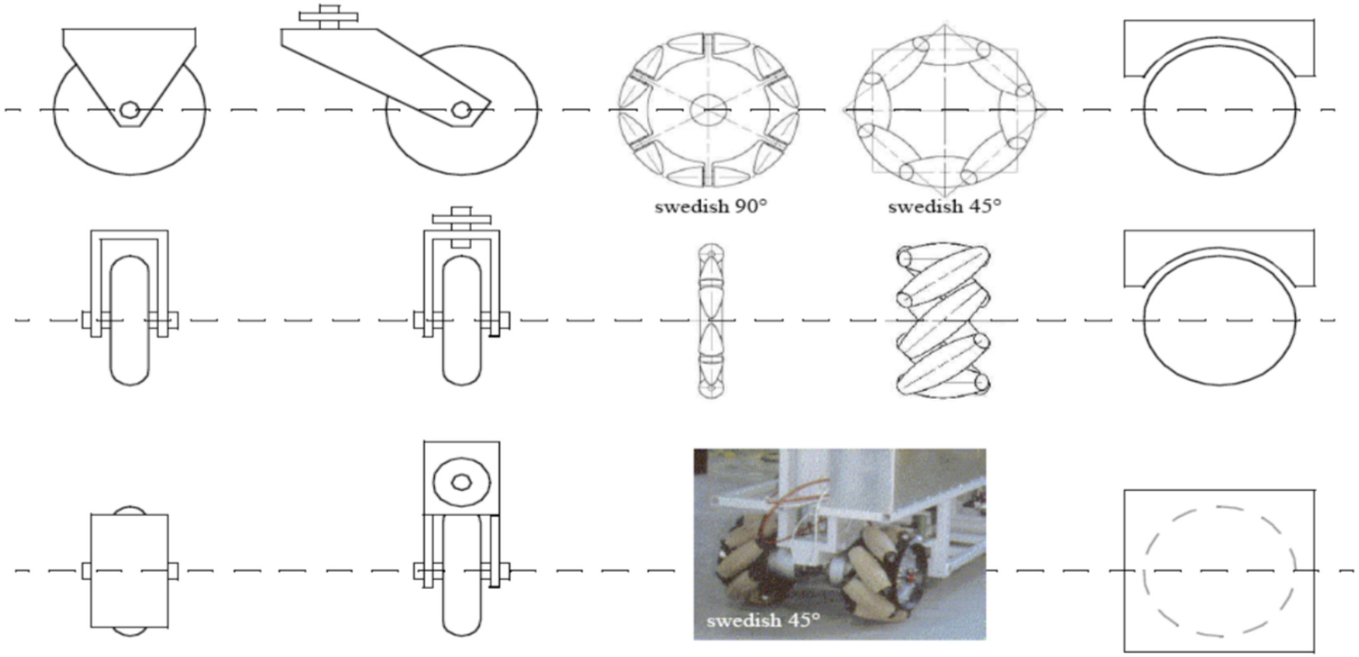
Mechanics - 4 Basic Wheel Types

a) **Standard wheel**: rotation around the (motorized) wheel axle and the contact point.

b) **Castor wheel**: rotation around the wheel axle, the contact point and the castor axle.

c) **Swedish (or mecanum) wheel**: rotation around the (motorized) wheel axle, around the rollers and around the contact point.

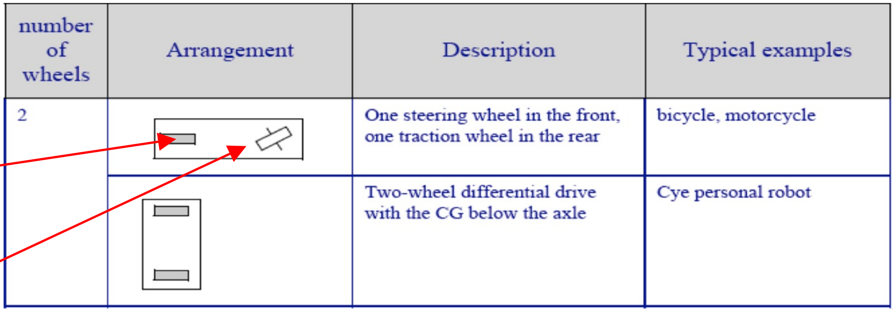
d) **Ball or spherical wheel.**



Different arrangements with 2, 3, 4 and 6 wheels exist

Mechanics – Arrangements of wheels

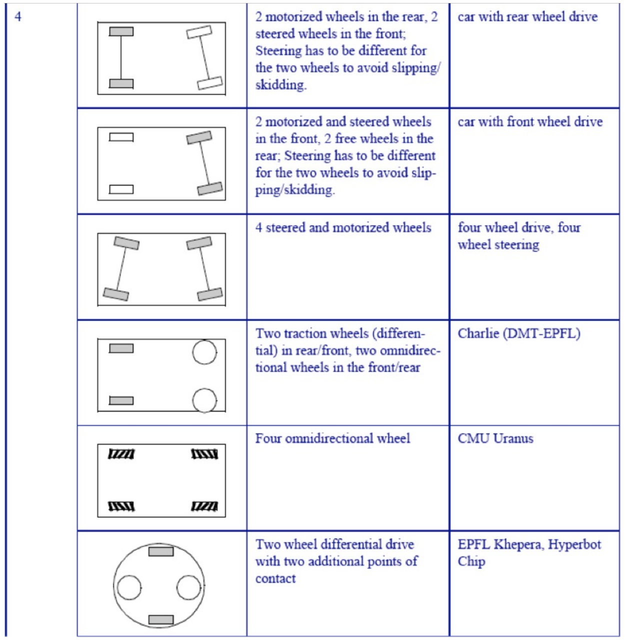
Different arrangements with 2, 3, 4 and 6 wheels exist



number 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 CG below the axle	Cye personal robot

actuated wheel

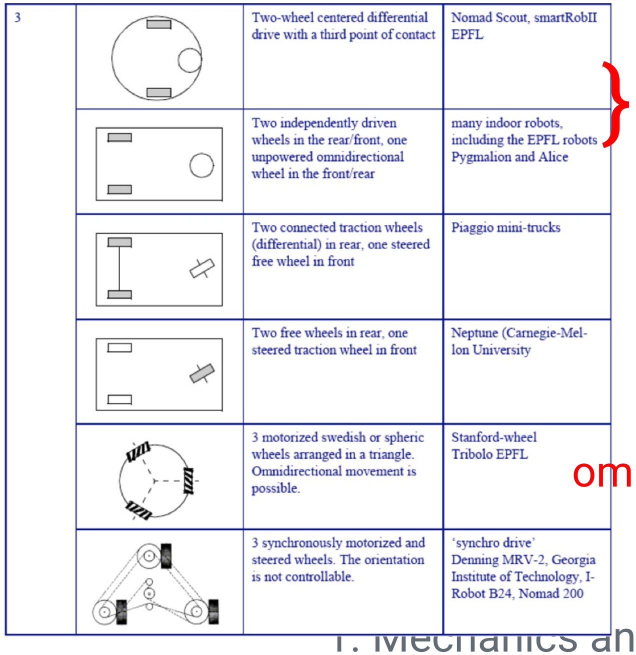
free wheel



4		2 motorized wheels in the rear, 2 steered wheels in the front; Steering has to be different for the two wheels to avoid slipping/ skidding.	car with rear wheel drive
		2 motorized and steered wheels in the front, 2 free wheels in the rear; Steering has to be different for the two wheels to avoid slipping/skidding.	car with front wheel drive
		4 steered and motorized wheels	four wheel drive, four wheel steering
		Two traction wheels (differential) in rear/front, two omnidirectional wheels in the front/rear	Charlie (DMT-EPFL)
		Four omnidirectional wheel	CMU Uranus
		Two wheel differential drive with two additional points of contact	EPFL Khepera, Hyperbot Chip

“Ackermann”

differential drive



3		Two-wheel centered differential drive with a third point of contact	Nomad Scout, smartRobII EPFL
		Two independently driven wheels in the rear/front, one unpowered omnidirectional wheel in the front/rear	many indoor robots, including the EPFL robots Pygmalion and Alice
		Two connected traction wheels (differential) in rear, one steered free wheel in front	Piaggio mini-trucks
		Two free wheels in rear, one steered traction wheel in front	Neptune (Carnegie-Mellon University
		3 motorized swedish or spheric wheels arranged in a triangle. Omnidirectional movement is possible.	Stanford-wheel Tribolo EPFL
		3 synchronously motorized and steered wheels. The orientation is not controllable.	‘synchro drive’ Denning MRV-2, Georgia Institute of Technology, I-Robot B24, Nomad 200

} differential drive

omnidirectional drive

synchro drive

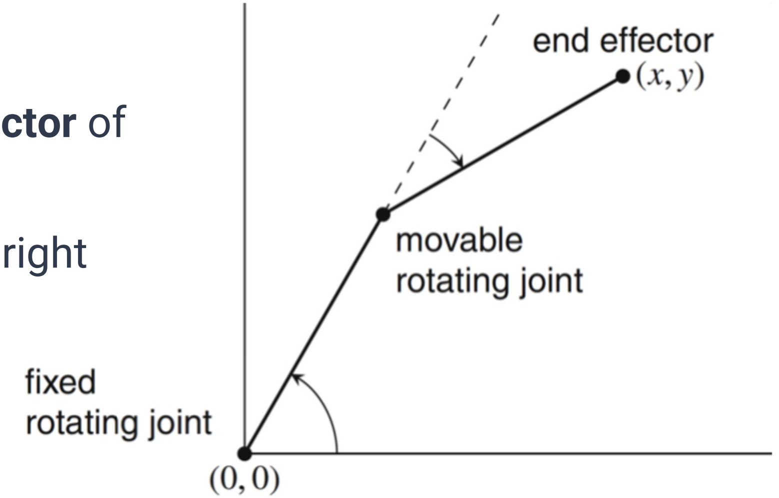
Mechanics - Degrees of Freedom (DOF)

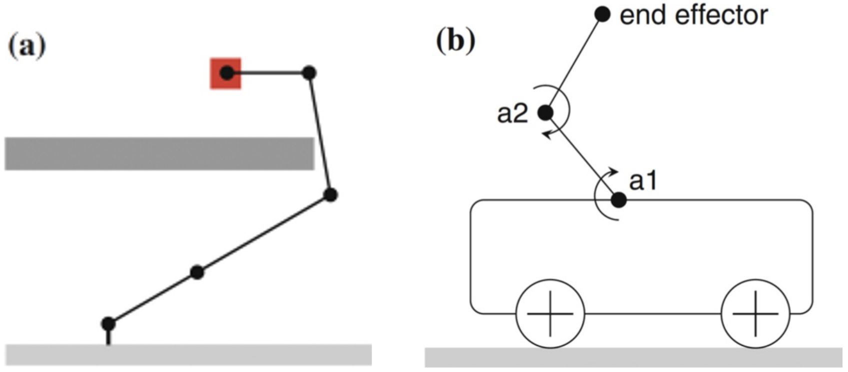
Number of DOF = dimensionality of the coordinates needed to describe the **pose** of a mobile robot or the pose of **the end effector** of a robotic manipulator

- e.g. Thymio has 3 DOF, a train has 1 DOF, the arm on the right has 2

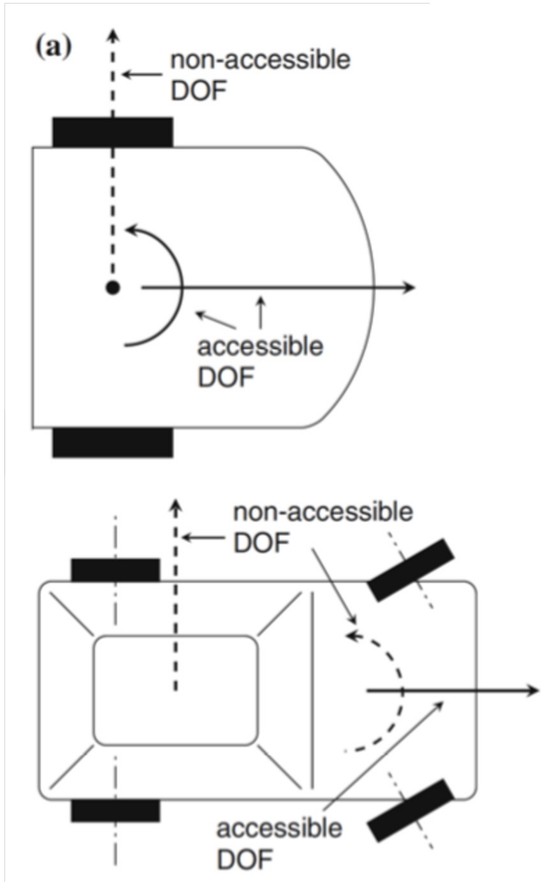
Different relationships between DOF and Actuators

- **n DOF = n Actuators** : e.g. a train, the two-line robotic arm shown
- **n Actuators < n DOF** : e.g. a differential drive robot which has 2 actuators but can reach all 3 dimensional poses in the plane -> cheaper but harder to plan and control
- **n Actuators > n DOF** : redundant systems which can be useful in practice for complex movements or combining several characteristics (a)(b)





Mechanics - Degrees of Mobility (DOM)



The controllable DOF or degrees of mobility (DOM) δm = number of degrees of freedom that can be directly accessed by the actuators.

