MTRN4110 Robot Design

Week 1 – Introduction, Locomotion, and Perception

Liao "Leo" Wu, Lecturer

School of Mechanical and Manufacturing Engineering

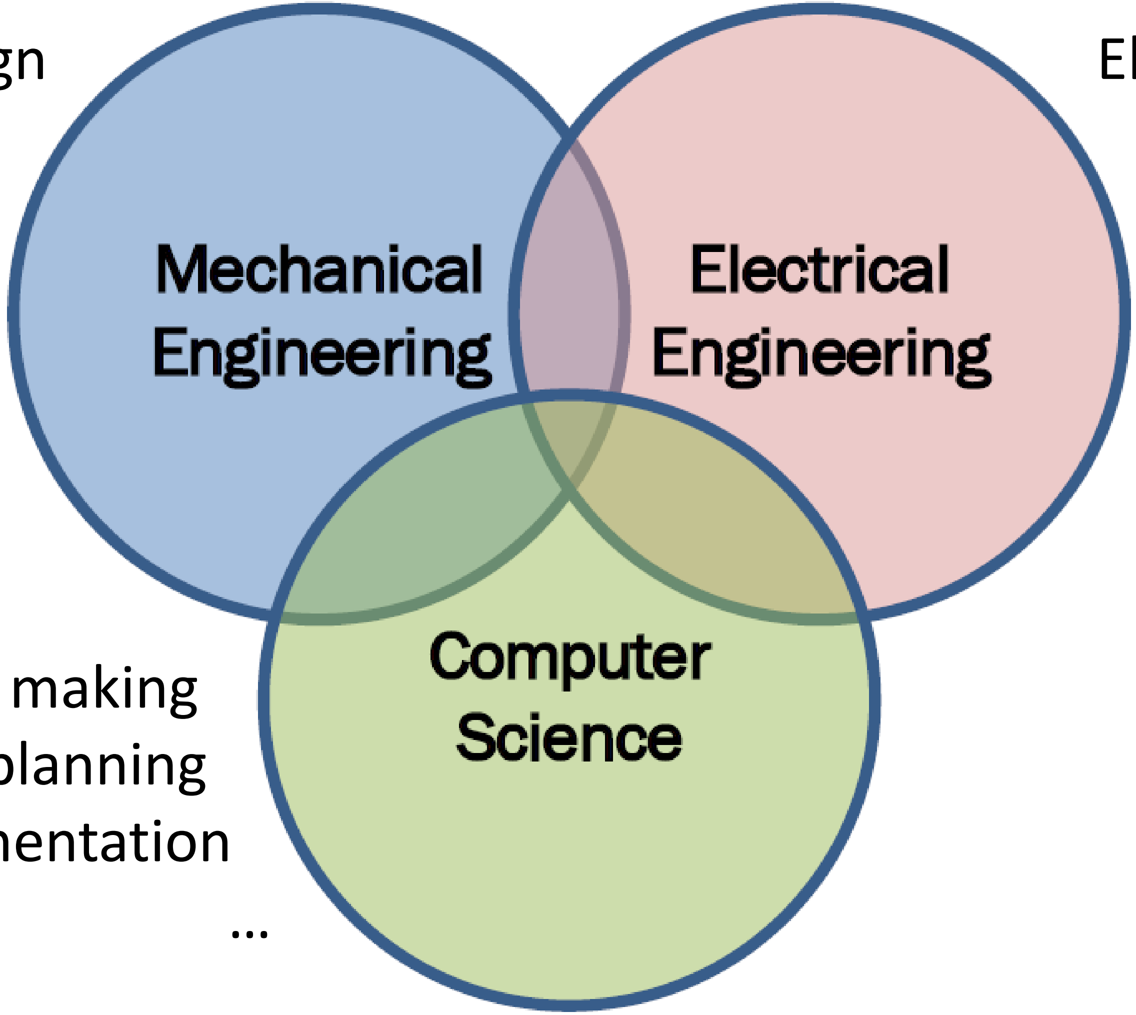
University of New South Wales, Sydney, Australia

https://sites.google.com/site/wuliaothu/

Robotics – An interdisciplinary area of engineering and science

Mechanical design
Fabrication
Materials
…

Electronics design
Sensing and control
Energy
…



Autonomous Decision making
Cognitive planning
Software implementation
…

The world of robotics

- Robotics has evolved into a broad discipline;
- This course will focus on

Autonomous Mobile Robots

Today's agenda

- Course overview

- Locomotion
  - Key issues
  - Wheel geometry
  - A little bit of kinematics

- Perception
  - Wheel/motor sensors
  - Inertial sensors
  - Active ranging sensors

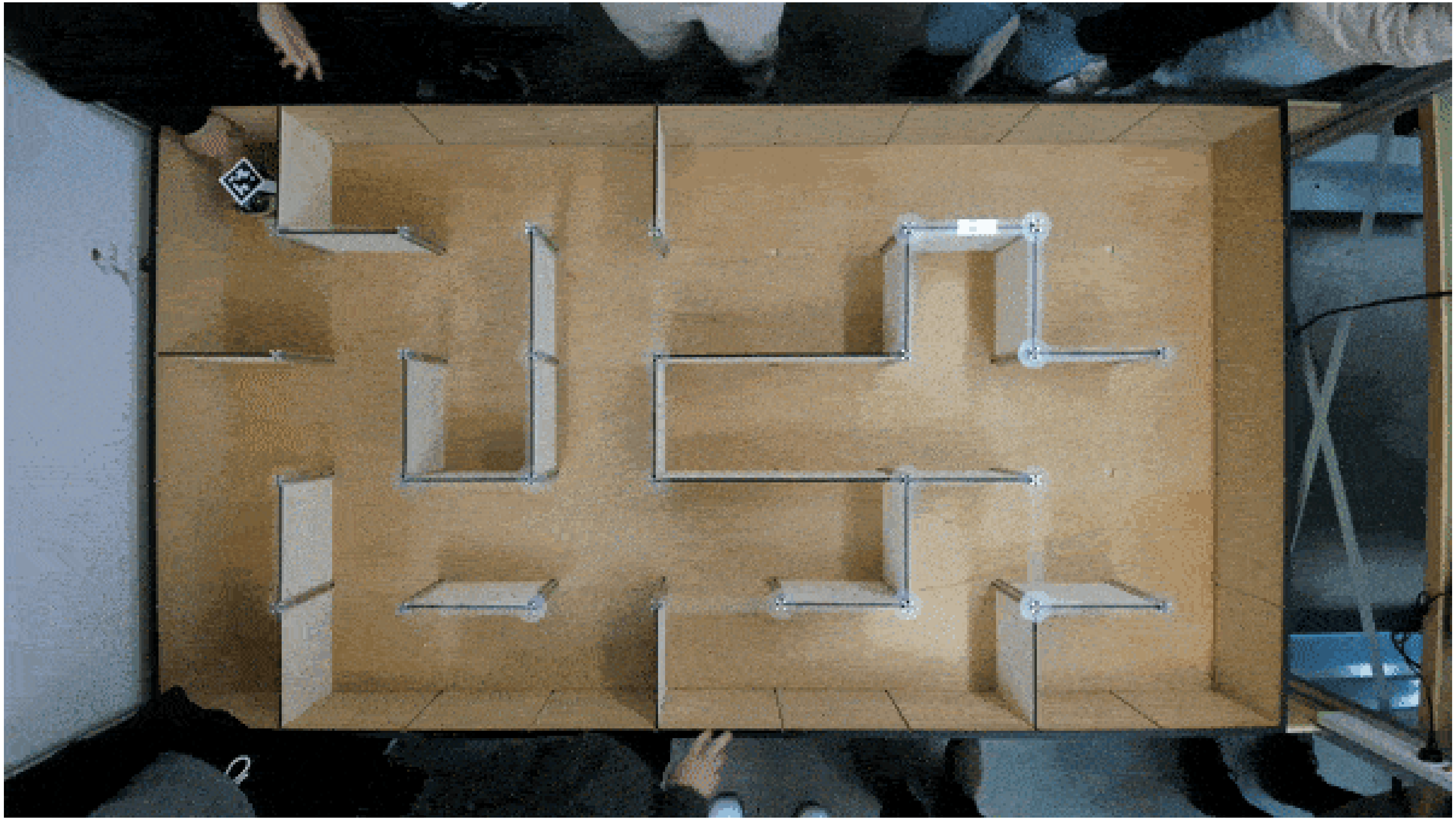
Course Overview

Micromouse

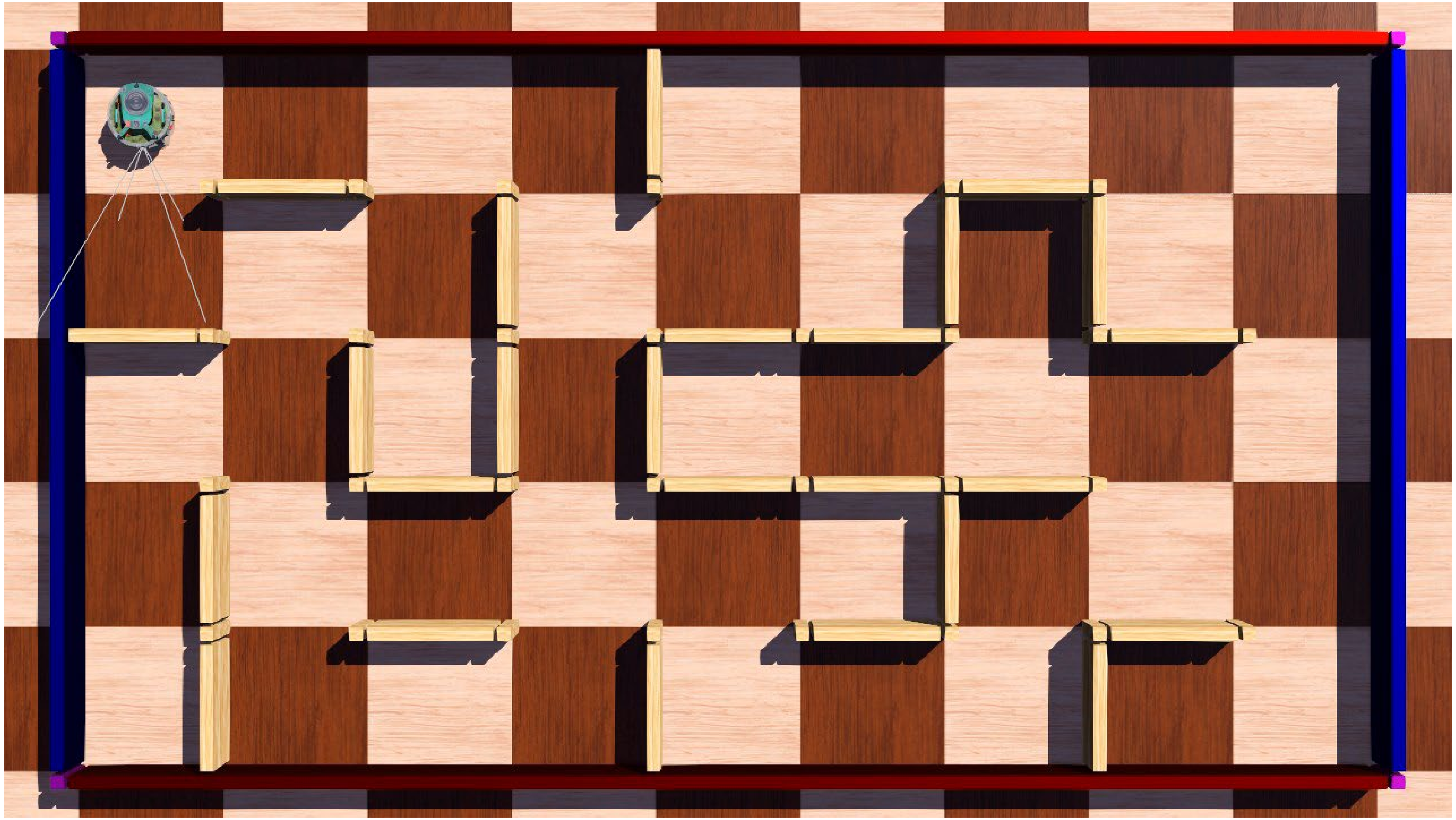
- Micromouse is an event where small robot mice solve a 16 × 16 maze.
- It began in the late 1970s. Competitions and conferences are still run regularly.
- Search Run
  - The mouse must find their way from a predetermined starting position to the central area of the maze unaided.
  - The mouse will need to keep track of where it is, discover walls as it explores, map out the maze and detect when it has reached the goal.
  - Having reached the goal, the mouse will typically perform additional searches of the maze until it has found an optimal route from the start to the centre.
- Speed Run
  - Once the optimal route has been found, the mouse will execute that route in the shortest possible time.

https://youtu.be/aXMcEDy-ly8
https://en.wikipedia.org/wiki/Micromouse

MTRN4110 2019

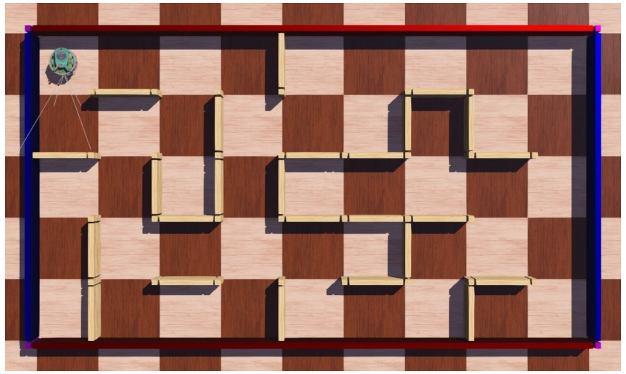


Winning team – Short_Stack



https://cyberbotics.com/

Phase A



Driving and Perception

Week 1-3

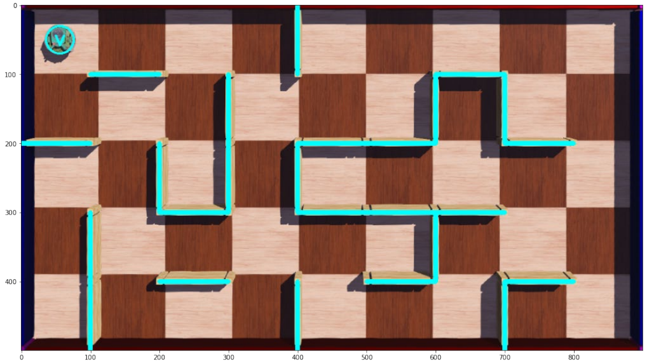
Phase B

```
Start - Find shortest path with least turns:
 --- --- --- --- --- --- --- --- ---
| v   15  14  13| 10  9   8   7   6 |
     ---                 ---
|           | 12  11    |   |     5 |
 ---             --- ---     ---
|       |   |   | 0   1   2   3   4 |
         ---     --- --- ---
|   |                   |           |
         ---         ---     ---
|   |           |           |       |
 --- --- --- --- --- --- --- --- ---
steps: 23 - 00SLFFFRFLFLFRFFFFRFFRFFFF
Done - Shortest path with least turns found!
```

Path Planning

Week 4-6

Phase C

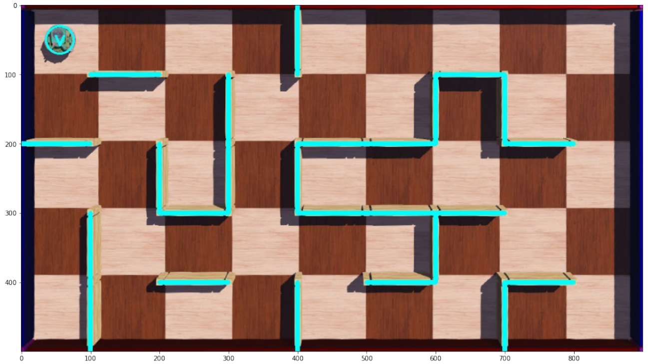


Computer Vision

Week 7-9

MTRN4110 2021

Phase C



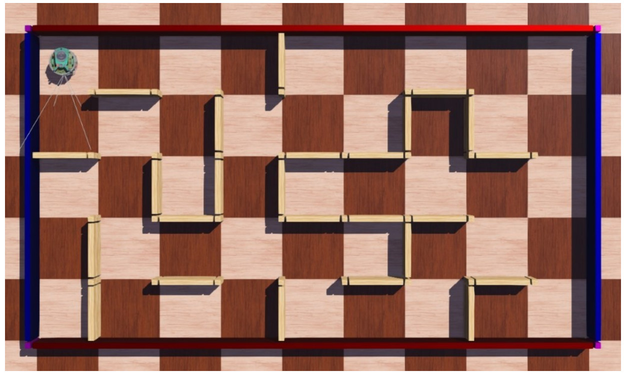
Computer Vision

Phase B

```
Start - Find shortest path with least turns:
 --- --- --- --- --- --- --- --- ---
| v   15  14  13| 10  9   8   7   6 |
     ---                 ---
|           | 12  11    |   |     5 |
 ---             --- ---     ---
|       |   |   | 0   1   2   3   4 |
         ---     --- --- ---
|   |                   |           |
         ---         ---     ---
|   |           |           |       |
 --- --- --- --- --- --- --- --- ---
steps: 23 - 00SLFFFRFLFLFRFFFFRFFRFFFF
Done - Shortest path with least turns found!
```