- A differential drive robot has 3 DOF: position (x,y) and orientation (θ). But only 2 DOF are directly accessible: forward speed and rotation.
- A car has also 3 DOF but only 1 DOF is directly accessible: forward speed. The other actuator, the steering wheel, does not give direct access to any additional DOF, it can only orient the first DOF.

  -> A differential mobile robot has better mobility than a car. A car cannot turn on the spot.

Holonomicity implies that the controllable DOF or DOM is equal to the total degrees of freedom (in the task space). In other words, all DOF are directly controllable. If DOM < DOF then the robot is non holonomic (can move in some directions but not others)

Caution: (in general) omnidirectional ≠ holonomic. Example: synchro-drive

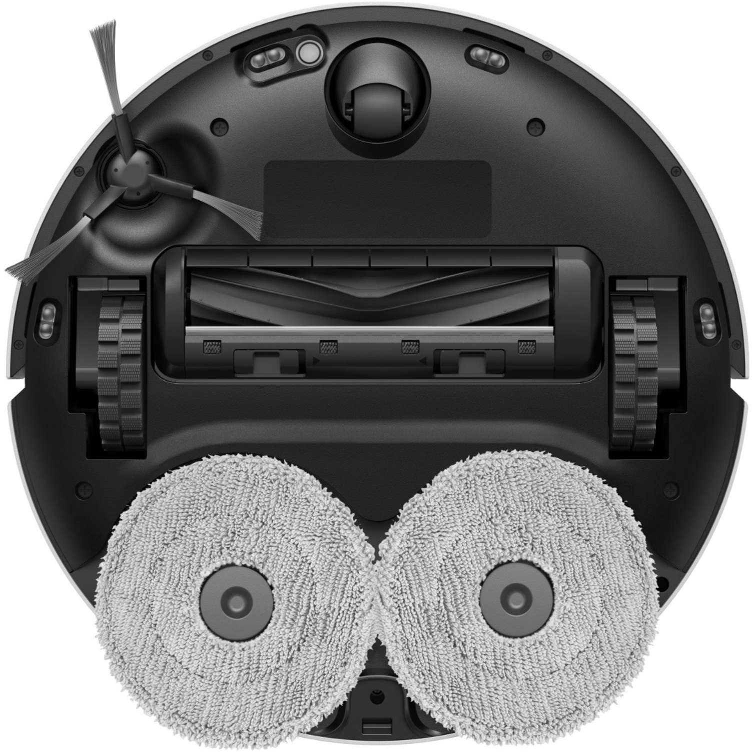
Mechanics - Differential Drive Motion Control

Motion Controller to follow a trajectory or to reach a target pose. Not straightforward for non holonomic or nonlinear systems.

Examples of controller (not perfect, does not consider all forces and velocities in the state vector)

There are several approaches to bring the robot at desired position and orientation

- option 1 : combination of rotations on the spot + straight segments -> simple but not smooth
- option 2 (Astolfi): control law that smoothly modulates forward and rotational velocities

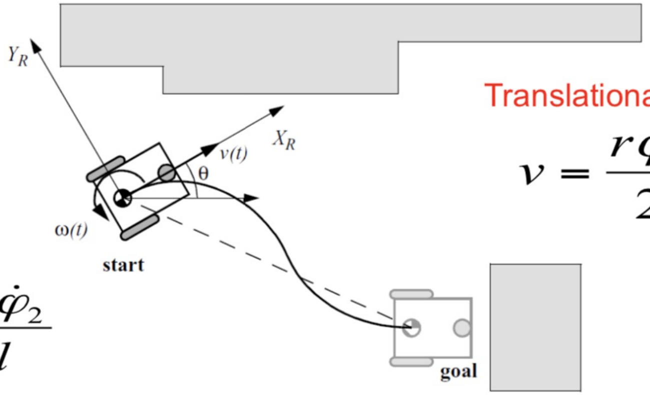


Mova e30 Ultra

Mechanics –Differential Drive Motion Control

Astolfi Controller - 1. Extracting Rotational and Translational Velocity From Motor Speeds. Provided the relation between linear and angular velocities, the following can be deduced from the robot's geometry

A Astolfi - Journal of dynamic systems, measurement, and control, 121 (1), pp 121-126,1999



Translational velocity

$$v = \frac{r\dot{\varphi}_1}{2} + \frac{r\dot{\varphi}_2}{2}$$

Rotational velocity

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

Where $\dot{\varphi}_i$ is the motor speed, *r* is the wheel radius, *l* is the axle length, *v* is translational velocity and ω is the rotational velocity.

Mechanics –Differential Drive Motion Control

Astolfi Controller - 2. Kinematic Model : Mapping velocities from the robot’s reference to the global reference frame. Requires using the inverse rotation matrix.

R(-θ) clockwise rotation

Translational velocity

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = R(\theta)^{-1}\begin{bmatrix}\dot{x}_R\\ \dot{y}_R\\ \dot{\theta}_R\end{bmatrix} = R(\theta)^{-1}\begin{bmatrix}v\\ 0\\ \omega\end{bmatrix} = \begin{bmatrix}cos\theta & sin\theta & 0\\ -sin\theta & cos\theta & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\frac{\dot{\varphi}_1 r+\dot{\varphi}_2 r}{2}\\ 0\\ \frac{\dot{\varphi}_1 r-\dot{\varphi}_2 r}{2l}\end{bmatrix}$$

Global Frame

Local Robot Frame

Rotational velocity

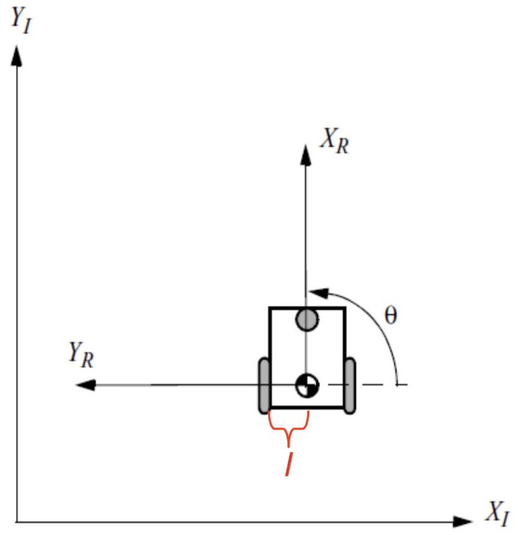


Figure 3.2
The mobile robot aligned with a global axis.

Mechanics –Differential Drive Motion Control

Astolfi Controller - 3. Transform to polar coordinates with origin at goal position to simplify the control law

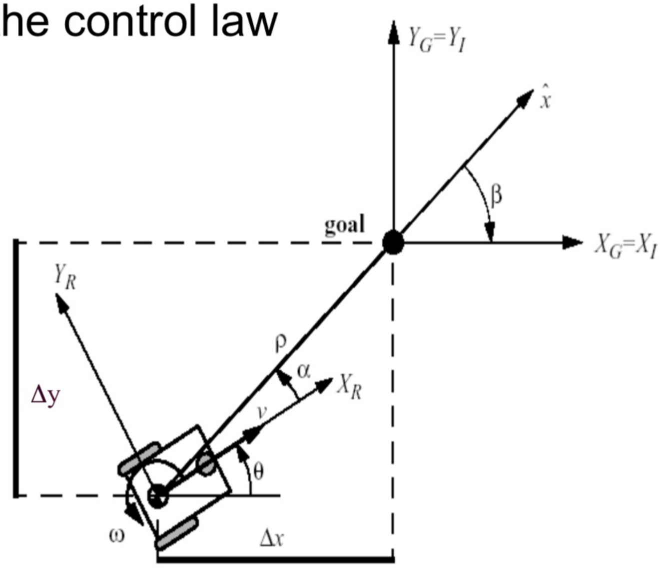
The following transformation into **polar coordinates** with origin at the goal position allows to simplify the control law

$$\begin{cases} \rho = \sqrt{\Delta x^2 + \Delta y^2} \\ \alpha = -\theta + \operatorname{atan2}(\Delta y, \Delta x) \\ \beta = -\theta - \alpha \end{cases}$$

note: $\operatorname{atan2}(a,b) = \arctan\left({}^{a}\!/\!{}_{b} \right)$

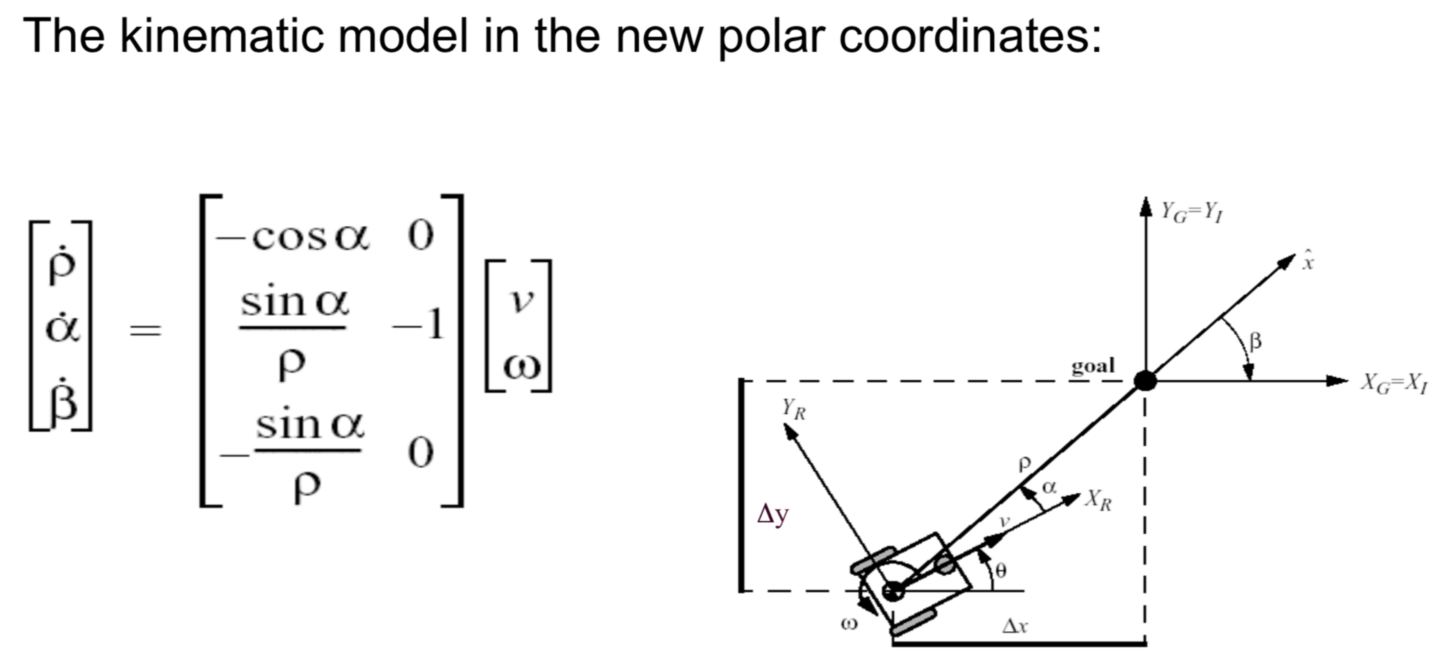
where the signs of both arguments are used to determine the quadrant of the result.

Target: $(\rho,\alpha,\beta) = (0, 0, 0)$



Mechanics –Differential Drive Motion Control

Astolfi Controller - 4.



The kinematic model in the new polar coordinates:

$$\begin{bmatrix} \dot{\rho} \\ \dot{\alpha} \\ \dot{\beta} \end{bmatrix} = \begin{bmatrix} -\cos\alpha & 0 \\ \dfrac{\sin\alpha}{\rho} & -1 \\ -\dfrac{\sin\alpha}{\rho} & 0 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix}$$

Mechanics –Differential Drive Motion Control

Astolfi Controller - 4.

It can be shown, that the linear control law: $\boxed{v = k_\rho \rho \qquad \omega = k_\alpha \alpha + k_\beta \beta}$

yields the closed loop system:

$$\begin{bmatrix} \dot{\rho} \\ \dot{\alpha} \\ \dot{\beta} \end{bmatrix} = \begin{bmatrix} -k_\rho \rho \cos\alpha \\ k_\rho \sin\alpha - k_\alpha \alpha - k_\beta \beta \\ -k_\rho \sin\alpha \end{bmatrix}$$

which has a **unique equilibrium point** at $(\rho,\ \alpha,\ \beta) = (0,\ 0,\ 0)$

Using the Lyapunov theory, it can be shown (Astolfi, 1995, 1997) that the closed loop control system is **exponentially stable** if:

$$k_\rho > 0\ ;\ k_\beta < 0\ ;\ k_\alpha - k_\rho > 0$$

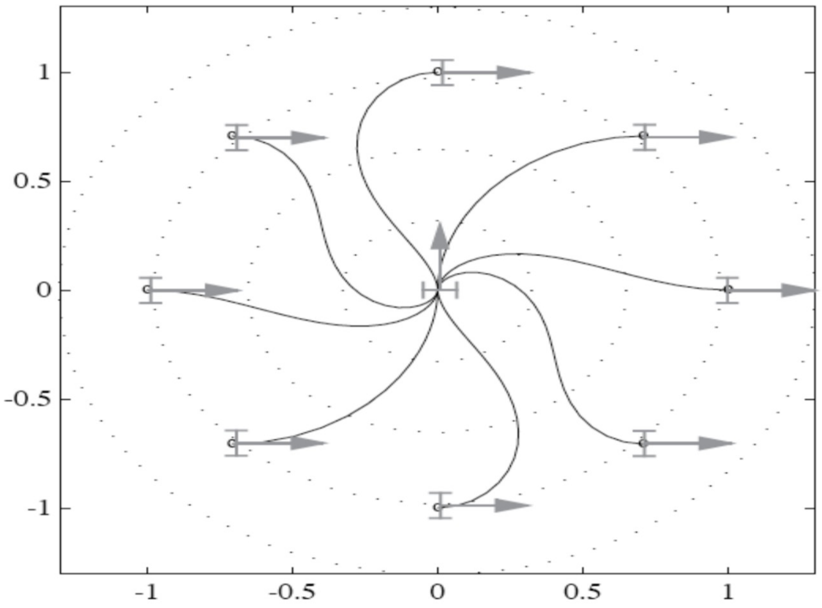
The control signal v has always constant sign:

- ⇒ the direction of movement is kept positive or negative during the entire movement.
- ⇒ parking maneuver is performed always in the most natural way and without ever inverting its motion.

Mechanics –Differential Drive Motion Control

Astolfi Controller - 4.

RESULTING PATHS



Exponential stabilization of a wheeled mobile robot via discontinuous control

A Astolfi - Journal of dynamic systems, measurement, and control, 121 (1), pp 121-126,1999

interactive demo link on moodle

Mechanics - Actuators

Actuators	Advantages	Inconveniences	Usage Examples
Combustion Engines	• High energy density (50-100x more than a Lithium-Polymer battery)	• Poor efficiency (30%) • Heavier for the same power • Pollutant (short-term toxic indoor) emissions	• robotized cars, trucks, etc. • flying robots • Sometimes used in outdoor legged robots (BigDog, Boston Dynamics)
Hydraulic Actuators	High torque-to-weight ratio, higher than electric motors. Useful for large loads	• Maintenance problems => not often used in mobile robotics. • Need for large compressor	Exceptions: Legged robots from BostonDynamics + some humanoid robots (CB from Sarcos, Atlas from Boston Dynamics)
Pneumatic Actuators	lightweight, easy attachment, toughness, high efficiency and high power over short distances	• Limited control • Highly nonlinear • Need for large compressor	e.g. air muscles
Electric Motors	• Large power range (mW-MW) • Easy to control • Excellent efficiency (~90%) • No pollutant emissions • Can integrate gears & encoder		most robots and more and more cars

Mechanics - Actuators : Electrical Motors

Actuator		Advantages	Inconveniences	Examples
DC Motors	Brushed (commutation at the level of the rotor)	• Brushed easier to control (mechanical commutation)	• Friction -> power losses, wear down • Speed & torque trade-off	
	Brushless (commutation at the level of the stator)	• Higher torque (w.r.t brushed) • No friction -> longer life	• Trade-off between speed and torque • Complex electronics for the controls	
Servomotors (integrated position control, generally DC brushed motor)		• Integrated regulation	• Limited range • Generally limited torque	
Stepper Motors (converts electrical pulses into discrete mechanical movements)		• Open-loop drive by counting steps, accuracy of ±1 step. • High holding torque when the rotor is stationary.	• Cannot tell when steps have not been counted and cannot be recovered • Complex electronic control	e-puck

Mechanics - Actuators : Electrical Motors

Actuator		Advantages	Inconveniences	Examples
AC Motors	Synchronous (rotor speed = stator magnetic field speed)	• Precise speed and position control • Speed independent of the load	• Complex start-up	
	Asynchronous (small difference between rotor speed and stator magnetic field speed), also called induction motor	• Robust • Easy start-up • No wear	• Slipping • More complex electronics compared to a synchronous motor	

Mechanics - Electric Energy Storage

What to consider :

- **Energy Density [Wh/g]:** determines the overall energy that can be delivered over one charge, w.r.t the weight. Should be high to guarantee best autonomy
- **Power Density [W/g]:** determines how much energy can be delivered at a given point in time, w.r.t the weight. Must be higher than the maximal consumption of all components (actuators, electronics, etc…).
- **Pulse load [A]:** determines the maximal current that can be delivered and must be sufficient for all components
- **Charge / discharge time [s]**: give the autonomy of the robot, ideally high discharge over charge ratio
- **Operating temperatures [C]**: must be considered for robots operating in special conditions
- **Operating voltages [V]**: determines which actuators and electronics can be used
- **Life [cycles]:** consider number of cycles needed for the application, progressive decrease in performance

Types :

- **Capacitors :** very fast charge and discharge, but low capacity
- **Super Capacitors :** when high output power density is needed and quick recharges are possible
- **Fuel Cells :** fuel in (hydrogen) and electricity out, 40-60% energy efficient
- **Batteries** : long missions, long down time, power density lower than capacitors

Mechanics – Electric Energy Storage

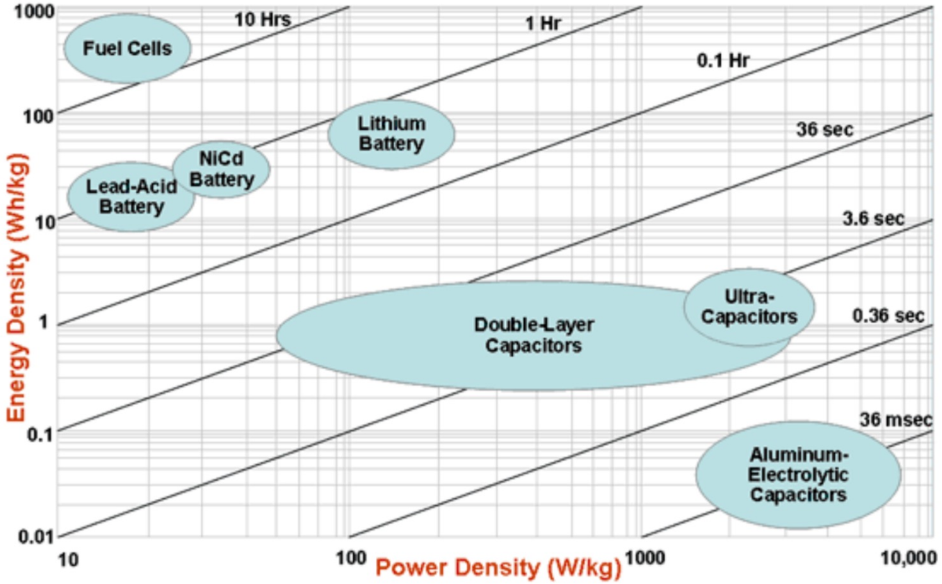
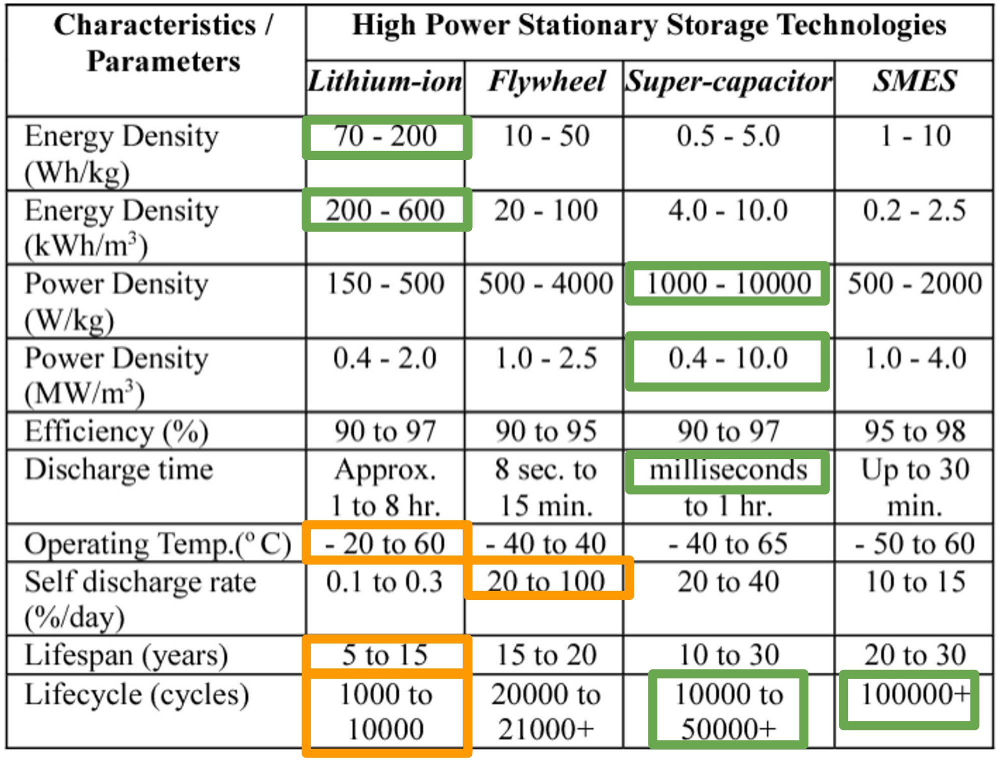


Figure 6. *A Ragone chart storage device energy density versus power density on a log-log coordinate system, with discharge times represented as diagonals.*

Artal, J. S., Dominguez, J. A., & Caraballo, J. (2012, March). Autonomous Mobile Robot with Hybrid PEM Fuel-Cell and Ultracapacitors Energy System, Dedalo 2.0. In *International Conference on Renewable Energies and Power Quality, Santiago de Compostela, Spain* (pp. 1-6).