Path Planning

Phase A



Driving and Perception

Phase D

Integration and Improvement

Week 10-11

Course map

Week	Assignment (Release Tue 17:00, Due Mon 17:00)	Lecture (Wed 9:00 - 11:00)	Tutorial (Fri 12:00 - 14:00)	Quiz (Fri 18:00 - 18:30)
1	Assignment Phase A Description (Individual, 12%)	Introduction Locomotion Perception	Webots Tutorial (Recorded)	
2		Localisation I	Progress Check 1 (Optional)[b]	Quiz 1 (Lecture 1, 10%)[c]
3		Kinematics	Help Session 1 (Bookable)	
4	Assignment Phase A Submission [a] Assignment Phase B Description (Individual, 12%)	Planning I	Planning Tutorial (Recorded)	Quiz 2 (Lecture 2&3, 10%)[c]
5		Planning II	Progress Check 2 (Optional)[b]	
6			Help Session 2 (Bookable)	
7	Assignment Phase B Submission [a] Assignment Phase C Description (Individual, 12%)	Vision I	Vision Tutorial (Recorded)	Quiz 3 (Lecture 4&5, 10%)[c]
8		Vision II	Progress Check 3 (Optional)[b]	
9		Localisation II	Help Session 3 (Bookable)	Quiz 4 (Lecture 7&8, 10%)[c]
10	Assignment Phase C Submission [a] Assignment Phase D Description (Group, 19%)	Summary	Progress Check 4 (Optional)[b]	Quiz 5 (Lecture 9, 5%)[c]
11				
12	Assignment Phase D Submission [a]			

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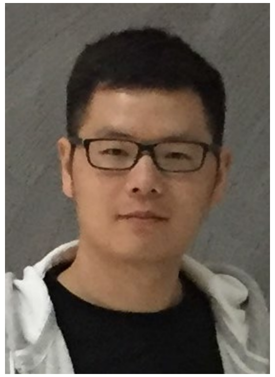
[a] Late submission penalty will apply; refer to the task descriptions for more details.
[b] A demonstrator will check your progress and mark it as Pass/Fail; if you get four "P"s by the end of the course (or you get three "P"s AND your raw mark > 64, or you get two "P"s AND your raw mark > 74, or you get one "P" AND your raw mark > 84), your final mark will be rounded up, e.g., from 84.1 to 85. No penalty will be applied for Progress Check.
[c] Quizzes will be run online via Moodle at the specified time. No supplementary tests will be organised.

Teaching team

- Lecturer



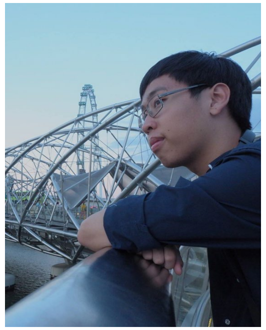
Leo Wu
liao.wu@unsw.edu.au
sites.google.com/site/wuliaothu

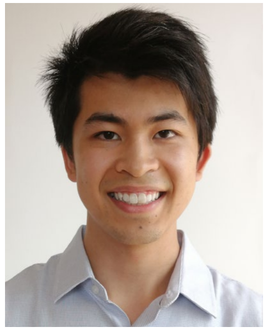
- Demonstrators

Carlo Pane
c.pane
@unsw.edu.au

Hikari Hashida
h.hashida
@unsw.edu.au

Jason Dam
j.dam
@unsw.edu.au





Kenny Wong
kenny.wong2
@unsw.edu.au

Leigh Huang
leigh.huang
@unsw.edu.au

Matthew Chhoeu
m.chhoeu
@unsw.edu.au

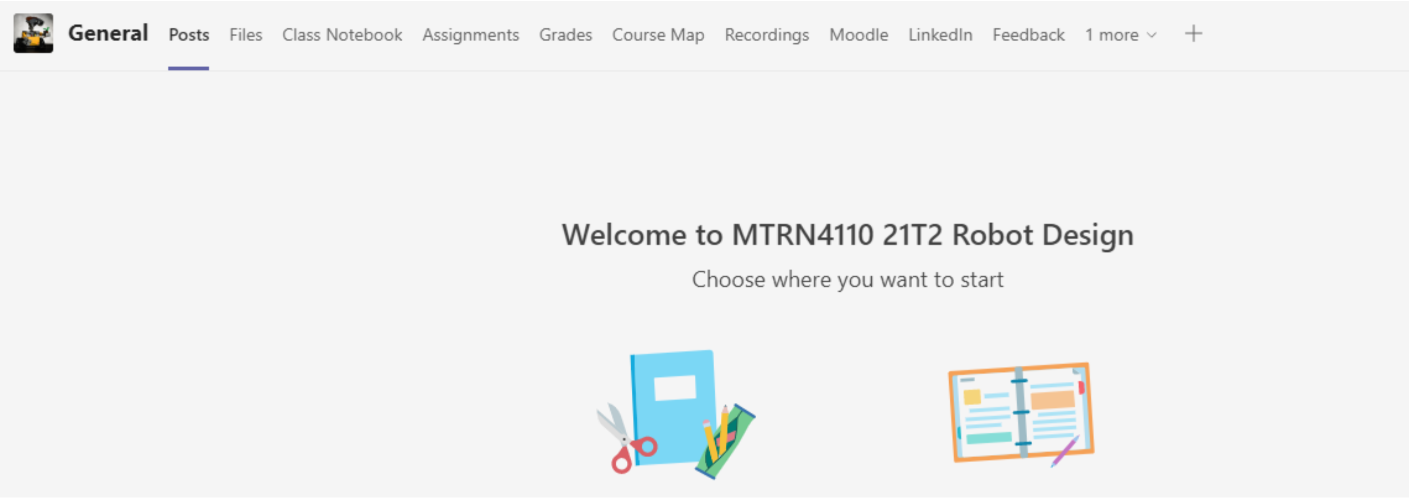
Ming Xuan Chua
mingxuan.chua
@unsw.edu.au

Rawan Abdo
r.abdo
@unsw.edu.au

Rowan Ramamurthy
r.ramamurthy
@unsw.edu.au

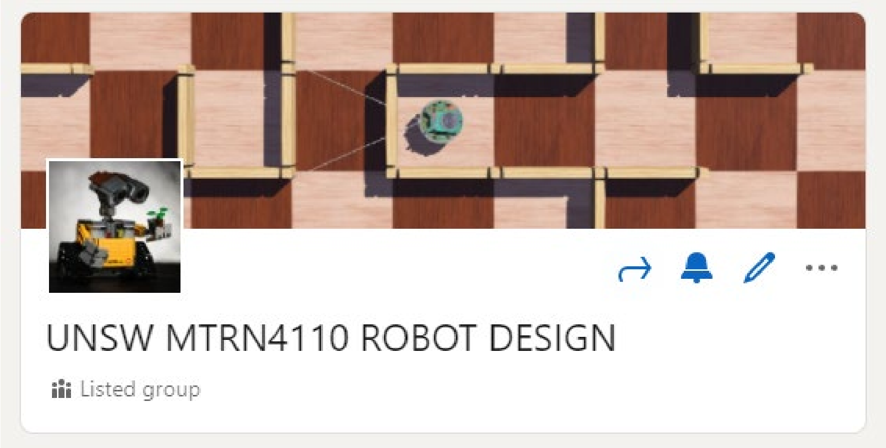
Course platforms

- [Microsoft Teams]()
  - Materials
  - Meetings
  - Recordings
  - Forum

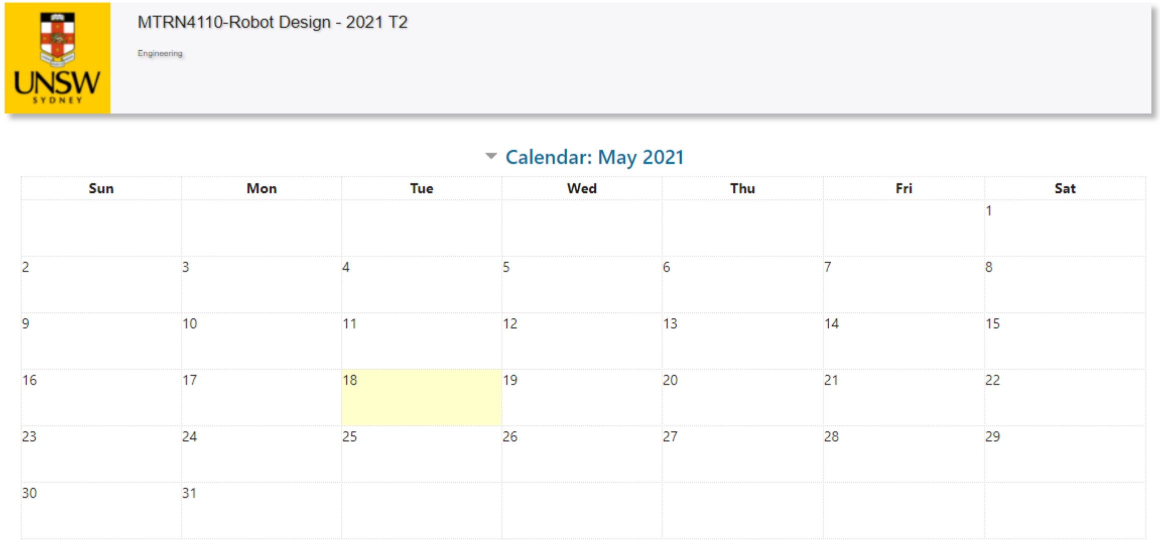


- [LinkedIn Group]()
  - Informal posts
  - Intern/job information sharing
  - Long term connection

Please let the Admin know your <u>name</u> in your request to join.



- [Moodle]()
  - Quizzes
  - Assignments



Useful resources

- Textbook (not required, but recommended)
  - R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to autonomous mobile robots. The MIT Press. Second edition. 2011.
- Other reference books
  - B. Siciliano, O. Khatib. Springer handbook of robotics. Springer. Second Edition. 2016.
  - P. Corke. Robotics, Vision and Control. Springer. Second Edition. 2016.
- Conferences (state-of-the-art in research)
  - ICRA (IEEE International Conference on Robotics and Automation)
  - IROS (IEEE/RSJ International Conference on Intelligent Robots and Systems)

- Software
  - Webots: https://cyberbotics.com/
  - ANACONDA (Python): https://www.anaconda.com/
- Programming
  - Webots user guide: https://cyberbotics.com/doc/guide/index
  - Webots reference manual: https://cyberbotics.com/doc/reference/index
  - C++ tutorials: https://www.tutorialspoint.com/cplusplus/index.htm
  - Python tutorials: https://www.tutorialspoint.com/python/index.htm
  - OpenCV-Python tutorials: https://docs.opencv.org/master/d6/d00/tutorial_py_root.html
- Google Search (or any other search engines)
  - https://www.google.com/

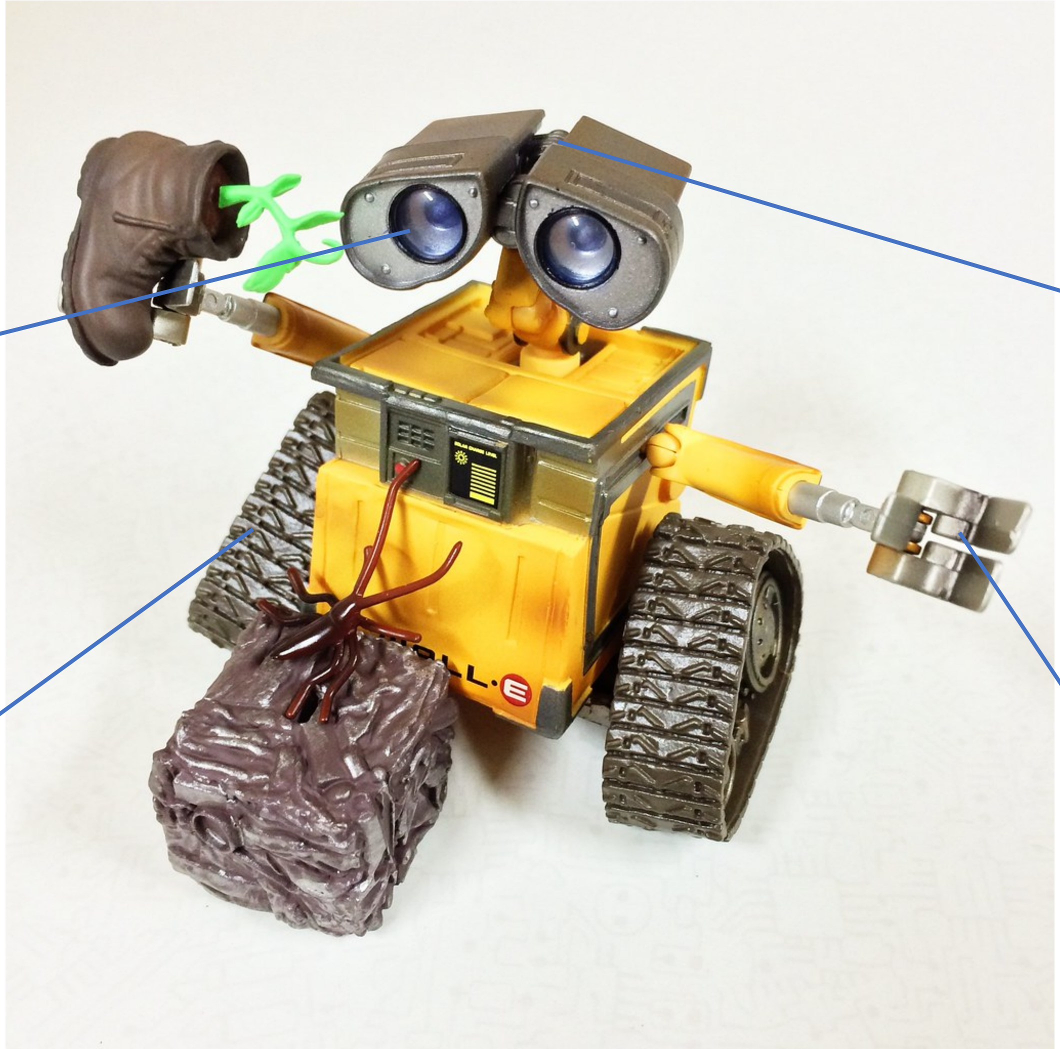
Audience Q&A Session

ⓘ Start presenting to display the audience questions on this slide.

Key capabilities of mobile robots

Eye - Perception including Vision

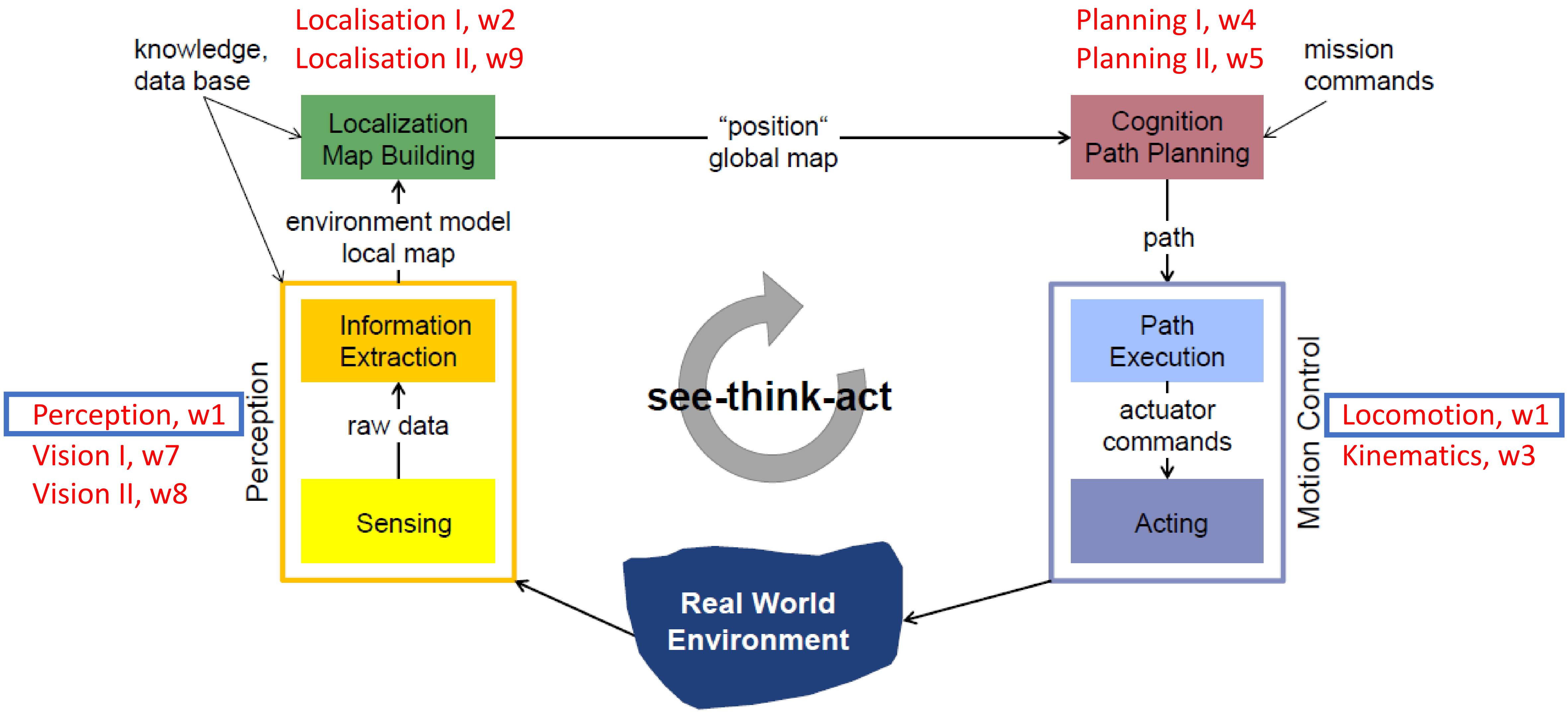
Foot - Locomotion and Kinematics



Brain – Localisation and Planning

Hand – Manipulation (Covered by MTRN4230)

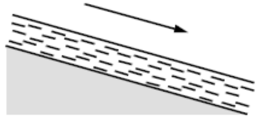
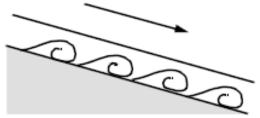
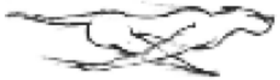
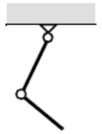
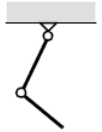
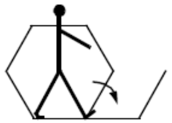
The See-Think-Act cycle



R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to autonomous mobile robots. The MIT Press. Second edition. 2011.

Locomotion

What is locomotion?

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) 

- A collective name for the various methods that robots use to transport themselves from place to place
- Nature has developed various ways of locomotion;
- Trying to replicate nature, however, may not be a good idea sometimes.
- Why?
  - Mechanical complexity through structural replication
  - Miniaturization with robustness
  - Efficiencies

R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to autonomous mobile robots. The MIT Press. Second edition. 2011.
https://en.wikipedia.org/wiki/Robot_locomotion

Key issues for locomotion

- Stability
  - Number and geometry of contact points
  - Centre of gravity
  - Static/dynamic stability
  - Inclination of terrain
- Characteristics of contact
  - Contact point/path size and shape
  - Angle of contact
  - Friction
- Type of environment
  - Structure
  - Medium (e.g., water, air, soft or hard ground)

Case study – DAPAR Robotics Challenge

- Stability
  - Number and geometry of contact points
  - Centre of gravity
  - Static/dynamic stability
  - Inclination of terrain
- Characteristics of contact
  - Contact point/path size and shape
  - Angle of contact
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https://www.youtube.com/watch?v=7urLgdzHS2U

Case study – HUBO developed by Prof Jun-Ho Oh @ KAIST

- Stability
  - Number and geometry of contact points
  - Centre of gravity
  - Static/dynamic stability
  - Inclination of terrain
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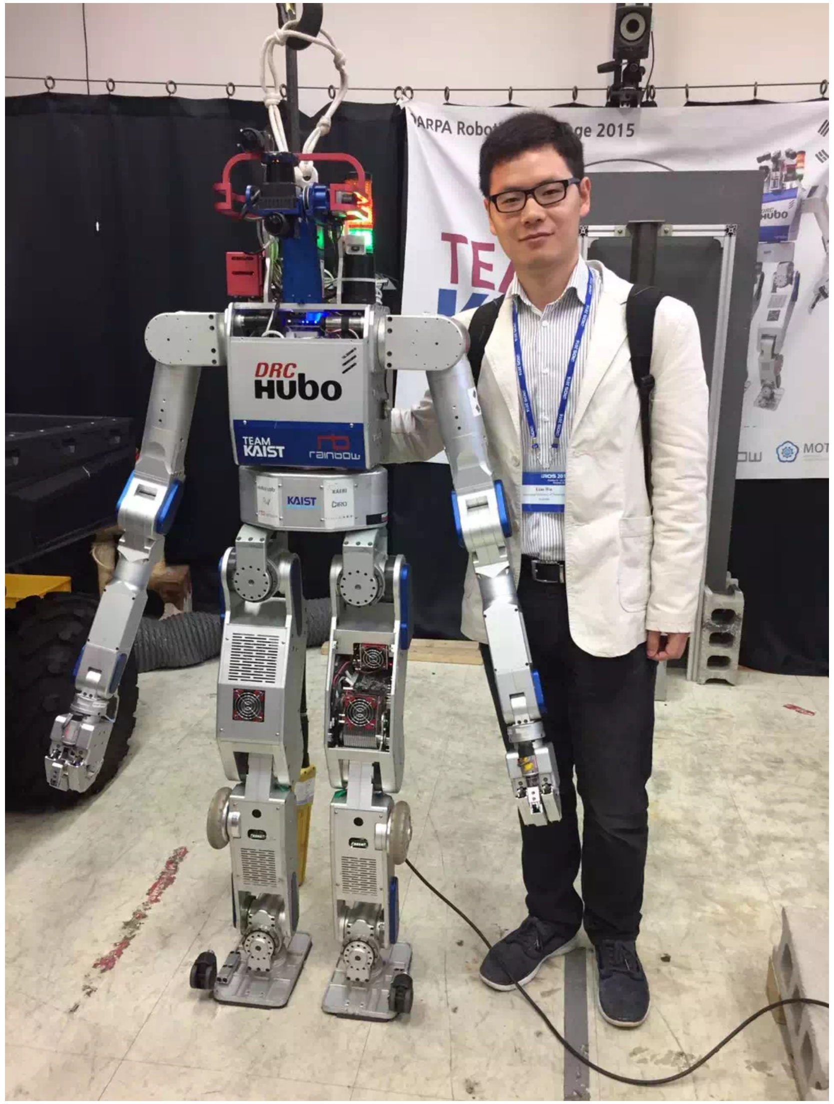

Case study – DAPAR Robotics Challenge

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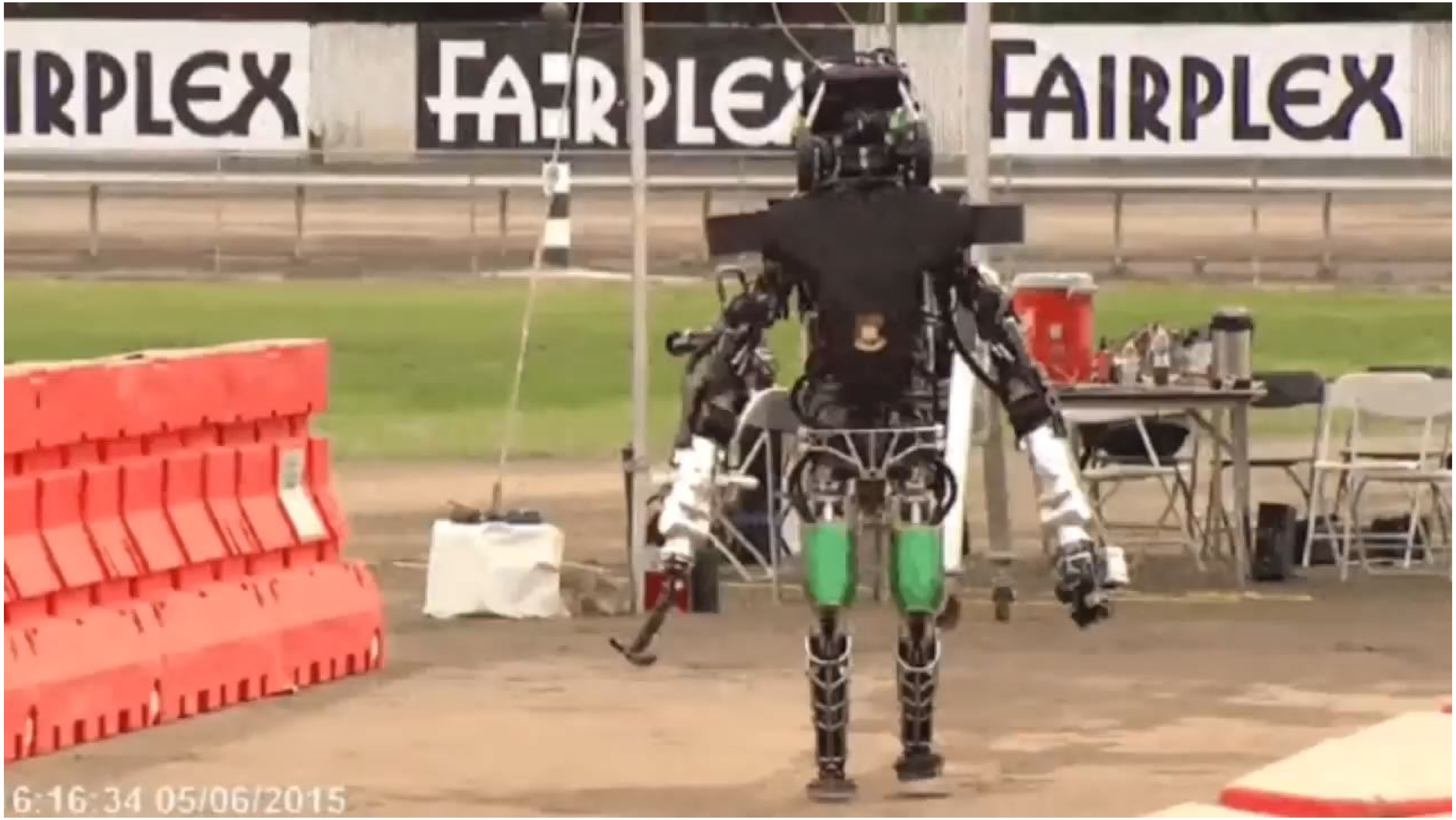
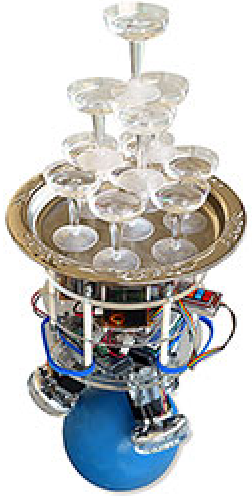


https://www.youtube.com/watch?v=g0TaYhjpOfo

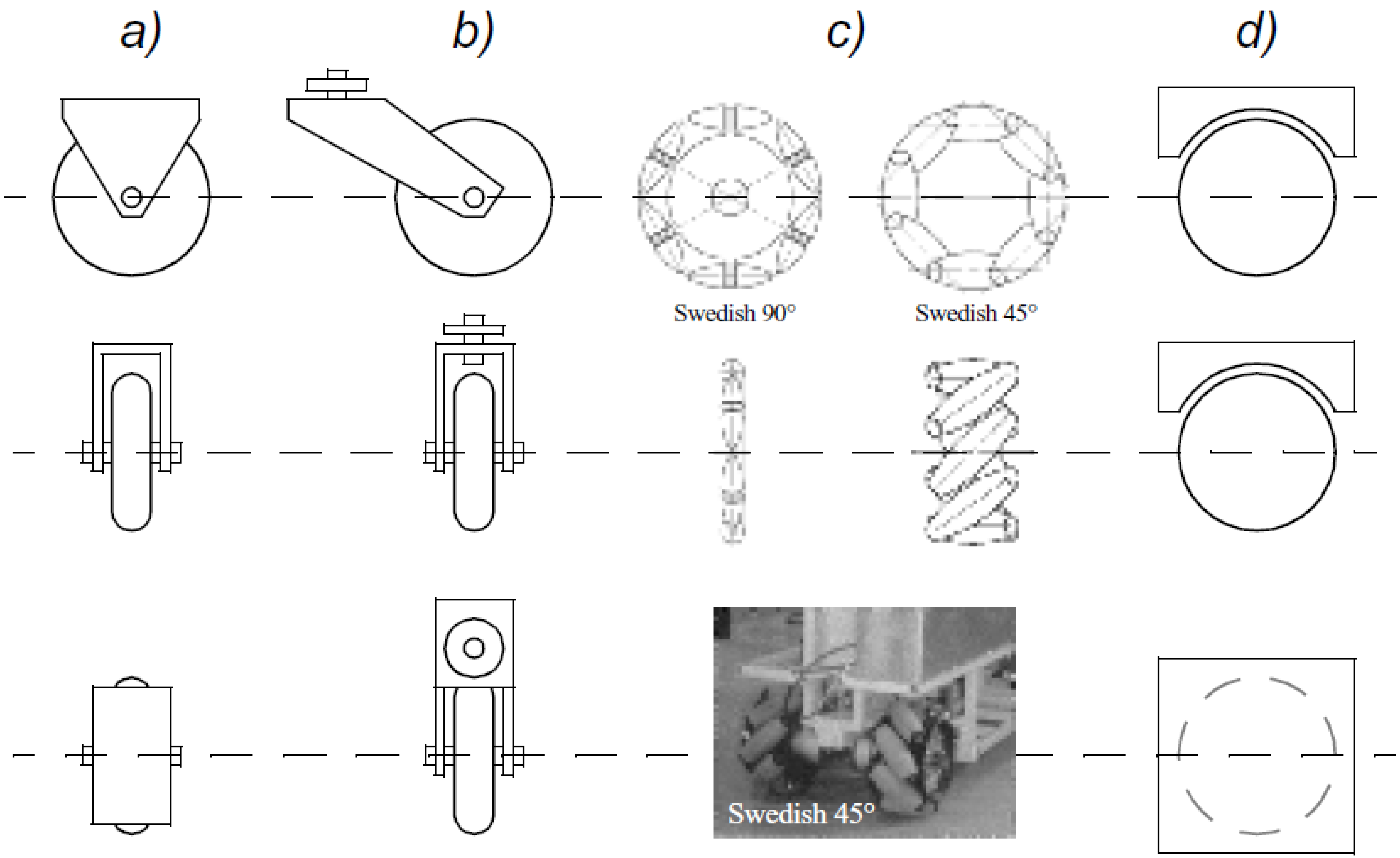
Wheeled robots

- Nature does not evolve rotating mechanisms
- But wheel has been the most popular locomotion mechanism
  - Good efficiency
  - Simple mechanical implementation
  - Easy balance


https://robots.ieee.org/robots/

Four major wheel classes



a) Standard wheel
- 2 DoFs (Degrees of Freedom)