Characteristics / Parameters	**High Power Stationary Storage Technologies**			
	Lithium-ion	***Flywheel***	***Super-capacitor***	***SMES***
Energy Density (Wh/kg)	70 - 200	10 - 50	0.5 - 5.0	1 - 10
Energy Density (kWh/m^3)	200 - 600	20 - 100	4.0 - 10.0	0.2 - 2.5
Power Density (W/kg)	150 - 500	500 - 4000	1000 - 10000	500 - 2000
Power Density (MW/m^3)	0.4 - 2.0	1.0 - 2.5	0.4 - 10.0	1.0 - 4.0
Efficiency (%)	90 to 97	90 to 95	90 to 97	95 to 98
Discharge time	Approx. 1 to 8 hr.	8 sec. to 15 min.	milliseconds to 1 hr.	Up to 30 min.
Operating Temp.(° C)	- 20 to 60	- 40 to 40	- 40 to 65	- 50 to 60
Self discharge rate (%/day)	0.1 to 0.3	20 to 100	20 to 40	10 to 15
Lifespan (years)	5 to 15	15 to 20	10 to 30	20 to 30
Lifecycle (cycles)	1000 to 10000	20000 to 21000+	10000 to 50000+	100000+

Lachuriya, A., & Kulkarni, R. (2017). Stationary electrical energy storage technology for global energy sustainability: A review. *2017 International Conference on Nascent Technologies in Engineering (ICNTE)*, 1-6.

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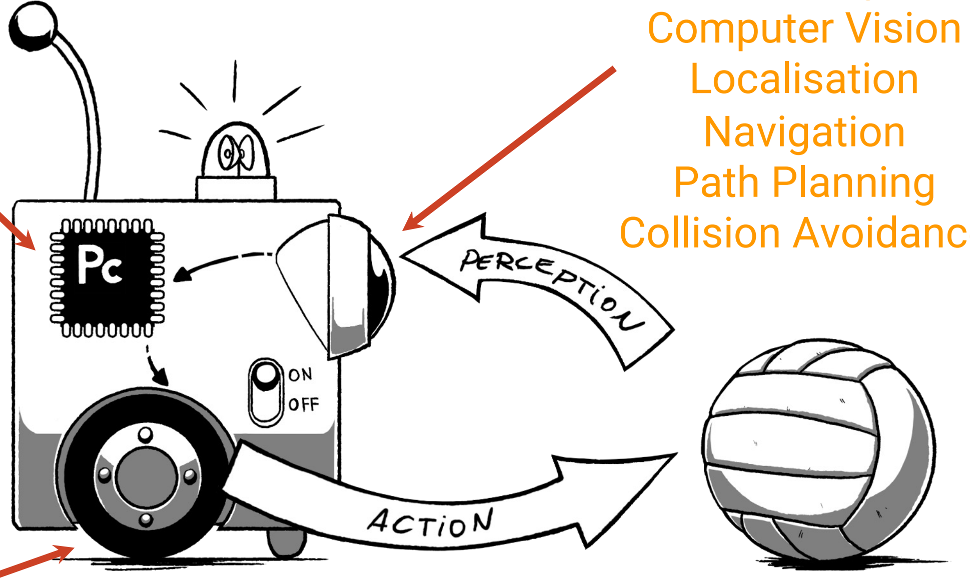
System Integration



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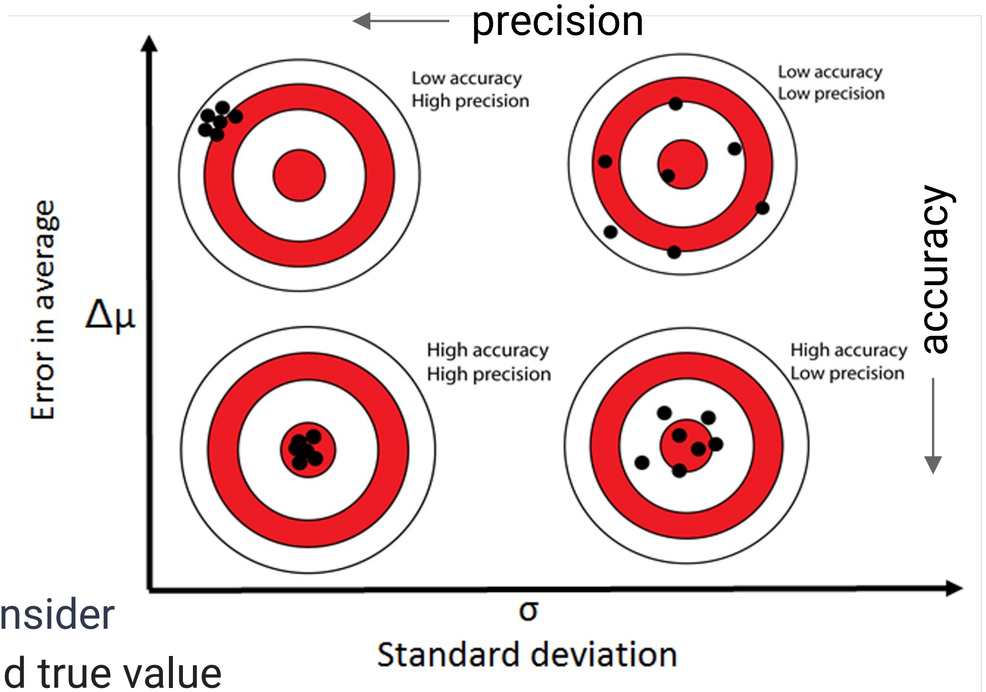
Sensors – What are they?

A sensor measures a physical quantity by converting it into a signal which can be read (processed) by an observer (an electronic system).

An **ideal sensor** is

- Only sensitive to the measured property
- Not sensitive to other properties it is exposed to
- Does not influence the measured property
- Has a clearly defined relationship between the measured property and its output signal (e.g. proportional)



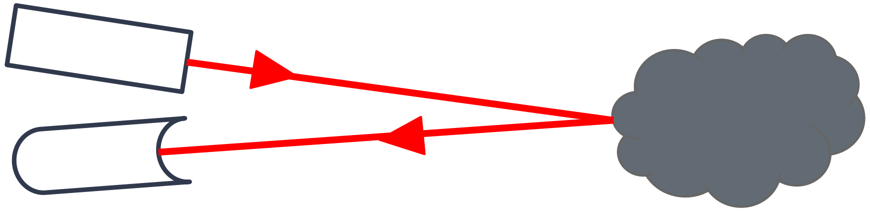
Unfortunately sensors **are not ideal**, that is why we must consider

- **Accuracy** : conformity between the measurement and true value
- **Precision** : random spread of measured values around the average measured values
- **Resolution** : smallest input change that can be detected (due to noise, physical limitations or determined by the A/D conversion)

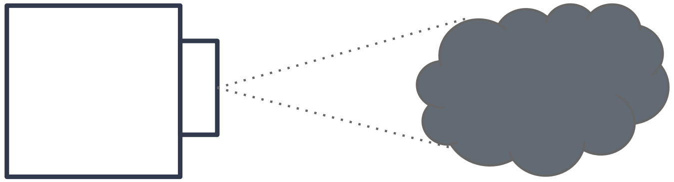
Sensors – Main Characteristics

Active vs. Passive

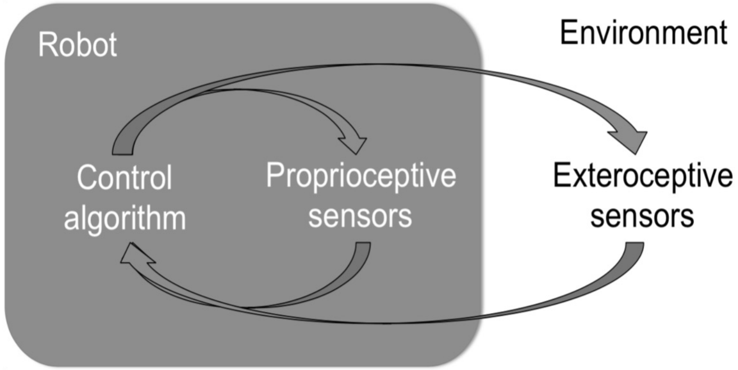
Active : emit their own energy & measure the reaction ; rely less on the environment, but has some influence on the environment and generally consumes more energy



Passive : energy from the environment



Proprioceptive vs. Exteroceptive



Proprioceptive : measure the internal state of the system (motor speed, joint position, battery status...)

Exteroceptive : information about the environment (distances, light intensity...)

Sensors – Other Properties

Range (or full scale)

Lower and upper limits of what may be measured.

Bandwidth or Frequency

- The **speed** at 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 **delay** (phase) of the signal

Dynamic Range

- Ratio between the full scale and the smallest reasonable value (noise floor)
- often specified in decibels (ratio between powers)

$$D = 20 \log_{10}((x_{max} - x_{min})/x_{min})$$

Sensitivity

- **Ratio** of output change to input change

Linearity

- Form of the variation of output signal with respect to the input signal
- Sometimes expressed as % of the deviation from a linear behavior from the full scale

Cross-sensitivity (and cross-talk)

- sensitivity to other **environmental** parameters
- influence of other active **sensors**

Sensors – Errors

Systematic errors: deterministic

- caused by factors that can (in theory) be modeled and predicted
- e.g. distortion caused by the optics of a camera

Random errors: non-deterministic

- no prediction possible
- however, they may be described probabilistically
- e.g. hue instability of camera, black level noise of photoreceptors, non-returning echoes in ultrasonic sensors, etc.

Others

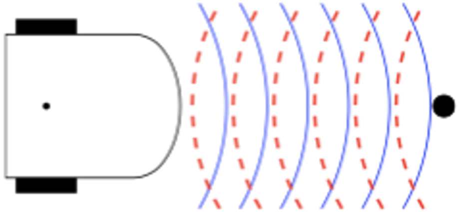
- cross-sensitivity (or cross-talk) of sensors (sensitivity to other environmental parameters or influence of other active sensors), motion blur
- rarely possible to model -> appear as random errors but are neither systematic nor random
- systematic errors and random errors might be well defined in controlled environment. This is often not the case for mobile robots!

Sensors – Use Cases

Motion (relative localisation)

- Accelerometer (acceleration and inclination, noisy)
- Gyroscope (changes in orientation, drifts)
- IMU (accelerometer, gyroscope, magnetometer)
- Wheel / Motor incremental encoders (relative, high resolution, two signals are necessary for direction detection, homing is necessary for absolute positioning)
- Wheel / Motor absolute encoders (limited resolution)

Object Detection (obstacle avoidance)



IR Proximity sensor : wide area but based on intensity of reflection

TOF Sensors :

- IR TOF range sensors
- Ultrasonic sensors (conical beams)
- Laser scanner (high field of view and range, precise), e.g. LIDAR - expensive
- Radars - similar to LIDAR but with radio waves, expensive

Tactile : pressure sensor, bumpers...