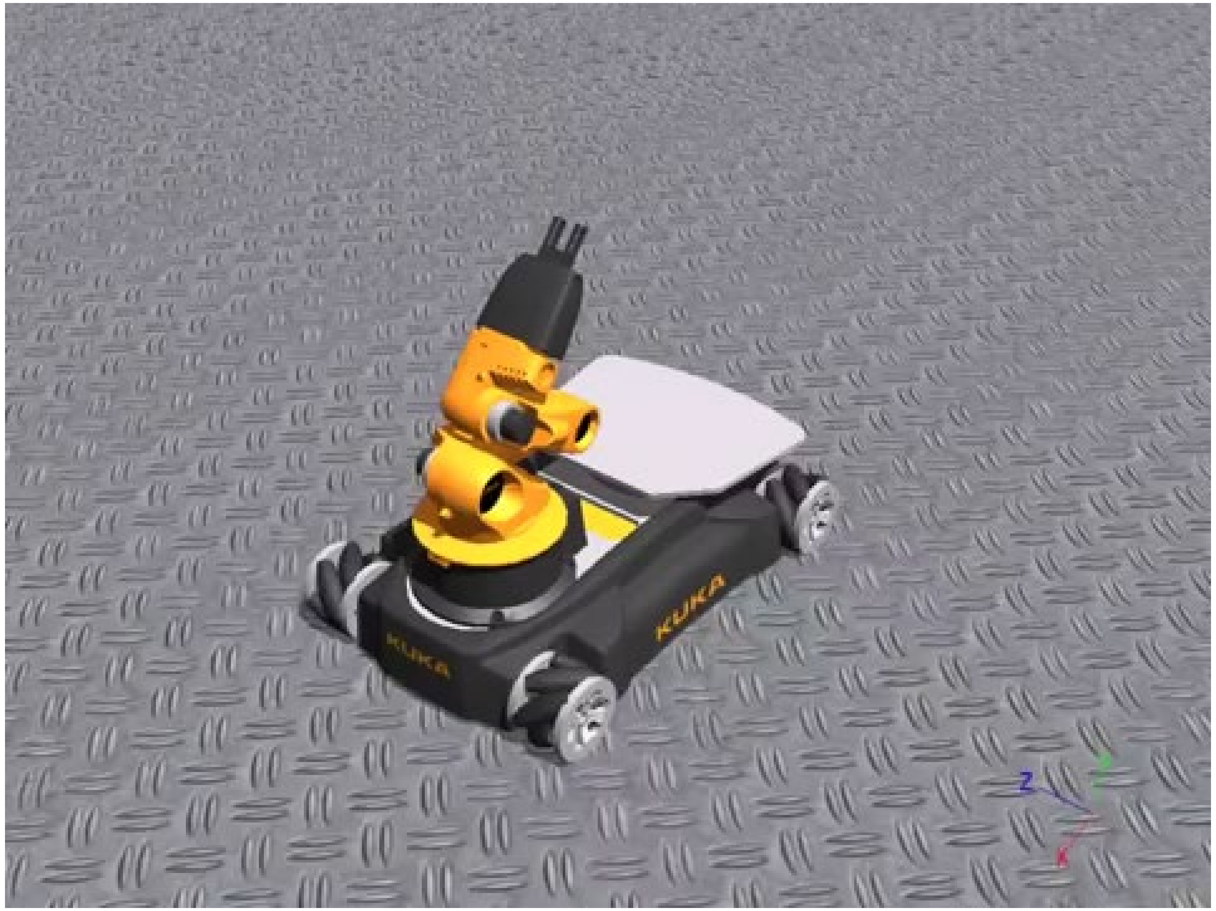
b) Castor wheel
- 2 DoFs

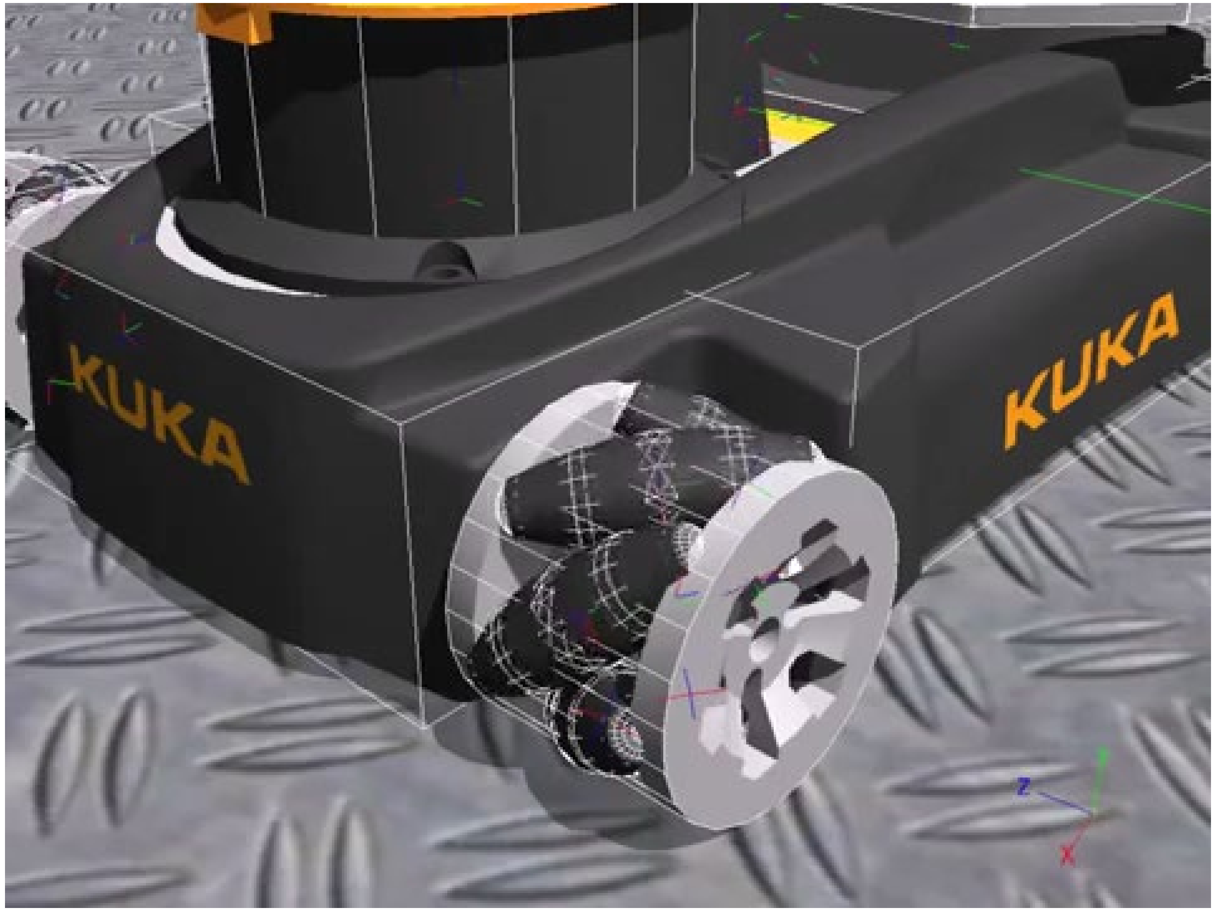
c) Swedish/Mecanum wheel
- 3 DoFs

d) Ball/spherical wheel
- 3 DoFs

R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to autonomous mobile robots. The MIT Press. Second edition. 2011.

Swedish/Mecanum wheel





https://www.youtube.com/watch?v=vFwNwT8dZTU

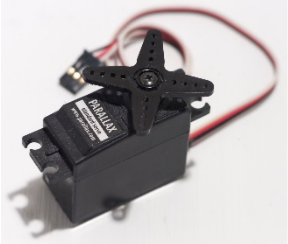
Ball/spherical wheel

Motor classification

Direct Current (DC) Motors

- Brushed Motors

- Brushless Motors
- Servo Motors



Alternating Current (AC) Motors

- Induction Motors
- Synchronous Motors
- Servo Motors
- Stepper Motors

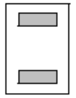
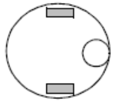
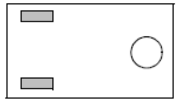
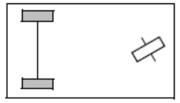
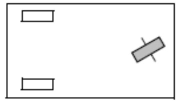
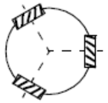
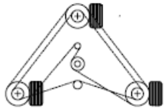
https://en.wikipedia.org/wiki/Brushed_DC_electric_motor
https://en.wikipedia.org/wiki/Servo_%28radio_control%29
https://en.wikipedia.org/wiki/Stepper_motor

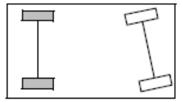
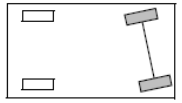
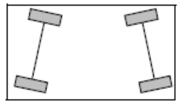
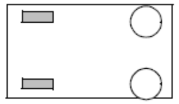
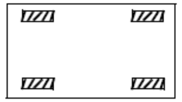
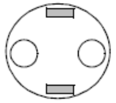
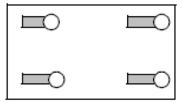
Comparison between Brushed DC, RC Servo, and Stepper

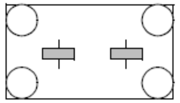
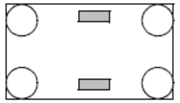
	Brushed DC	RC Servo	Stepper
Speed	High	Low	Low
Torque@High Speeds	Low	High	Low
Control	Simple	Simple	Moderate
Continuous Rotation	Yes	Typically, No	Yes
Position Control	No	Yes	Yes
Speed Control	No	No	Yes
Accuracy	Low	Moderate	High, but might skip steps at high loads
Efficiency	High	High	Low
Example Application	Computer fans, Toys, Medical devices, etc.	Radio controlled devices, Robotics, etc.	3D printers, CNC milling machines, Robotics, etc.

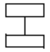
https://singleboardbytes.com/554/dc-servo-stepper-motors.htm

Wheel **geometry**

# 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

# 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

# of wheels	Arrangement	Description	Typical examples
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)

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.

R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to autonomous mobile robots. The MIT Press. Second edition. 2011.

slido

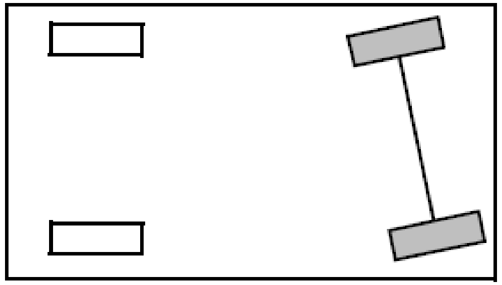
How many wheels are needed at least to make a wheeled robot statically stable?

ⓘ Start presenting to display the poll results on this slide.

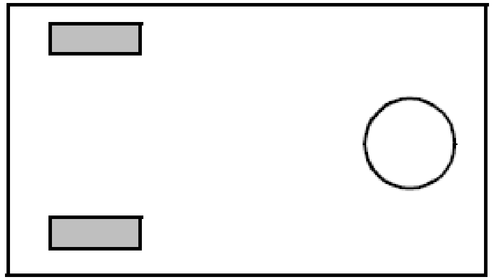
Three fundamental characteristics

- Stability
  - Number of wheels and the configuration

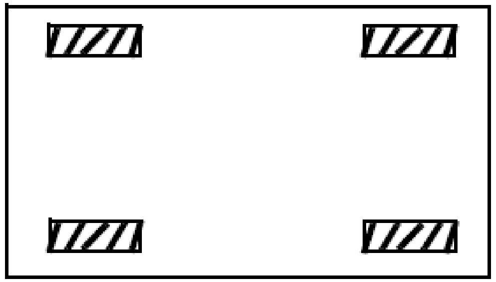
- Manoeuvrability
  - How easily the robot can be manoeuvred
  - Ackerman-steering



Two-wheel differential-drive



Omnidirectional

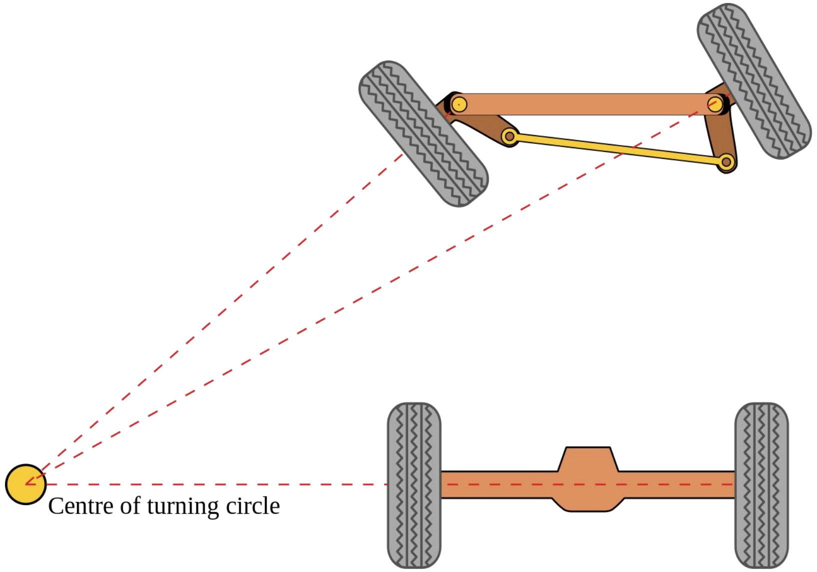


- Controllability
  - How easily the robot can be controlled
  - Generally inverse to manoeuvrability

https://www.joom.com/en/best/robotics-omnidirectional-wheel
https://techcrunch.com/2016/01/07/segway-has-created-a-robot-that-connects-to-your-two-wheeled-scooter/
https://stanleyinnovation.com/products-services/robotics/robotic-mobility-platforms/passive-stability/
R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to autonomous mobile robots. The MIT Press. Second edition. 2011.

Ackerman-steering

Stability? Manoeuvrability? Controllability?



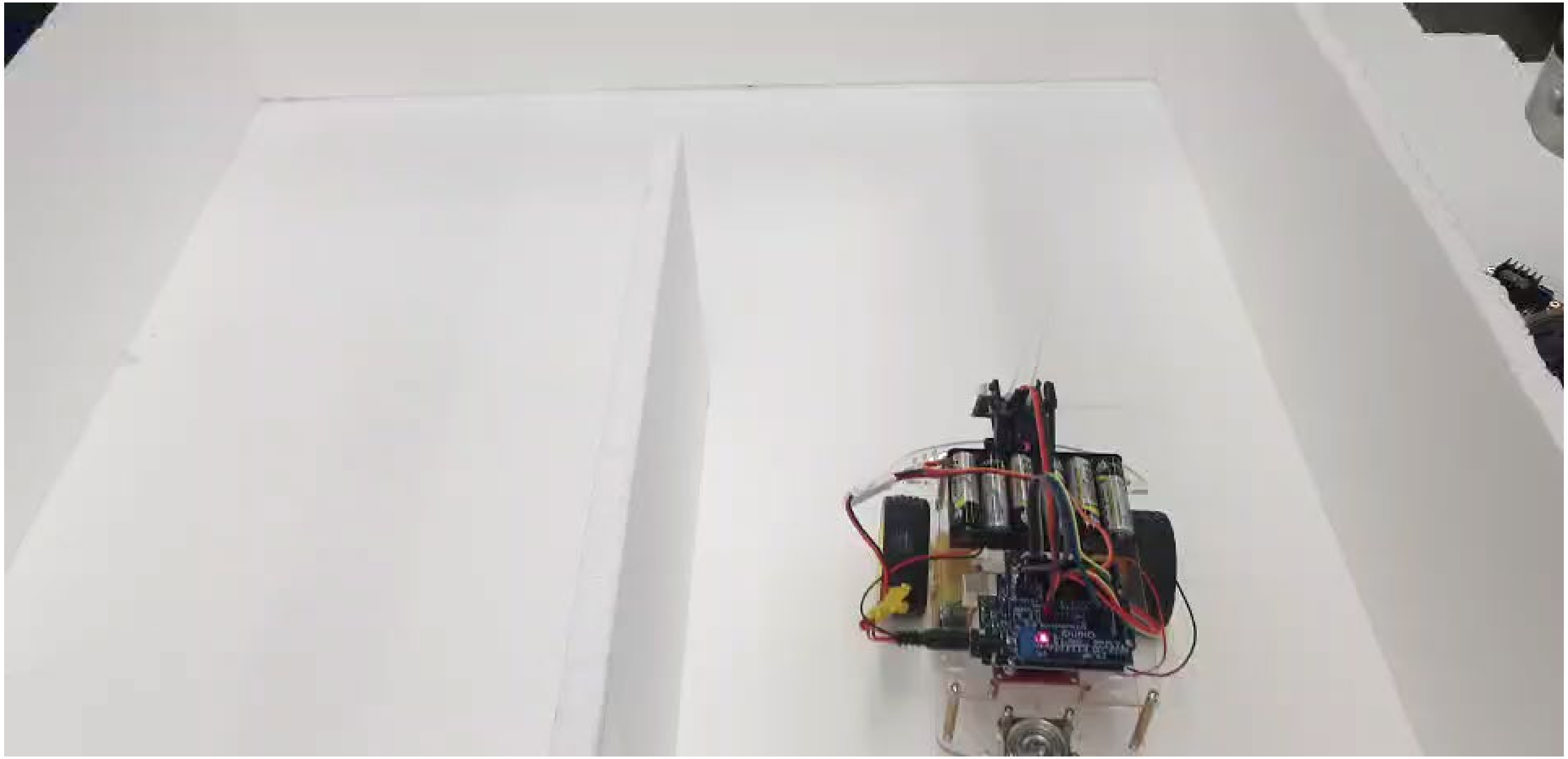
https://en.wikipedia.org/wiki/Ackermann_steering_geometry
https://www.youtube.com/watch?v=w3TX7kAhuvo

Omnidirectional

Stability? Manoeuvrability? Controllability?