Sensors – Use Cases

Absolute Localisation

- GPS (outdoor, limited resolution)
- Laser scanner (uses feature matching in controlled environments)
- Beacon based positioning (triangulation, indoor)
- Magnetometer (compass -> absolute orientation)

Vision (object detection, feature extraction, feature based localisation)

- 2D Cameras
- Depth Cameras
- Structured Light

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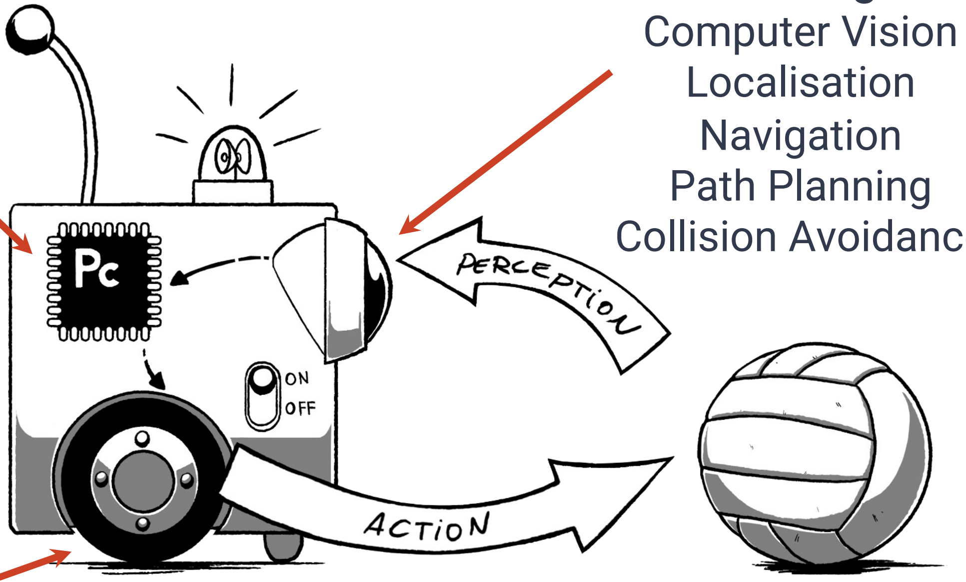

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System – Sustainability

Life Cycle Analysis

- ➢ Considering the impact of the whole life of a product
- ➢ Impact of production is massive
- ➢ Do not simplify to CO2 production (climate)

www.greenyoureveryday.com

System – Sustainability

Thymio

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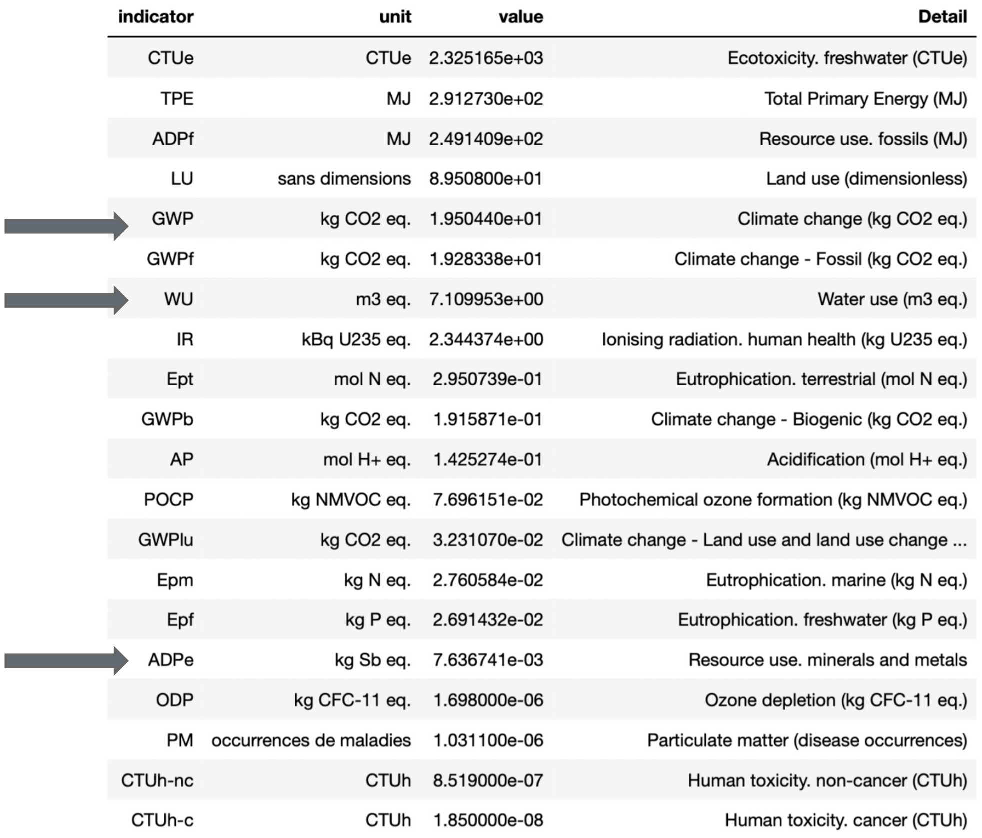


indicator	unit	value	Detail
CTUe	CTUe	2.325165e+03	Ecotoxicity. freshwater (CTUe)
TPE	MJ	2.912730e+02	Total Primary Energy (MJ)
ADPf	MJ	2.491409e+02	Resource use. fossils (MJ)
LU	sans dimensions	8.950800e+01	Land use (dimensionless)
GWP	kg CO2 eq.	1.950440e+01	Climate change (kg CO2 eq.)
GWPf	kg CO2 eq.	1.928338e+01	Climate change - Fossil (kg CO2 eq.)
WU	m3 eq.	7.109953e+00	Water use (m3 eq.)
IR	kBq U235 eq.	2.344374e+00	Ionising radiation. human health (kg U235 eq.)
Ept	mol N eq.	2.950739e-01	Eutrophication. terrestrial (mol N eq.)
GWPb	kg CO2 eq.	1.915871e-01	Climate change - Biogenic (kg CO2 eq.)
AP	mol H+ eq.	1.425274e-01	Acidification (mol H+ eq.)
POCP	kg NMVOC eq.	7.696151e-02	Photochemical ozone formation (kg NMVOC eq.)
GWPlu	kg CO2 eq.	3.231070e-02	Climate change - Land use and land use change ...
Epm	kg N eq.	2.760584e-02	Eutrophication. marine (kg N eq.)
Epf	kg P eq.	2.691432e-02	Eutrophication. freshwater (kg P eq.)
ADPe	kg Sb eq.	7.636741e-03	Resource use. minerals and metals
ODP	kg CFC-11 eq.	1.698000e-06	Ozone depletion (kg CFC-11 eq.)
PM	occurrences de maladies	1.031100e-06	Particulate matter (disease occurrences)
CTUh-nc	CTUh	8.519000e-07	Human toxicity. non-cancer (CTUh)
CTUh-c	CTUh	1.850000e-08	Human toxicity. cancer (CTUh)

by Alexandre de Terrasson de Montleau

System – Sustainability

Climate change

ADPe = Resource use. Minerals and metals

% of planet boundaries pro capita (for one year)

Thymio

- ➢ Considering the impact of the whole life of a product
- ➢ Impact of production is massive
- ➢ Do not simplify to CO2 production (climate)

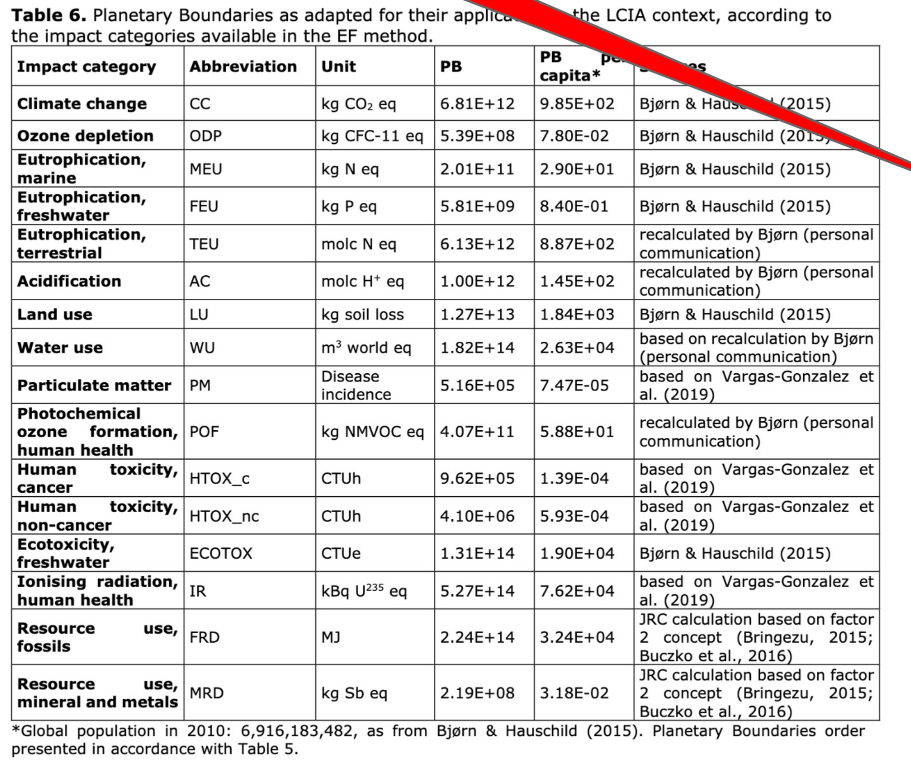
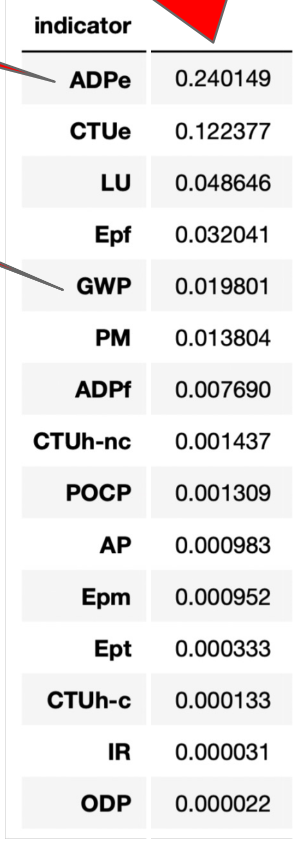


Table 6. Planetary Boundaries as adapted for their applica[illegible] the LCIA context, according to the impact categories available in the EF method.

Impact category	Abbreviation	Unit	PB	PB pe[illegible] capita*	[illegible]es
Climate change	CC	kg CO_2 eq	6.81E+12	9.85E+02	Bjørn & Haus[illegible] (2015)
Ozone depletion	ODP	kg CFC-11 eq	5.39E+08	7.80E-02	Bjørn & Hauschild (201[illegible]
Eutrophication, marine	MEU	kg N eq	2.01E+11	2.90E+01	Bjørn & Hauschild (2015)
Eutrophication, freshwater	FEU	kg P eq	5.81E+09	8.40E-01	Bjørn & Hauschild (2015)
Eutrophication, terrestrial	TEU	molc N eq	6.13E+12	8.87E+02	recalculated by Bjørn (personal communication)
Acidification	AC	molc H^+ eq	1.00E+12	1.45E+02	recalculated by Bjørn (personal communication)
Land use	LU	kg soil loss	1.27E+13	1.84E+03	Bjørn & Hauschild (2015)
Water use	WU	m^3 world eq	1.82E+14	2.63E+04	based on recalculation by Bjørn (personal communication)
Particulate matter	PM	Disease incidence	5.16E+05	7.47E-05	based on Vargas-Gonzalez et al. (2019)
Photochemical ozone formation, human health	POF	kg NMVOC eq	4.07E+11	5.88E+01	recalculated by Bjørn (personal communication)
Human toxicity, cancer	HTOX_c	CTUh	9.62E+05	1.39E-04	based on Vargas-Gonzalez et al. (2019)
Human toxicity, non-cancer	HTOX_nc	CTUh	4.10E+06	5.93E-04	based on Vargas-Gonzalez et al. (2019)
Ecotoxicity, freshwater	ECOTOX	CTUe	1.31E+14	1.90E+04	Bjørn & Hauschild (2015)
Ionising radiation, human health	IR	kBq U^{235} eq	5.27E+14	7.62E+04	based on Vargas-Gonzalez et al. (2019)
Resource use, fossils	FRD	MJ	2.24E+14	3.24E+04	JRC calculation based on factor 2 concept (Bringezu, 2015; Buczko et al., 2016)
Resource use, mineral and metals	MRD	kg Sb eq	2.19E+08	3.18E-02	JRC calculation based on factor 2 concept (Bringezu, 2015; Buczko et al., 2016)