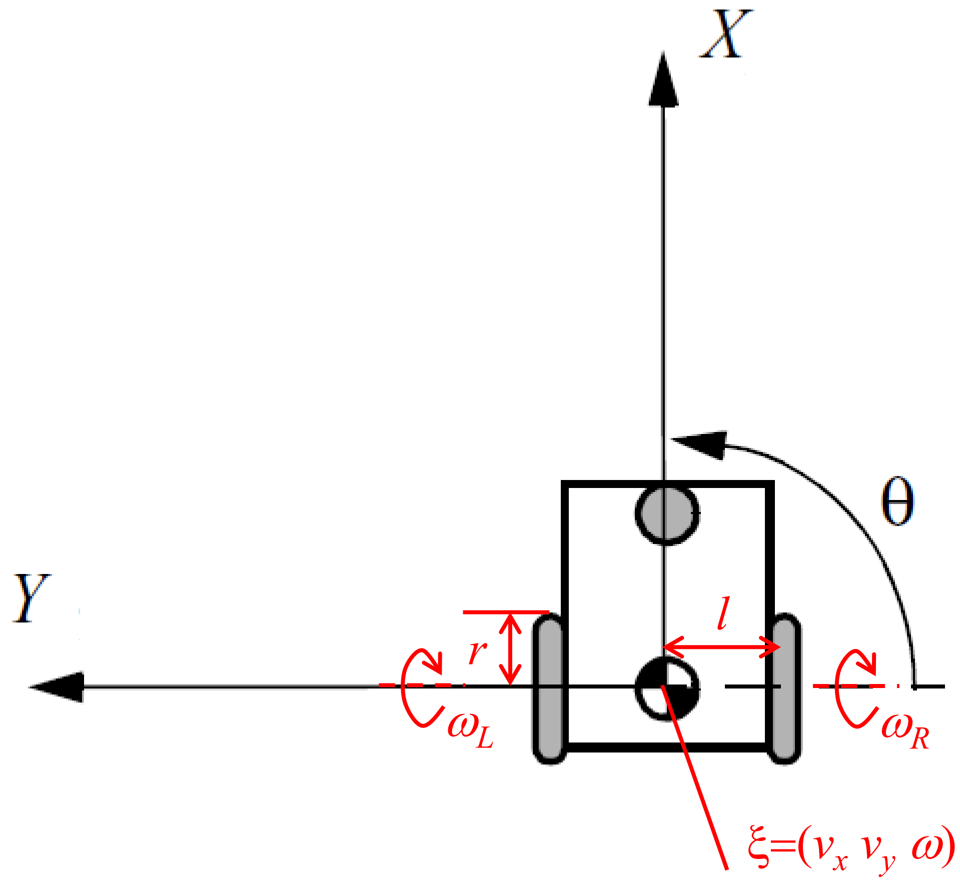
Two-wheel differential-drive

- Stability?
  - Good
- Manoeuvrability?
  - Moderate
- Controllability?
  - Moderate



Two-wheel differential-drive

- A little bit of kinematics



Contribution of ω_R to ξ: $\xi_R = \begin{bmatrix} v_x^R \\ v_y^R \\ \omega^R \end{bmatrix} = \begin{bmatrix} \frac{r\cdot\omega_R}{2} \\ 0 \\ \frac{r\cdot\omega_R}{2l} \end{bmatrix}$

Contribution of ω_L to ξ: $\xi_L = \begin{bmatrix} v_x^L \\ v_y^L \\ \omega^L \end{bmatrix} = \begin{bmatrix} \frac{r\cdot\omega_L}{2} \\ 0 \\ -\frac{r\cdot\omega_L}{2l} \end{bmatrix}$

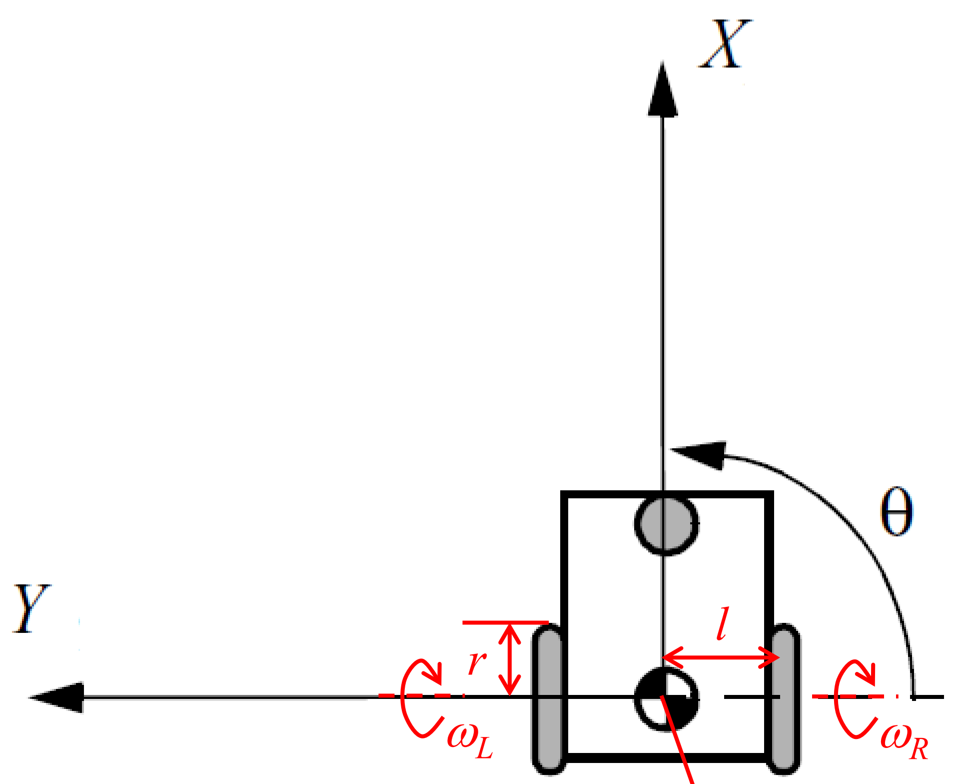
Contributions can be linearly combined:

$$\xi = \xi_L + \xi_R = \begin{bmatrix} \frac{r\cdot\omega_L}{2} + \frac{r\cdot\omega_R}{2} \\ 0 \\ -\frac{r\cdot\omega_L}{2l} + \frac{r\cdot\omega_R}{2l} \end{bmatrix}$$

R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to autonomous mobile robots. The MIT Press. Second edition. 2011.

Two-wheel differential-drive

- Forward kinematics



Suppose both wheels have diameter *40mm* and spaced at *100mm*. The left wheel spins at *30deg/s*, and the right at *60deg/s*. Specify v_x , v_y , and ω. ($\pi = 3.14$)

Contributions can be linearly combined:

$$\xi = \xi_L + \xi_R = \begin{bmatrix} \frac{r \cdot \omega_L}{2} + \frac{r \cdot \omega_R}{2} \\ 0 \\ -\frac{r \cdot \omega_L}{2l} + \frac{r \cdot \omega_R}{2l} \end{bmatrix}$$

Two-wheel differential-drive

- Forward kinematics

Suppose both wheels have diameter *40mm* and spaced at *100mm*. The left wheel spins at *30deg/s*, and the right at *60deg/s*. Specify v_x, v_y, and ω. ($\pi = 3.14$)

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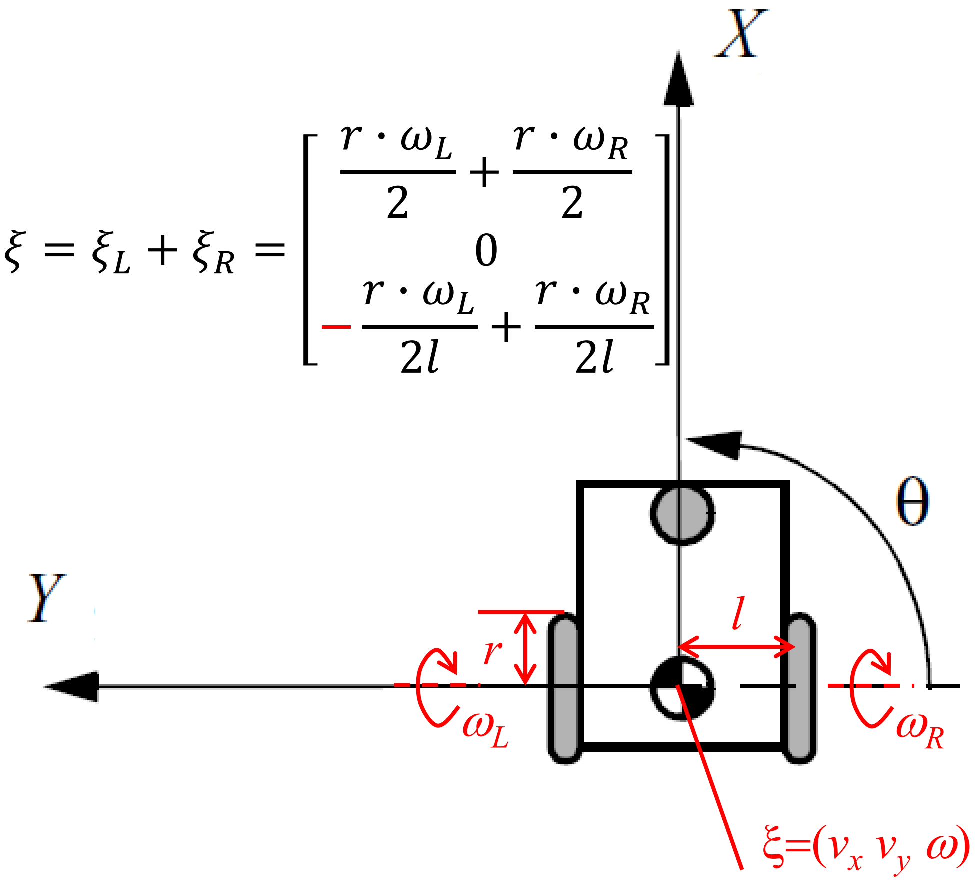
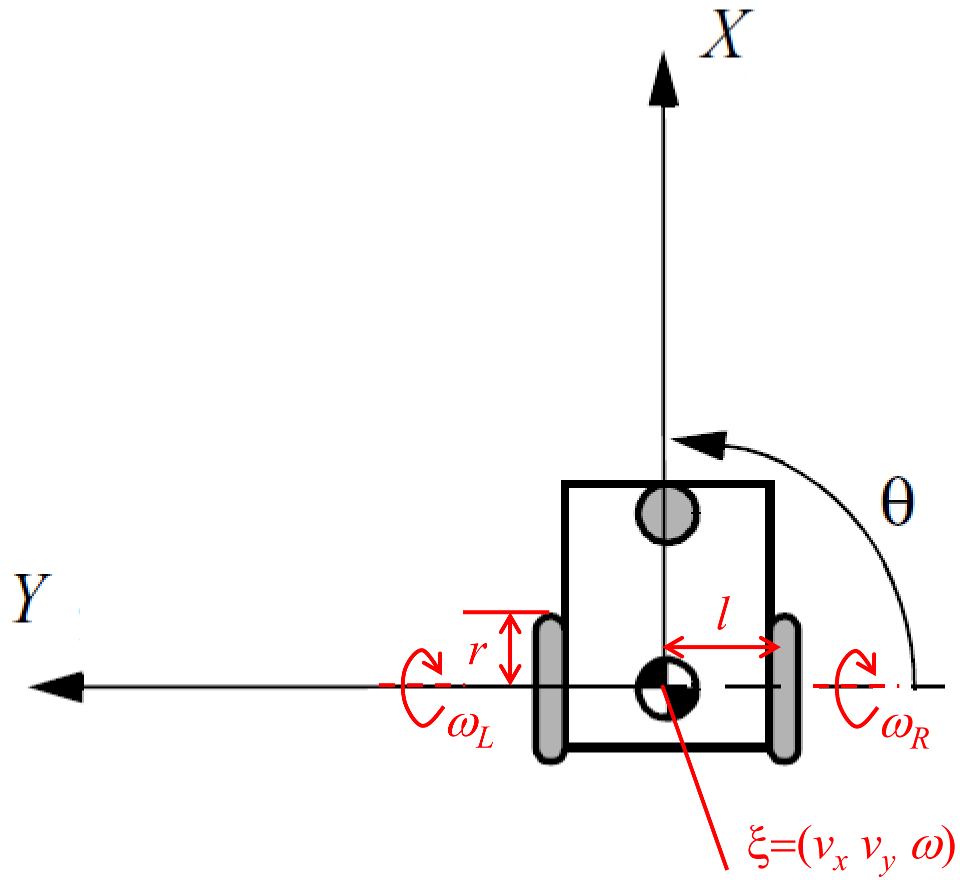


$\xi=(v_x\ v_y\ \omega)$ is the velocity of the centre point

Two-wheel differential-drive

- Inverse kinematics

Suppose both wheels have diameter *40mm* and spaced at *100mm*. The robot moves at $v_x = 10\pi\ mm/s$, $v_y = 0\ mm/s$, and $\omega = \pi/15\ rad/s$. What are the required speeds of the left and right wheels? ($\pi = 3.14$)



$\xi = (v_x\ v_y\ \omega)$ is the velocity of the centre point

Contributions can be linearly combined:

$$\xi = \xi_L + \xi_R = \begin{bmatrix} \frac{r \cdot \omega_L}{2} + \frac{r \cdot \omega_R}{2} \\ 0 \\ -\frac{r \cdot \omega_L}{2l} + \frac{r \cdot \omega_R}{2l} \end{bmatrix}$$

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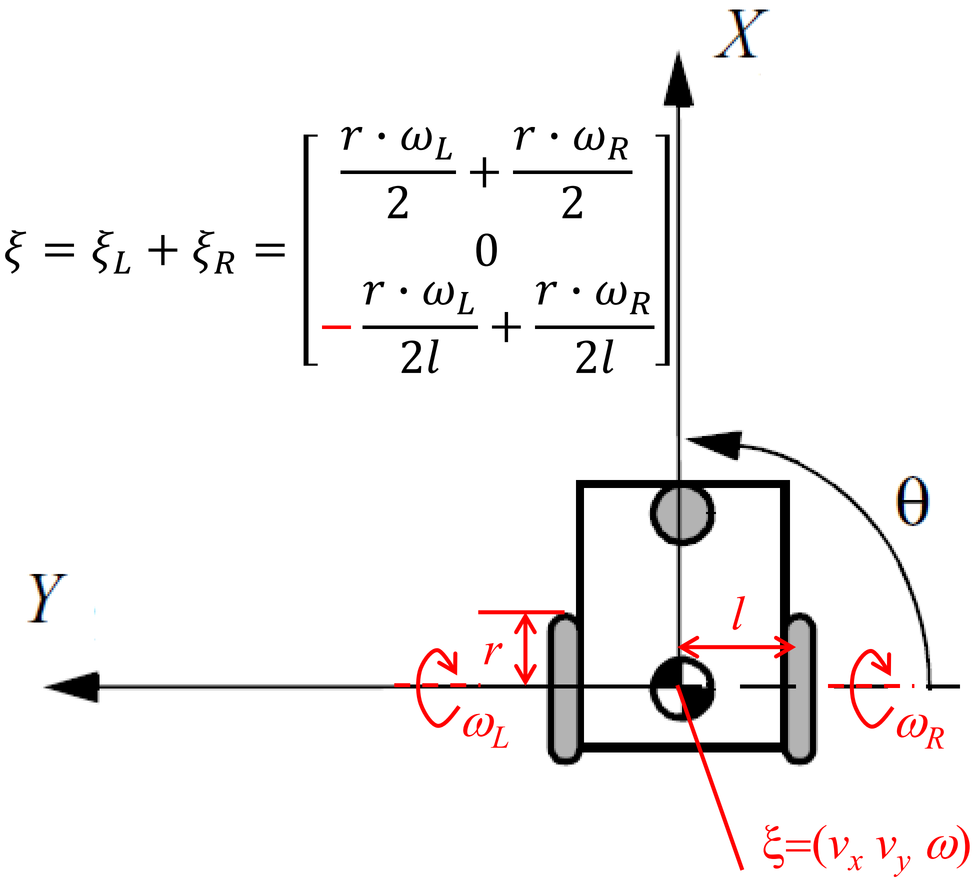
Two-wheel differential-drive