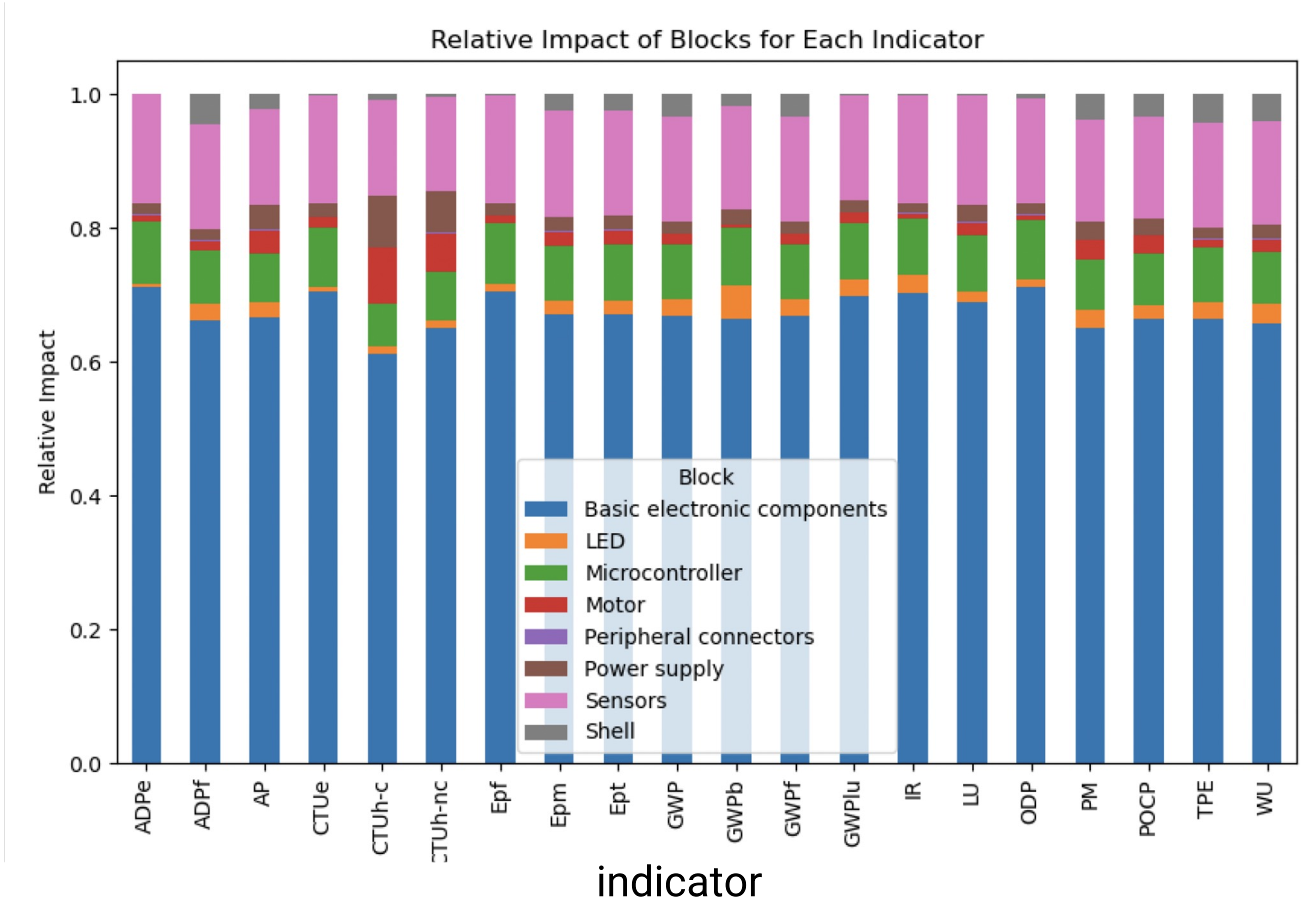
*Global population in 2010: 6,916,183,482, as from Bjørn & Hauschild (2015). Planetary Boundaries order presented in accordance with Table 5.

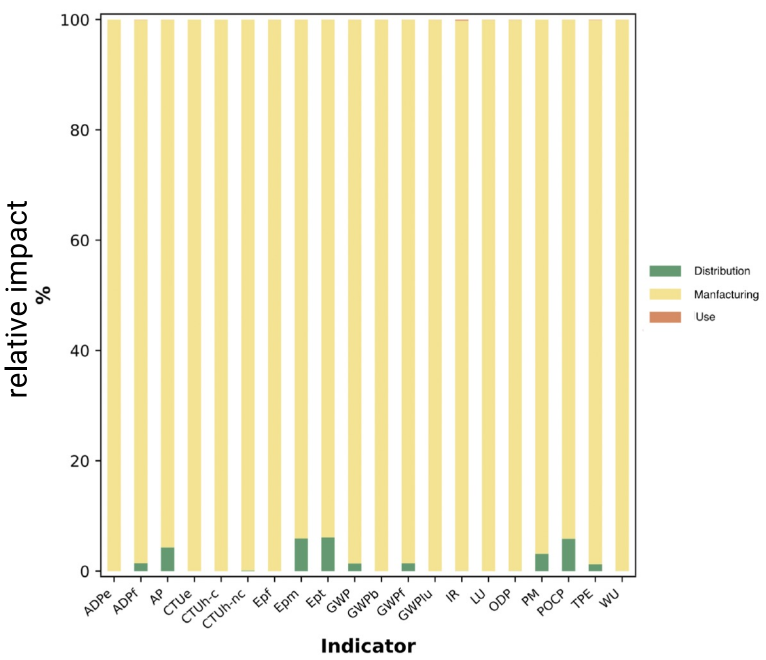
Sala, S., Benini, L., Beylot, A., Castellani, V., Cerutti, A., Corrado, S., Crenna, E., Diaconu, E., Sanye Mengual, E., Secchi, M., Sinkko, T. and Pant, R., Consumption and Consumer Footprint: methodology and results, EUR 29441 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-97256-0, doi:10.2760/98570, JRC113607.



indicator	
ADPe	0.240149
CTUe	0.122377
LU	0.048646
Epf	0.032041
GWP	0.019801
PM	0.013804
ADPf	0.007690
CTUh-nc	0.001437
POCP	0.001309
AP	0.000983
Epm	0.000952
Ept	0.000333
CTUh-c	0.000133
IR	0.000031
ODP	0.000022

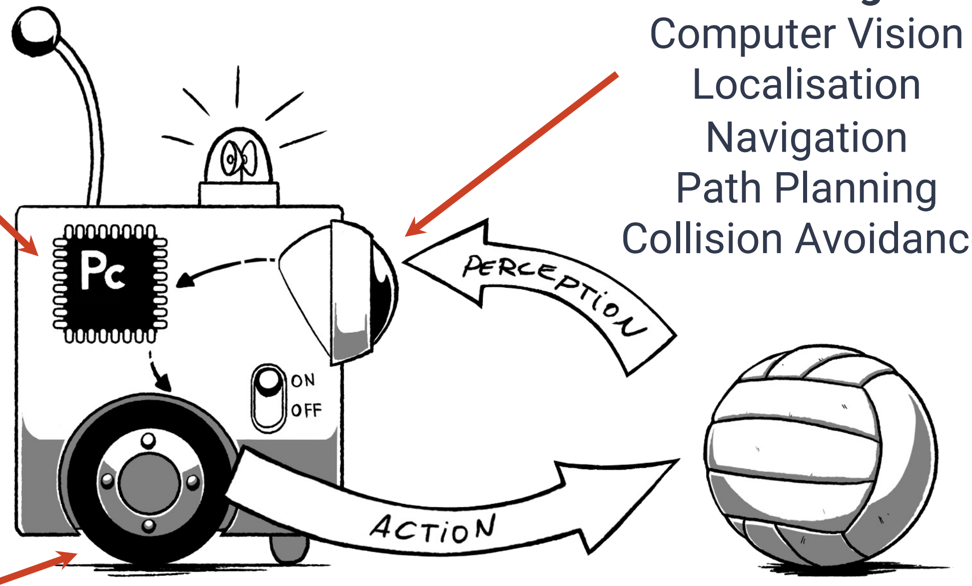
System – Sustainability





Overview of the Components of a Mobile Robot

System Integration



Processors
Embedded electronics
Architectures
Communication
Programming
Real-time Control

Sensors Integration
Computer Vision
Localisation
Navigation
Path Planning
Collision Avoidance

Mechanics
Actuators
Energy
Locomotion

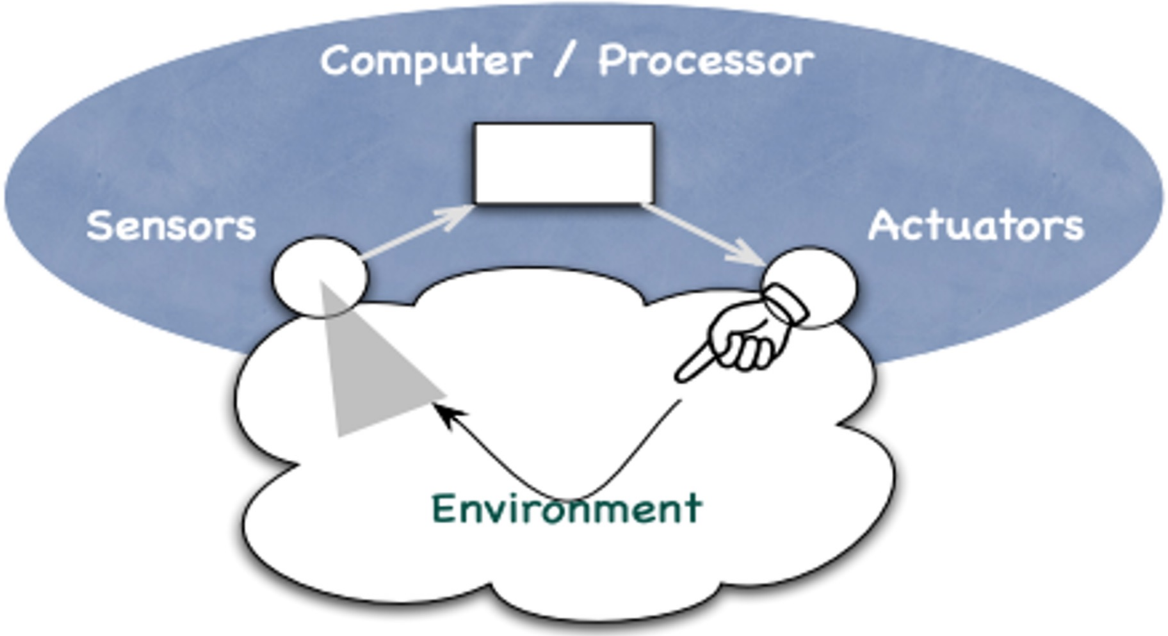
credits : Thymio MOOC

Architectures – Sensor Integration In a Robotic Syst.

The term robot architecture is often used to refer to **two related, but distinct, concepts**. Architectural structure refers to how a system is divided into subsystems and how those subsystems interact. The structure of a robotic system is often represented informally using traditional boxes and arrows diagrams ... In contrast, architectural style refers to the computational concepts that underlie a given system. (Handbook of Robotics, 2016)

- A well designed **architecture needs to be defined at the very early stage of system development!**

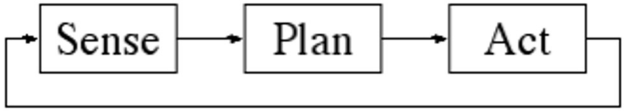
- All robotic systems use their own architectural structure and style.
- A single robotic system will often use several styles together
- Well-conceived, clean architecture can have significant advantages in the specification, execution, and validation of robotic systems



Architectures – Robotic Control Styles

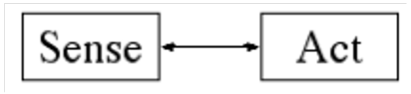
Deliberative control
“think hard, then act”

The robot takes all available **sensory information and all knowledge it has to create a plan of action** by search through potentially all possible plans. This can take a long time but allows the robot to act strategically.



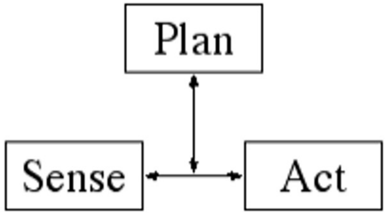
Reactive control
“don't think, (re)act”

Uses a **tight coupling between sensory inputs and effector outputs** to respond quickly to changing and unstructured environments. This type of control does not take advantage of any knowledge about the environment, have any memory or ability to learn over time.



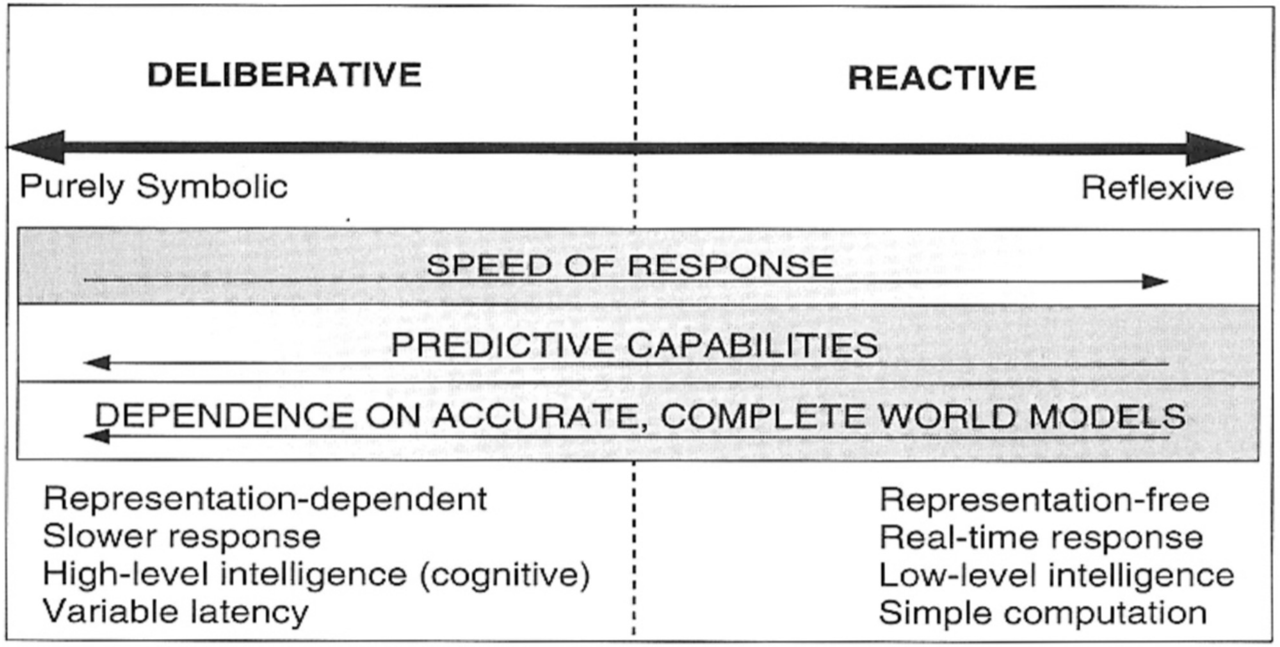
Hybrid control
“think and act in parallel”

Combines the **best of both reactive and deliberative control architectures**. One part of the “brain” plans while the other handles immediate reactions in order to avoid obstacles for example. The coordination between the two parts of the “brain” must handled by a third. That is why these systems are often callec



Architectures – Robotic Control Styles

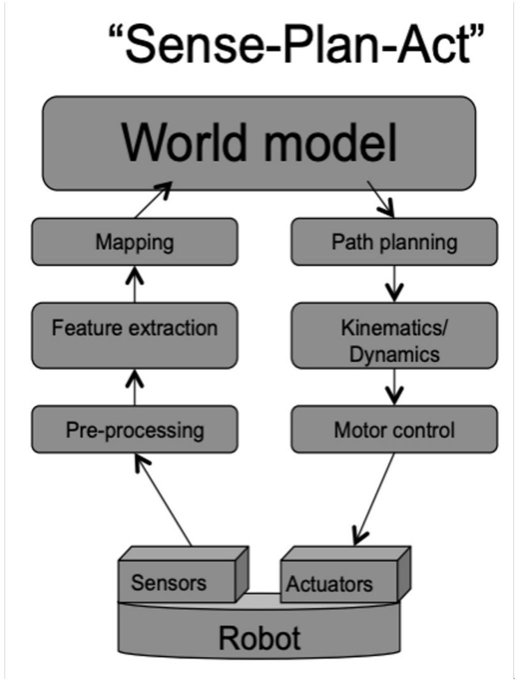
Model-based

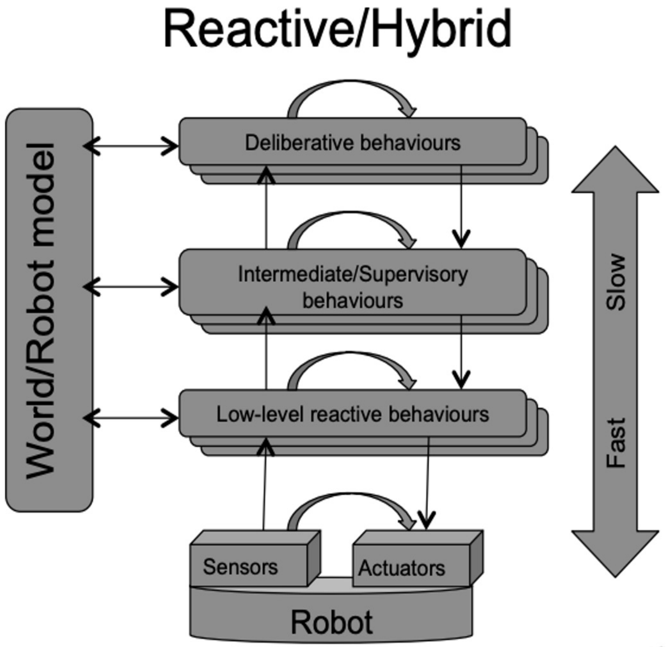


Behavior-based

Arkin, Behavior-based Robotics (MIT Press, 1998)

Architectures – Robotic Architecture Styles



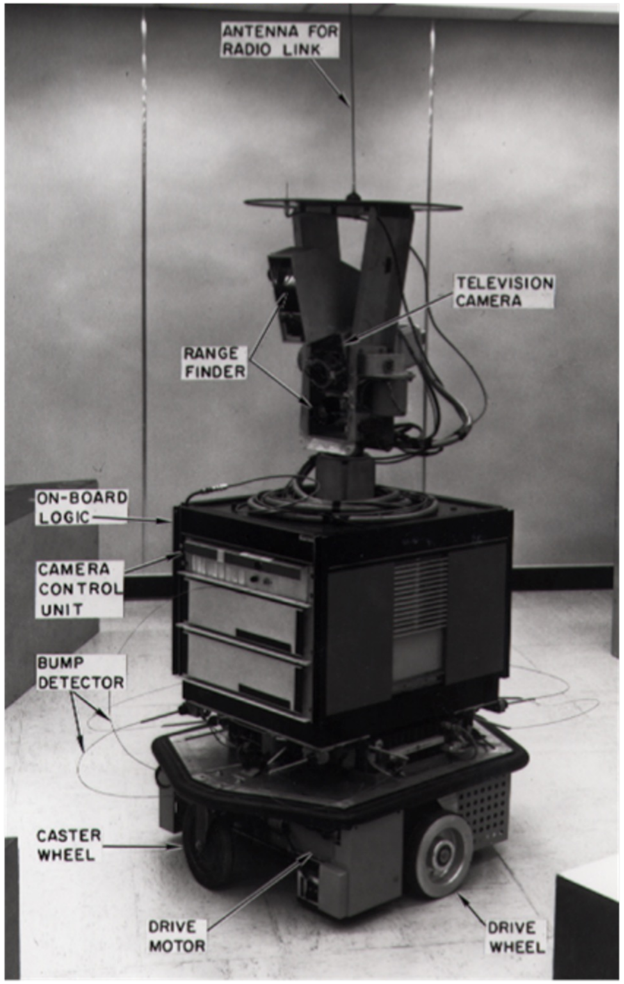


- Top down fashion, heavy on planning
- Sense the world, plan the next action, act at each step
- All sensing data gathered into one global world model

1. Deliberative planning to decompose the task into sub tasks
2. execute behaviours reactively, which is to say, in a succession of sense act couplings

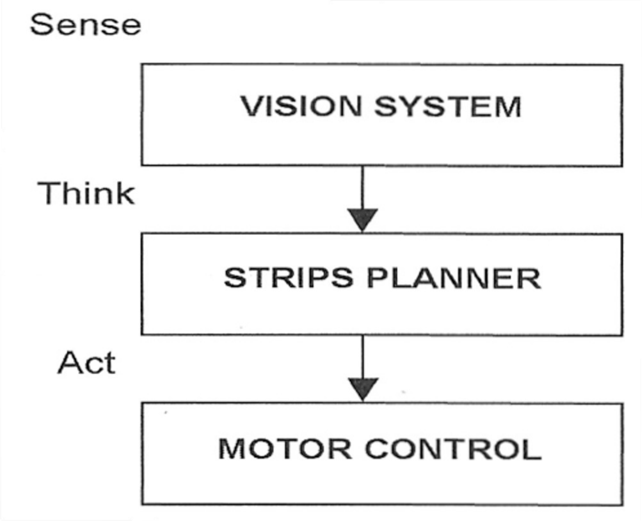
Sensor data gets routed to each behaviour that needs that sensor, but is also available to the planner for construction of a task-oriented global world model.

Architectures – Deliberative Architecture



"Shakey", one of the first mobile robot with the ability to perceive and reason about it surroundings (1972) *Wikipedia*

At the time of Shakey the dominant view in the AI community was that a control system for an autonomous mobile robot should be decomposed into three functional elements (Nilsson, 1980): **sensing, planning and executing the plan.**


Sense

VISION SYSTEM

Think

STRIPS PLANNER

Act

MOTOR CONTROL

Architectures – Reactive Architecture

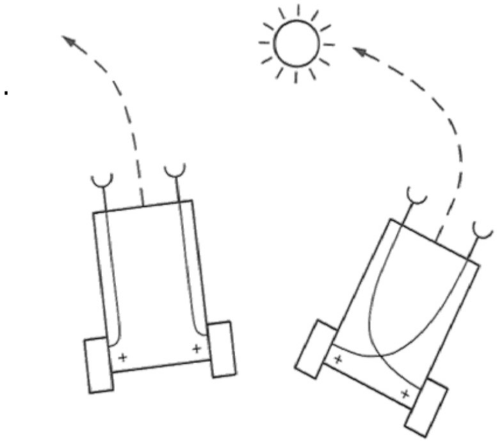
Assumptions :

- The environment lacks temporal consistency and stability.
- The robot’s immediate sensing is adequate for the task at hand.
- It is difficult to localize a robot relative to a world model.
- Symbolic representational world knowledge is of little or no value.