- Inverse kinematics

$$\xi = \xi_L + \xi_R = \begin{bmatrix} \frac{r \cdot \omega_L}{2} + \frac{r \cdot \omega_R}{2} \\ 0 \\ -\frac{r \cdot \omega_L}{2l} + \frac{r \cdot \omega_R}{2l} \end{bmatrix}$$



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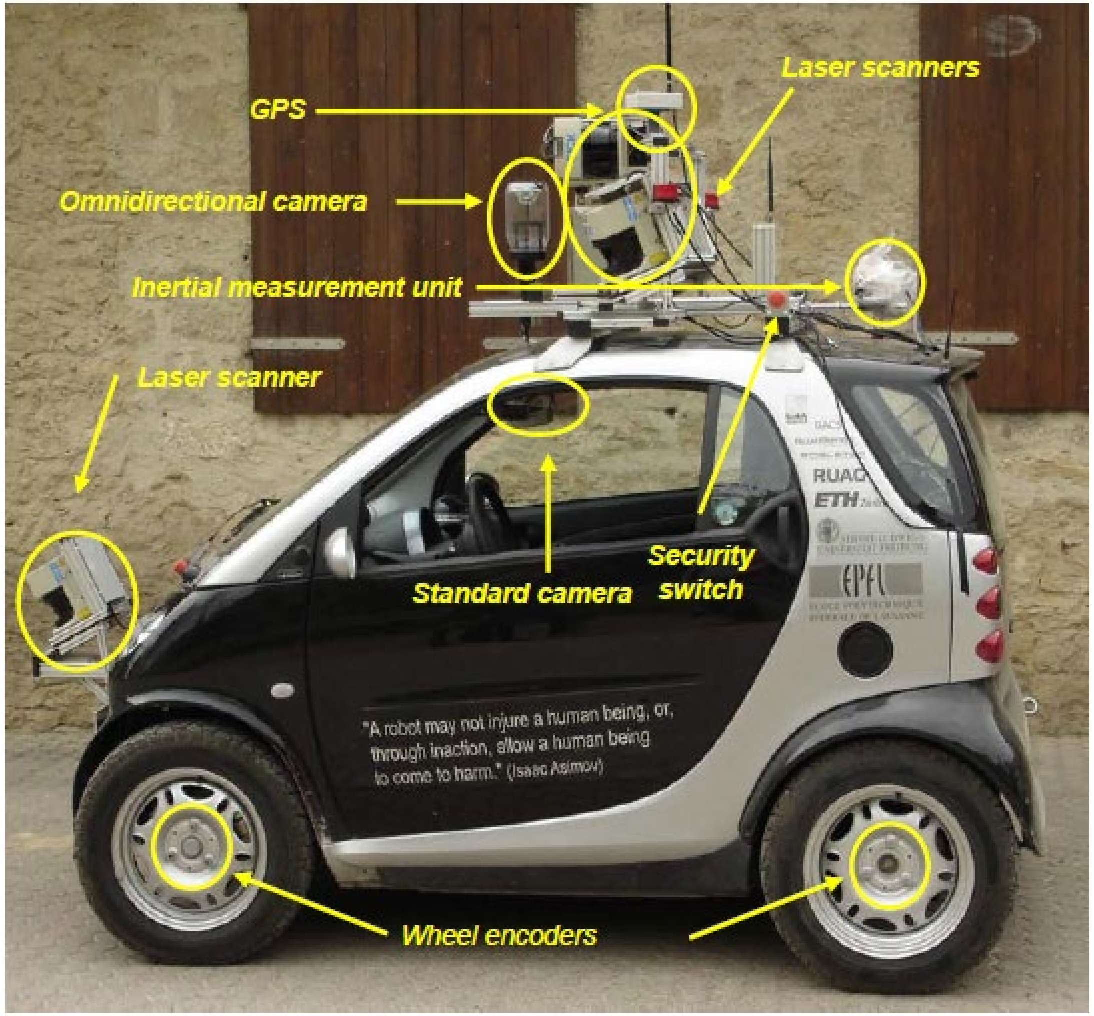
Homework:

Solve this problem and write a program in MATLAB (or any other language) for the calculation.

Hints: The solutions are: $\omega_L=\pi/3$, $\omega_R=2\pi/3$.

Perception

Sensors for mobile robots

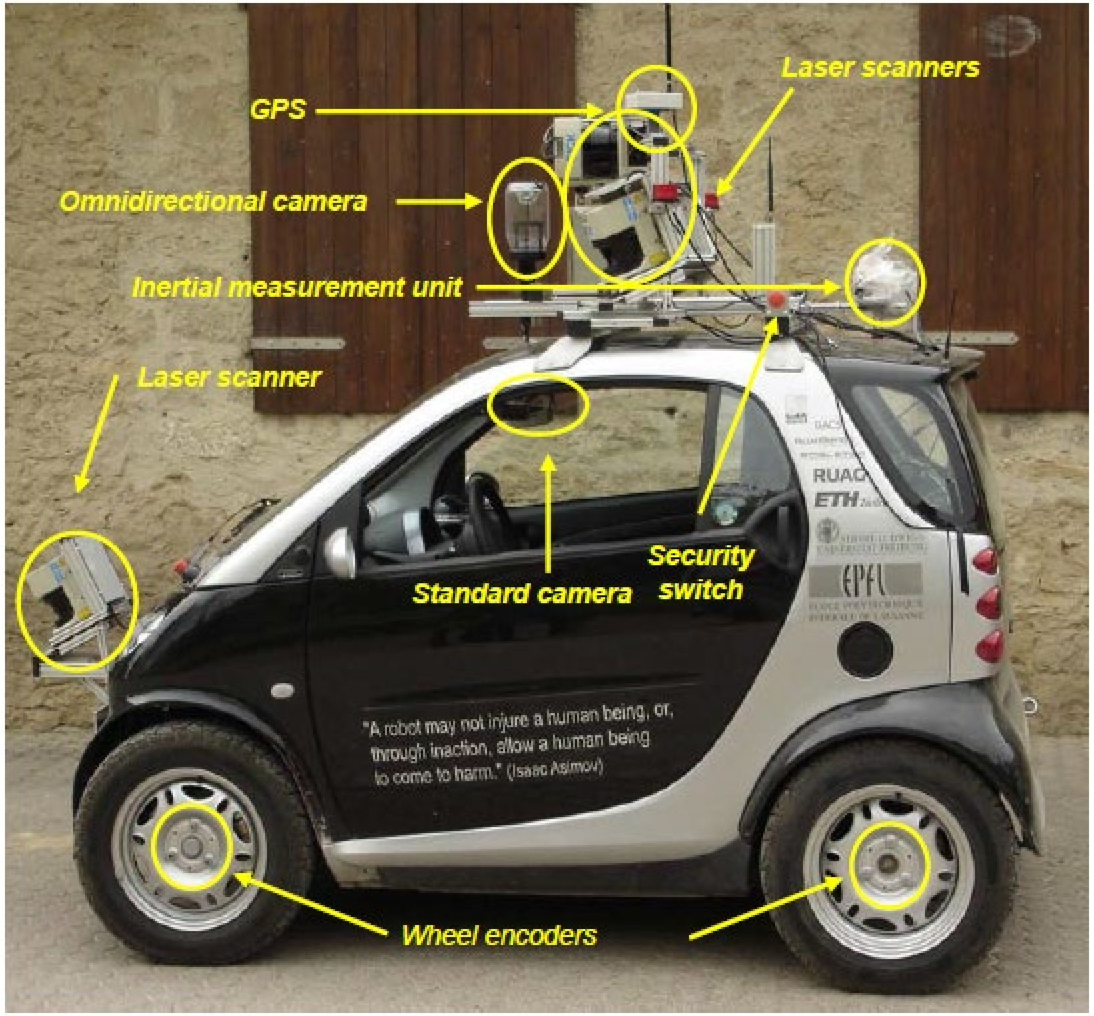


R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to autonomous mobile robots. The MIT Press. Second edition. 2011.

Wheel/motor sensors

- Incremental encoders

- Absolute encoders



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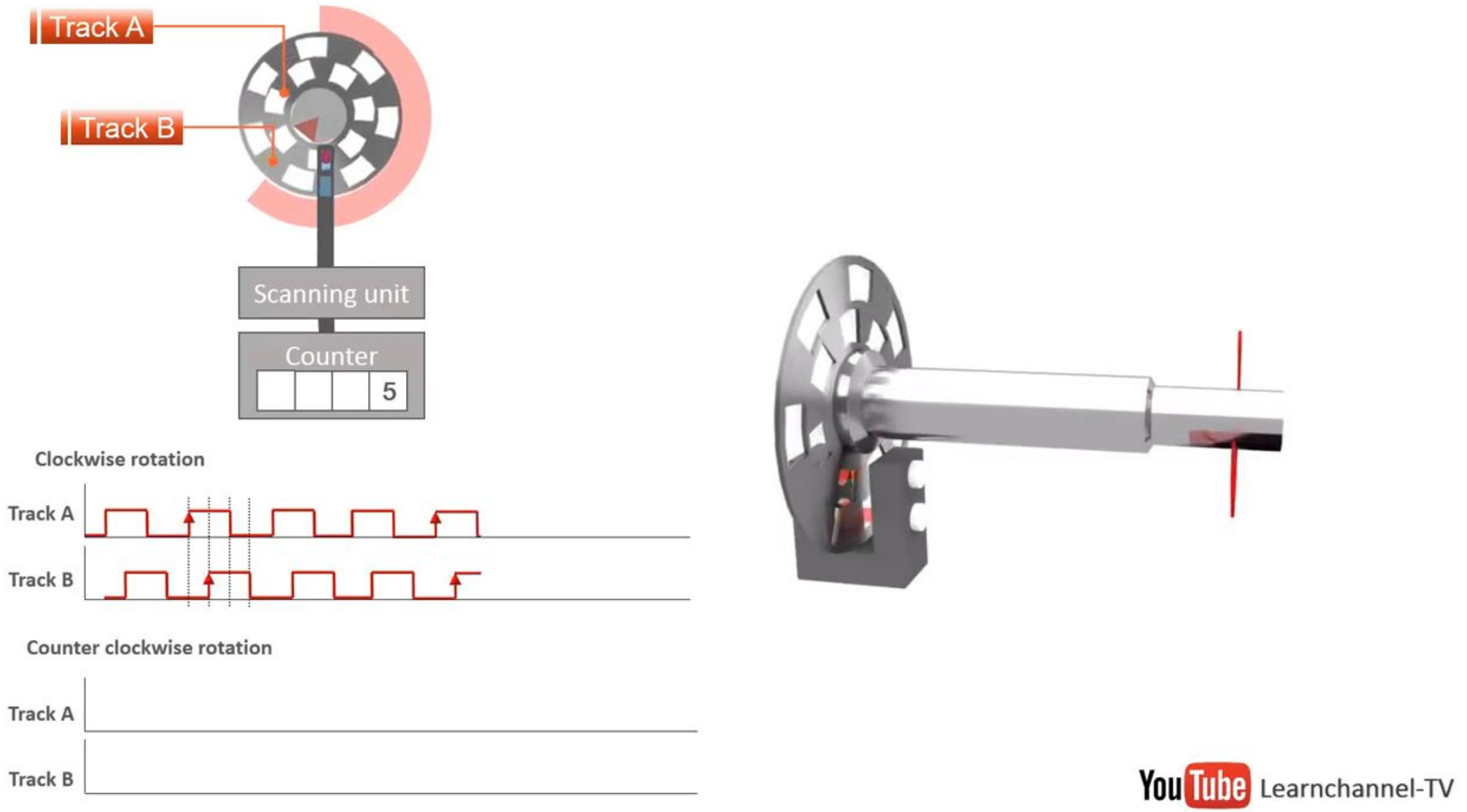
Wheel/motor sensors

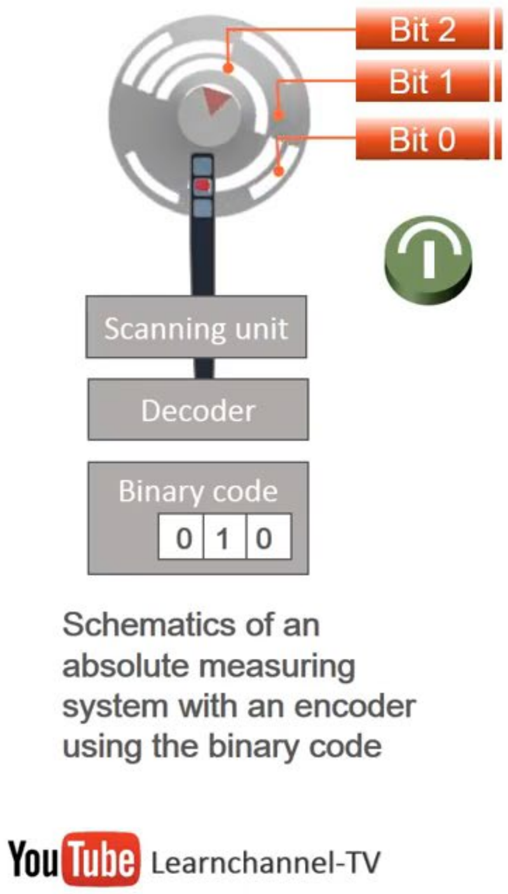
- Incremental encoders

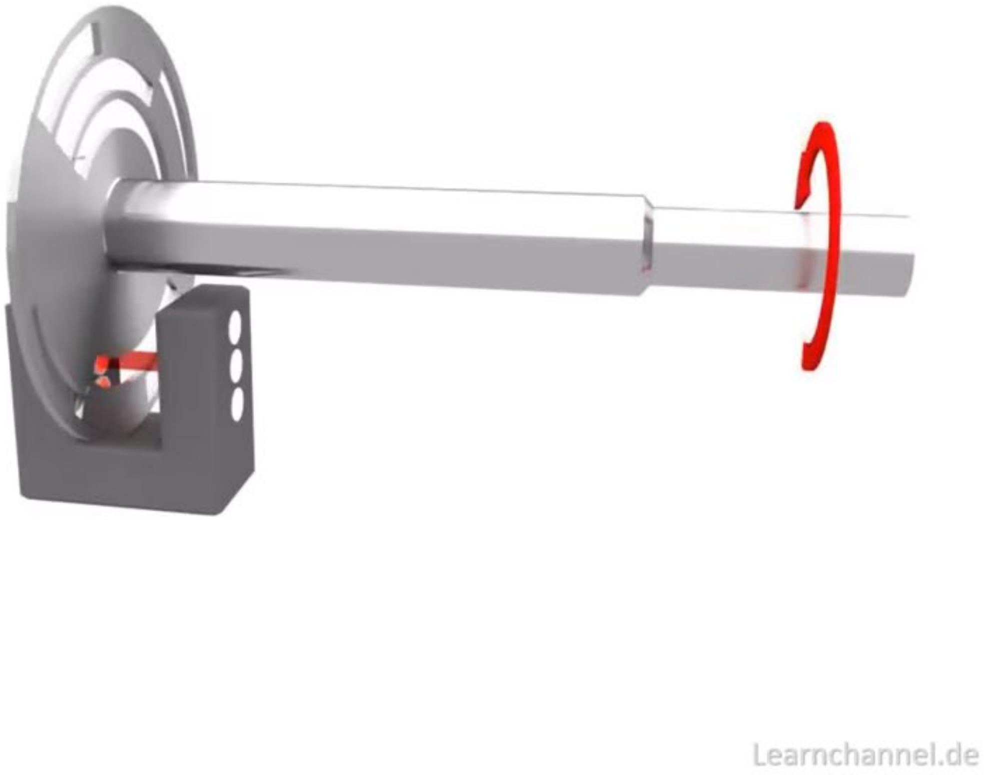


https://www.youtube.com/watch?v=zzHcsJDV3_o

Wheel/motor sensors

- Absolute encoders





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

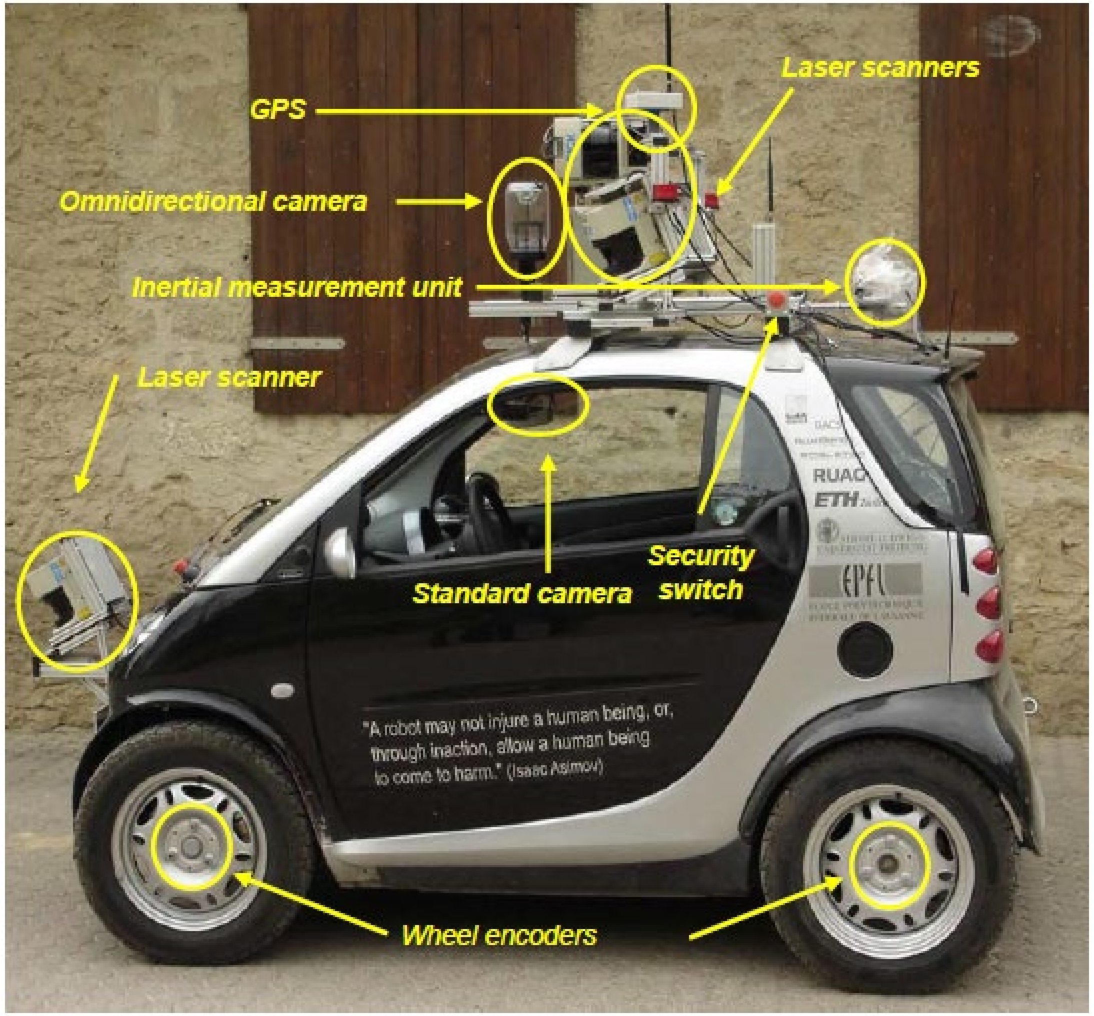
Wheel/motor sensors

- Accuracy and reliability are usually good
  - Working in the controlled environment of a mobile robot's internal structure

- Resolution correlates to cost
  - Cycles Per Revolution (CPR)
  - Ranging from 10+ CPR to 10,000+ CPR

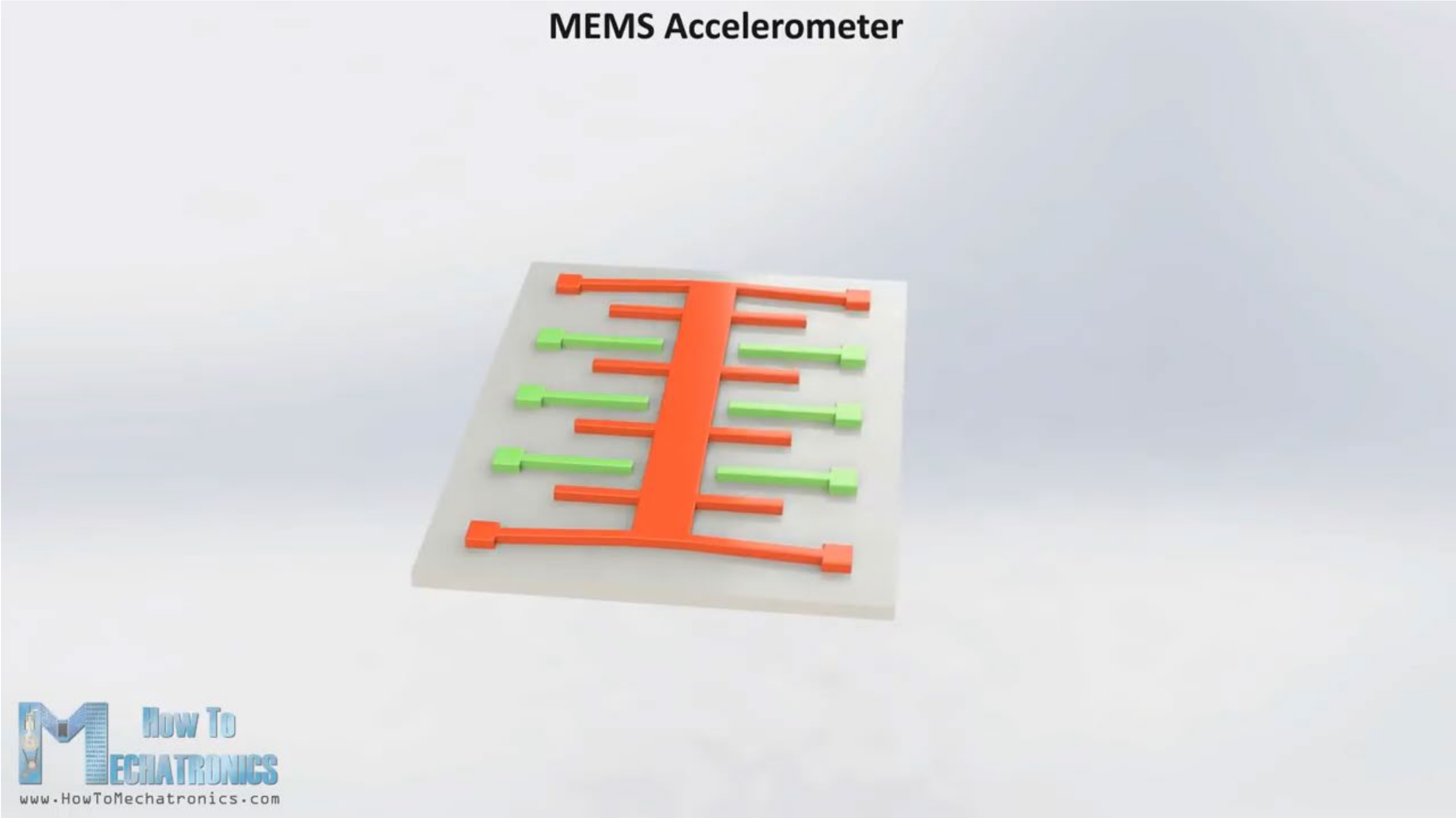
Inertial sensors

- Accelerometers
- Gyroscopes
- Magnetometer
- Inertial measurement unit (IMU)



Inertial sensors

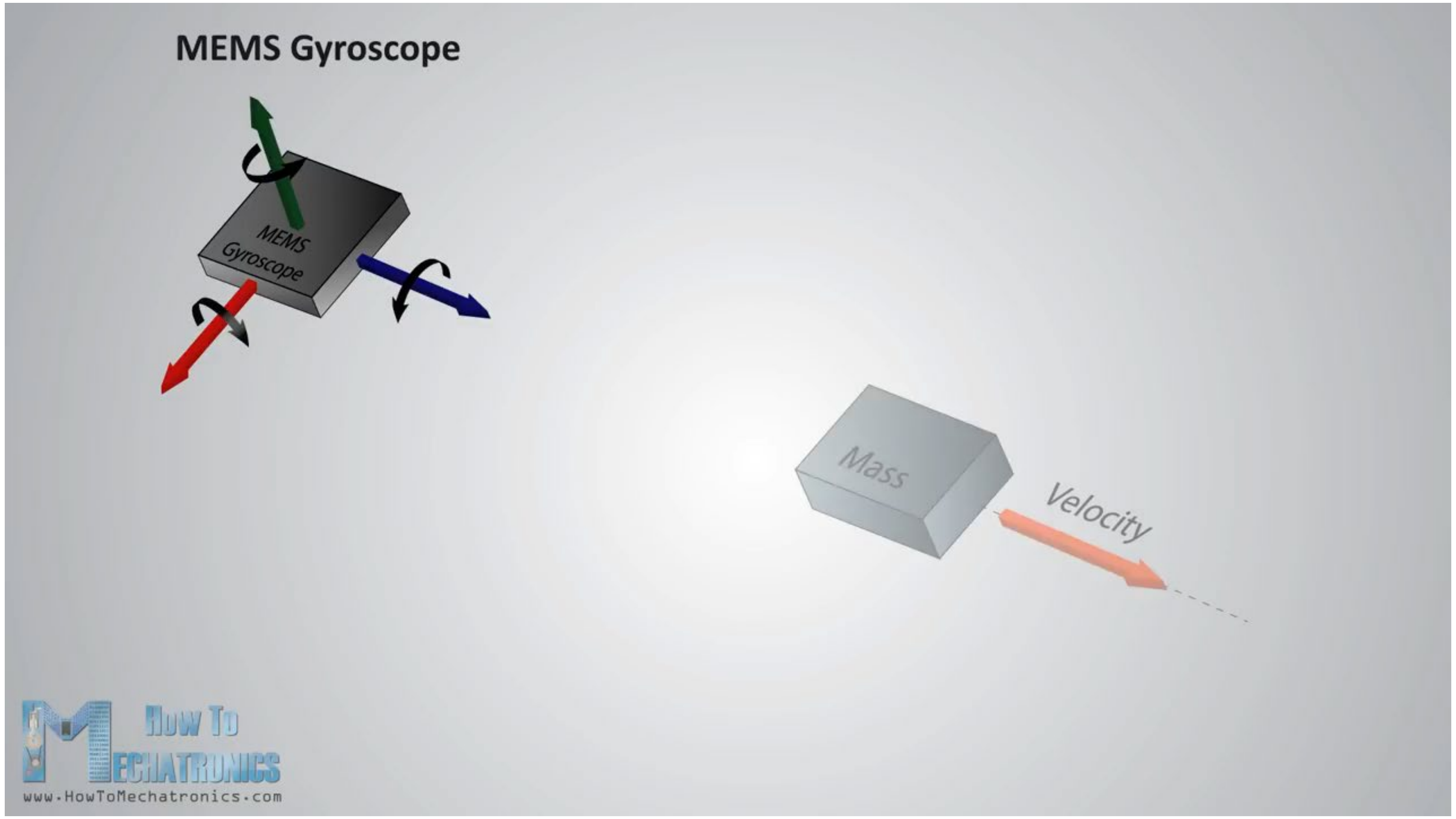
- Accelerometers (MEMS)

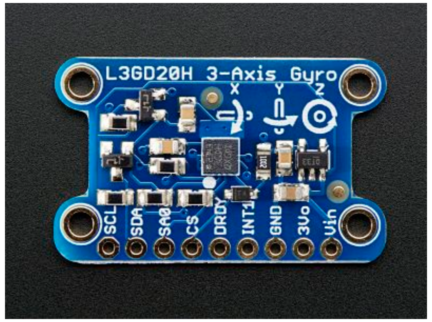


https://www.youtube.com/watch?v=eqZgxR6eRjo&t=110s

Inertial sensors

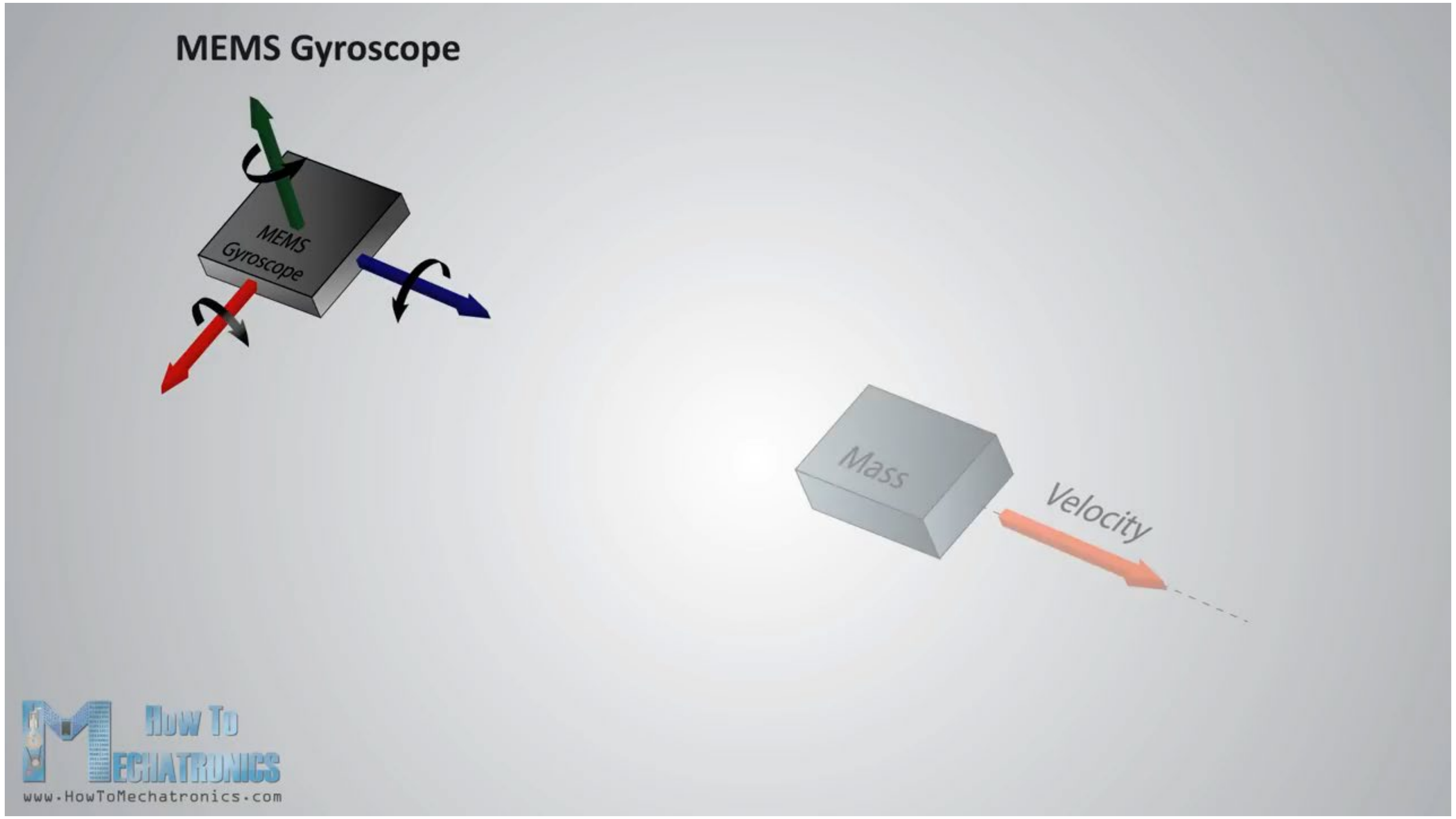
- Gyroscopes (MEMS)

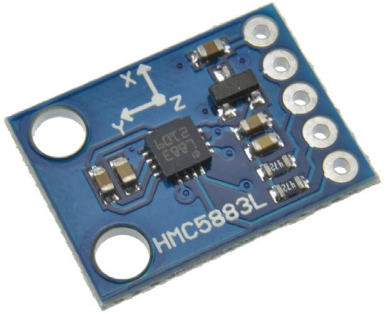




Inertial sensors

- Magnetometer (MEMS)

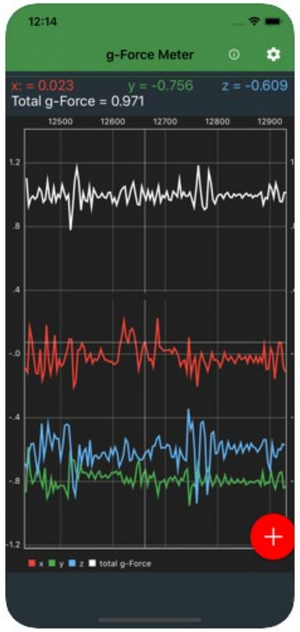




Inertial sensors – On your phone

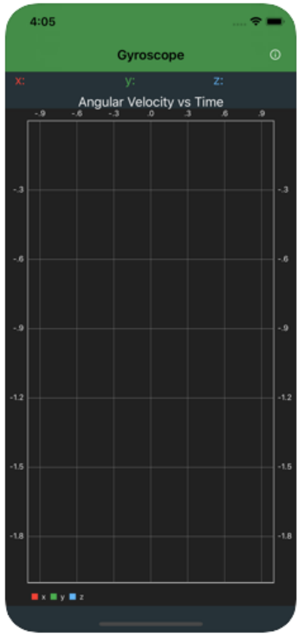
Physics Toolbox Accelerometer
Chrystian Vieyra
Free