Examples : Braitenberg, feedforward neural networks, behaviour based architectures

Here : Braitenberg applied to the Thymio robot to mimic neural networks for obstacle avoidance using the horizontal proximity sensor (Ben-Ari, Mondada, 2018)

Behaviour Based Architectures are a type of reactive architecture and are used when the real world cannot be accurately characterized or modeled.There is a big emphasis on on the importance of coupling sensing and action tightly. This is done by decomposing behaviours or situation-action pairs into contextually meaningful units, the granularity of which may vary. This can be represented by a Finite State Machine that is defined by a set of states, transition conditions and actions that take place when changing state



Braitenberg (1984) Vehicles:

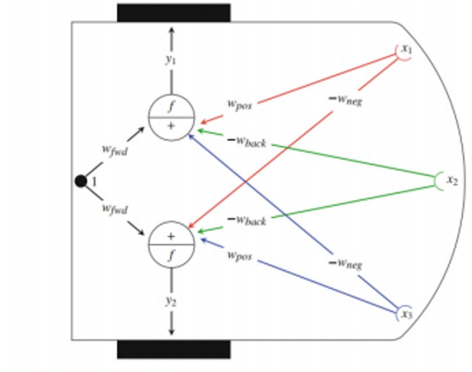


Fig. 13.4 Neural network for obstacle avoidance

Architectures – Reactive Architecture Example

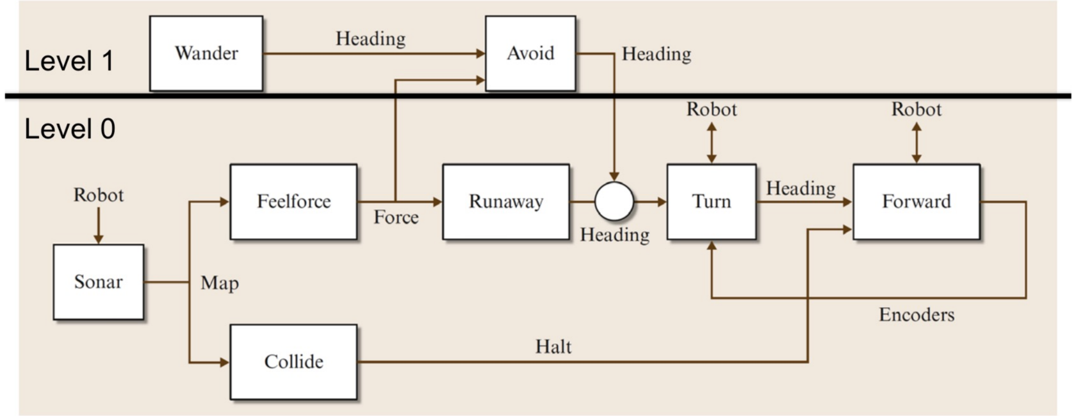
The **Subsumption Architecture** (Brooks, 1986) is a reactive architecture heavily associated with behaviour based robotics.

Brooks 1986, when designing an autonomous robot for offices did

1. The lowest level (layer 0) of control so that the robot did not come in contact with other objects
2. The second level (layer 1) of control, when combined with the lowest, imbues the robot with the ability to wander around aimlessly without hitting obstacles.
3. The third layer (level 2) is meant to add an exploratory mode of behavior to the robot, using visual observations to select interesting places

Principles

- The architecture is built incrementally
- Start by building in lowest level of competence
- Validate on robot, debug, adjust, validate, adjust, …
- Robot is immediately operational



Architectures – Hybrid Reactive Architecture

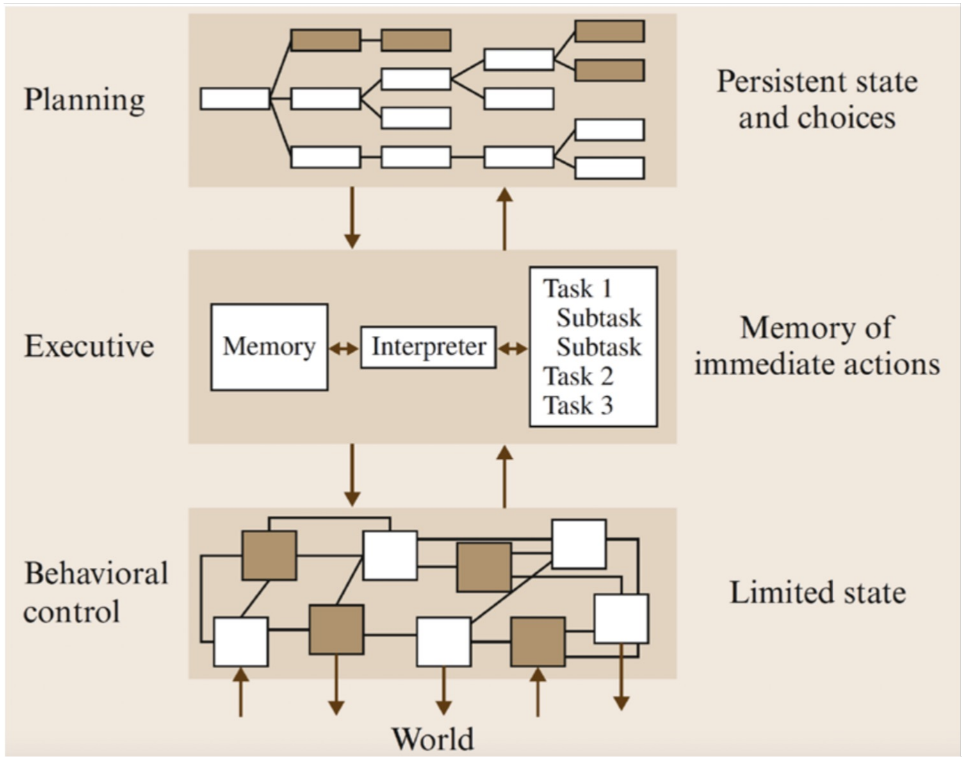
Combines the responsiveness, robustness, and flexibility of purely reactive systems with more traditional symbolic/deliberative methods.

Reasons:
- Purely reactive systems lack the ability to take into account a priori knowledge (e.g. about the world) and to keep track of the history (memory).
- Purely symbolic/deliberative system lack reactivity.

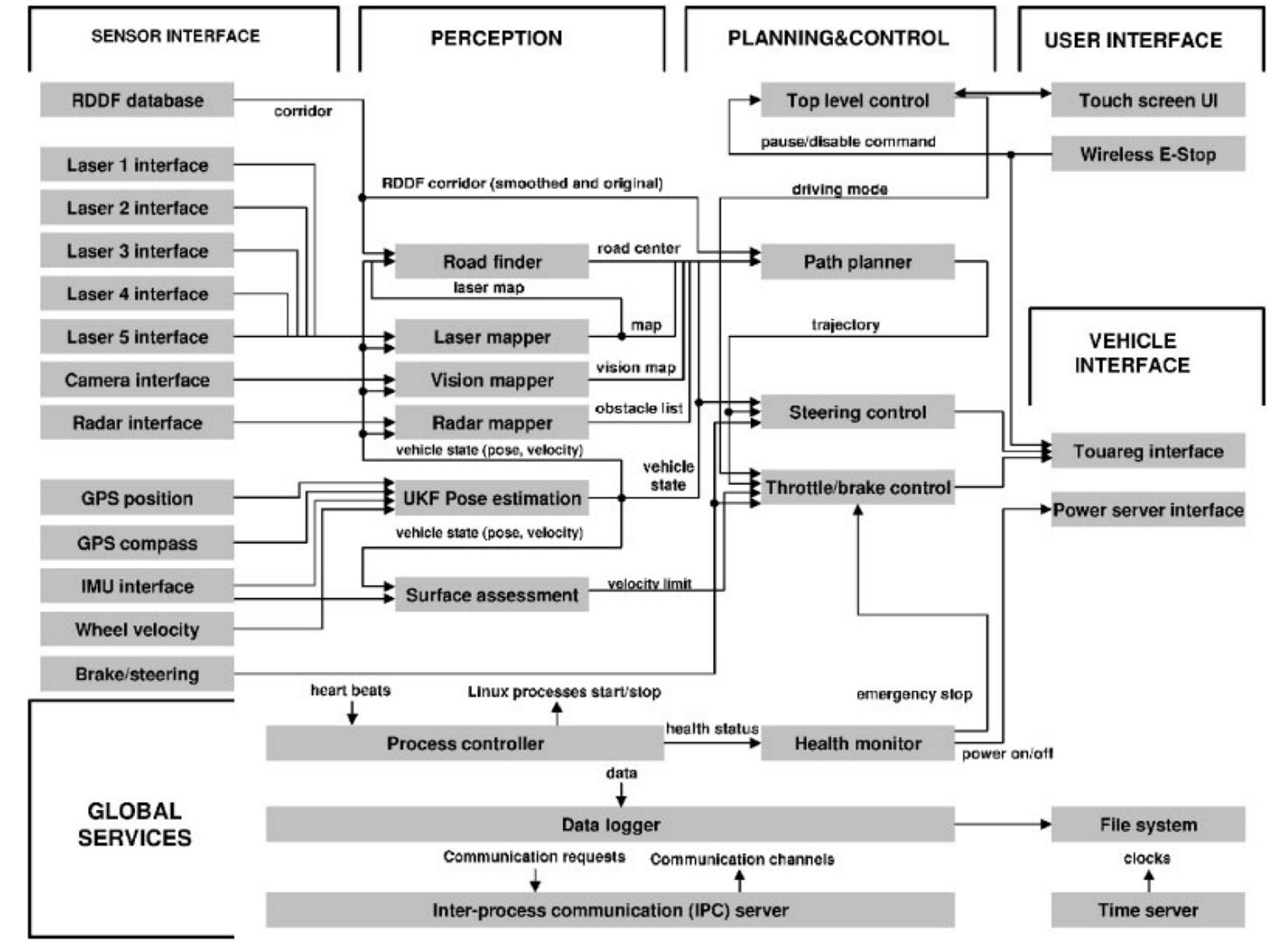
Planning Layer : handles long range activities, high level goals. Plans algorithms and does replanning on demand, based on the monitoring of task execution.

Executive Layer : at the interface between the deliberative and reactive layers. Translates high-level plans in sequences of behaviors, monitors executions, handles exceptions.

Behaviour-Based Layer



Architectures – Structure



SENSOR INTERFACE

RDDF database
Laser 1 interface
Laser 2 interface
Laser 3 interface
Laser 4 interface
Laser 5 interface
Camera interface
Radar interface
GPS position
GPS compass
IMU interface
Wheel velocity
Brake/steering

PERCEPTION

Road finder
Laser mapper
Vision mapper
Radar mapper
UKF Pose estimation
Surface assessment

PLANNING&CONTROL

Top level control
Path planner
Steering control
Throttle/brake control

USER INTERFACE

Touch screen UI
Wireless E-Stop

VEHICLE INTERFACE

Touareg interface
Power server interface

GLOBAL SERVICES

Process controller
Health monitor
Data logger
File system
Inter-process communication (IPC) server
Time server

corridor
RDDF corridor (smoothed and original)
pause/disable command
driving mode
road center
laser map
map
trajectory
vision map
obstacle list
vehicle state (pose, velocity)
vehicle state
vehicle state (pose, velocity)
velocity limit
heart beats
Linux processes start/stop
emergency stop
health status
power on/off
data
Communication requests
Communication channels
clocks

Thrun, Sebastian, Mike Montemerlo, Hendrik Dahlkamp, David Stavens, Andrei Aron, James Diebel, Philip Fong et al. "Stanley: The robot that won the DARPA Grand Challenge." *Journal of field Robotics* 23, no. 9 (2006): 661-692.

What should I remember

- Main definition
    - The definition of mobile robot, based on an interaction with the environment
- Locomotion
    - What is a DOF and what is a “controllable DOF” or degrees of mobility (DOM)
    - Understand the link between DOF - DOM and controllability - maneuverability
    - Definition and features of a redundant system
    - The Basic Wheel Types and their main possible arrangement
- Controller
    - role of a controller
    - the basic principle of the Astolfi Controller
- Actuators & energy storage
    - Main classes and their global characteristics
- Sensors
    - Understanding definition and features of accuracy and precision, active vs passive, proprio vs exteroceptive, linearity, cross-sensitivity, frequency and range, deterministic vs non-deterministic errors.
    - Have an idea of the main sensors and their use
- Sustainability
    - understand the concept of life cycle and have an idea of the values for a mobile robot
- Architectures

This week’s exercises

Part A : mechanics

1. Degrees of freedom and of mobility
2. Redundant systems

Part B : sensors

1. Sensors overview
2. Accelerometers

Part C : Introduction to Python and Jupyter Notebooks