Screenshots iPhone iPad



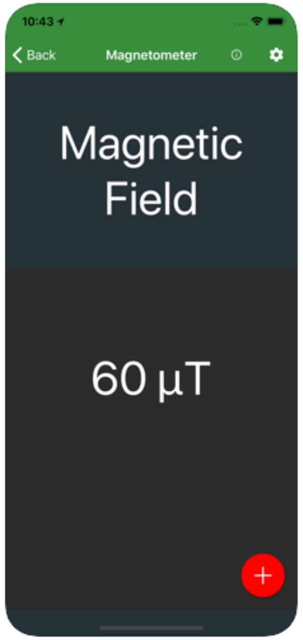
Physics Toolbox Gyroscope
Chrystian Vieyra
Free

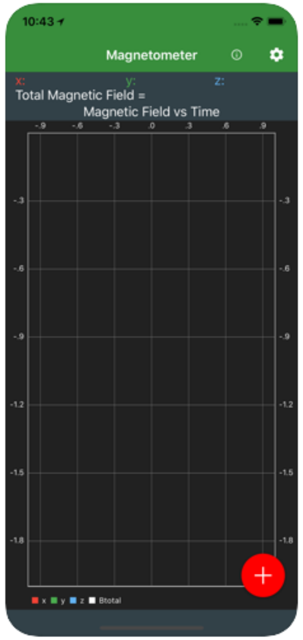
Screenshots iPhone iPad



Physics Toolbox Magnetometer
Chrystian Vieyra
★★★★★ 5.0, 2 Ratings
Free

Screenshots iPhone iPad

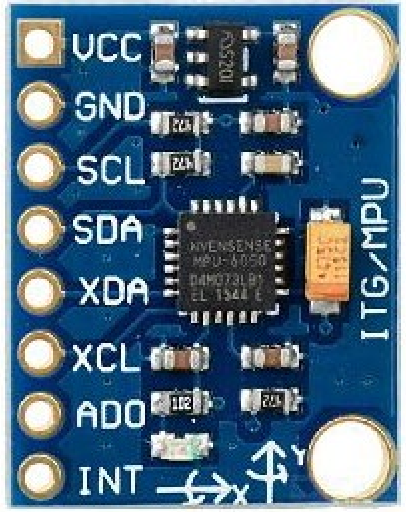




https://apps.apple.com/au/app/physics-toolbox-accelerometer/id1008160133
https://apps.apple.com/au/app/physics-toolbox-sensor-suite/id1128914250
https://apps.apple.com/au/app/physics-toolbox-magnetometer/id1003749103

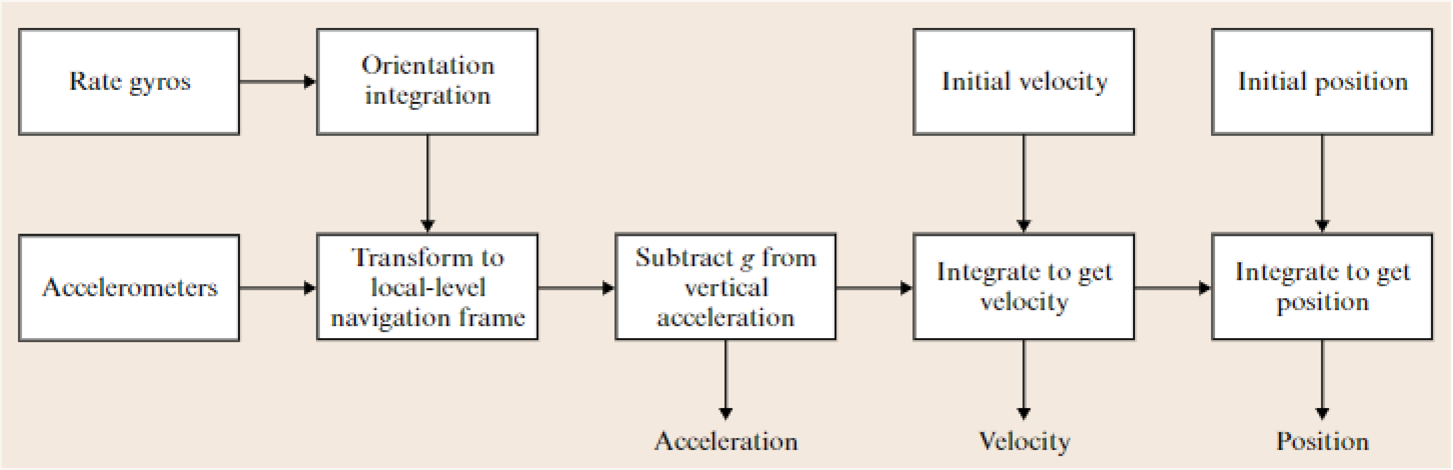
Inertial sensors

- Inertial measurement unit (IMU)
  - Combination of Accelerometers and Gyroscopes (and sometimes Magnetometers as well)



https://www.youtube.com/watch?v=6ijArKE8vKU

Inertial sensors

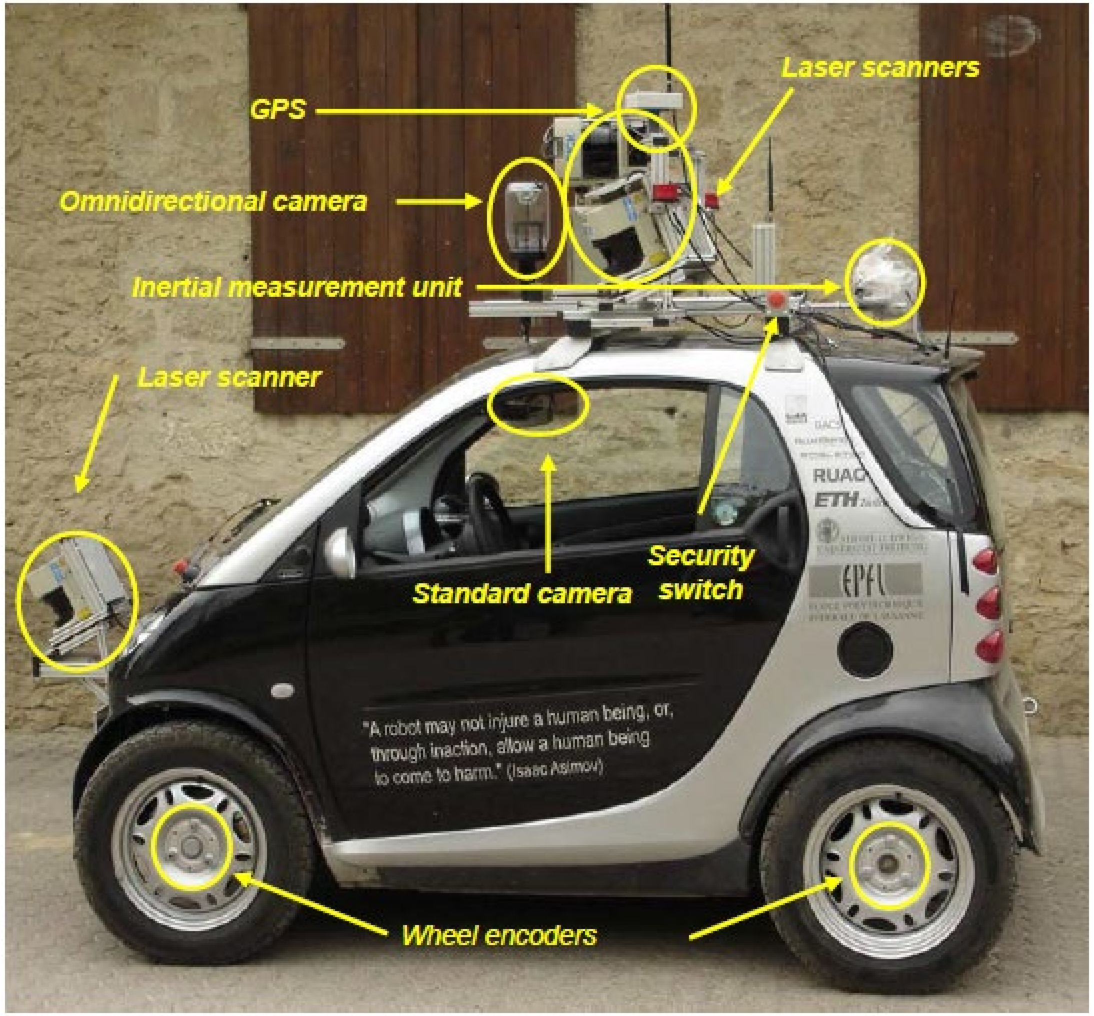


- Extremely sensitive to measurement errors
- Effect of gravity vector
- Drift due to integration
- Reference to external measurement is required after long period of operation

Dudek, G., Jenkin, M., “Inertial sensors, GPS, and odometry”, Springer Handbook of Robotics, Springer, 2008

Active ranging

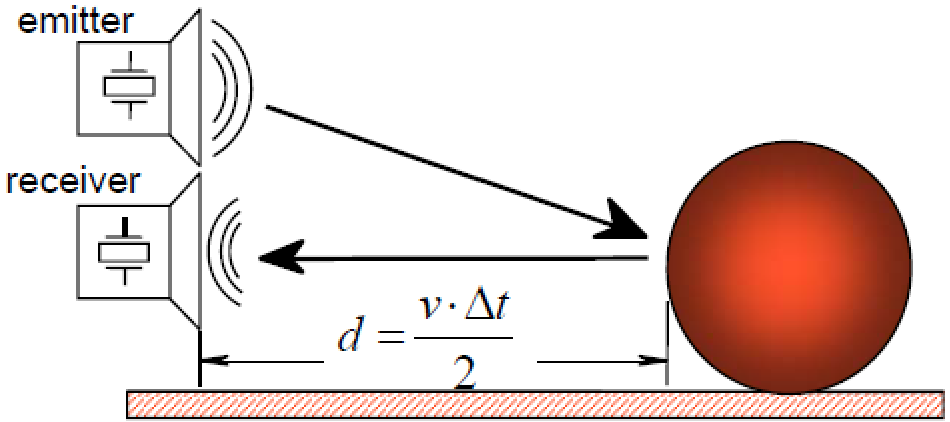
- Time of flight
  - Ultrasonic
  - LiDAR
- Triangulation
  - Optical triangulation
  - Structured light

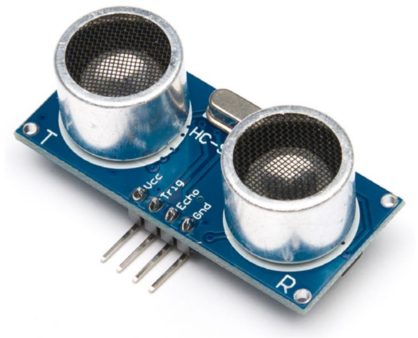


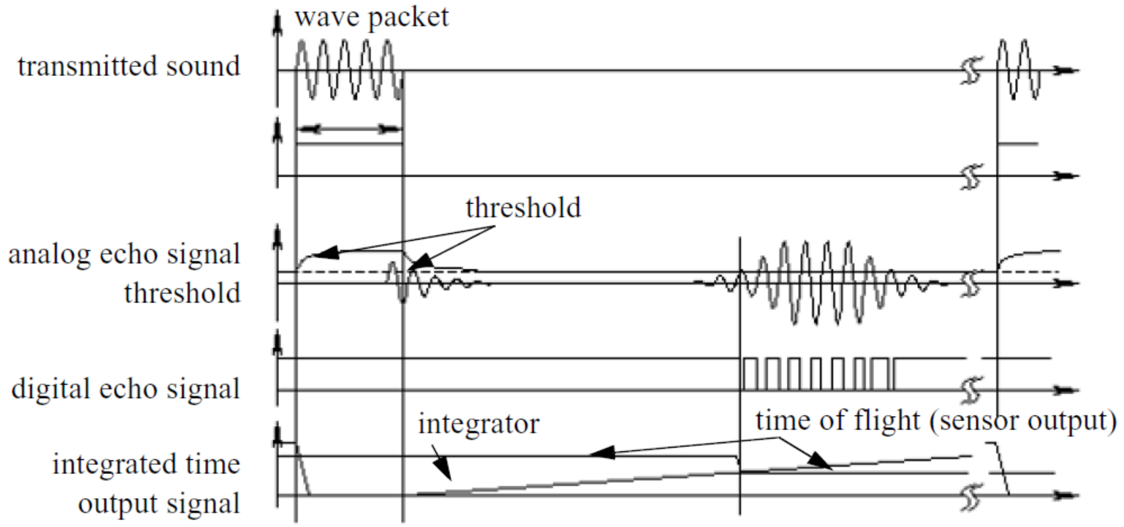
R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to autonomous mobile robots. The MIT Press. Second edition. 2011.

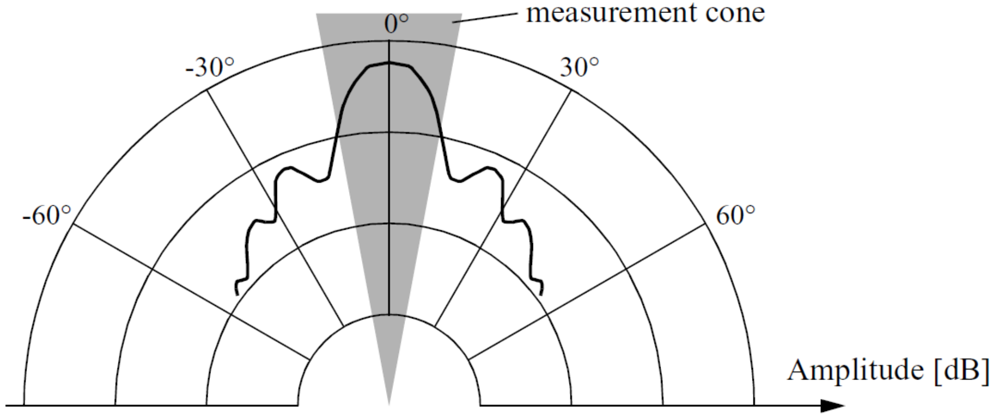
Active ranging – Time of flight

- Ultrasonic sensors









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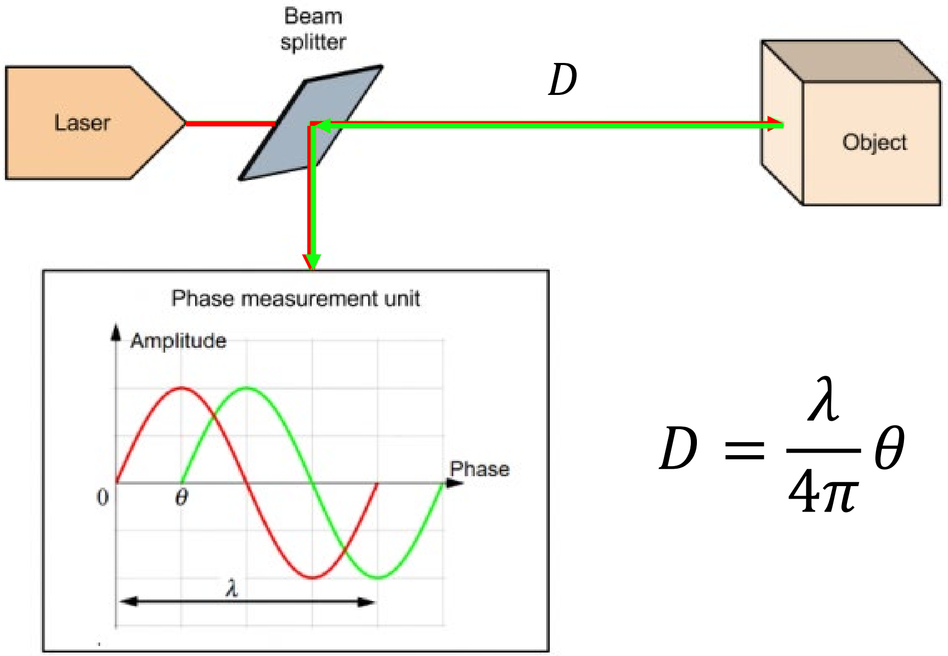
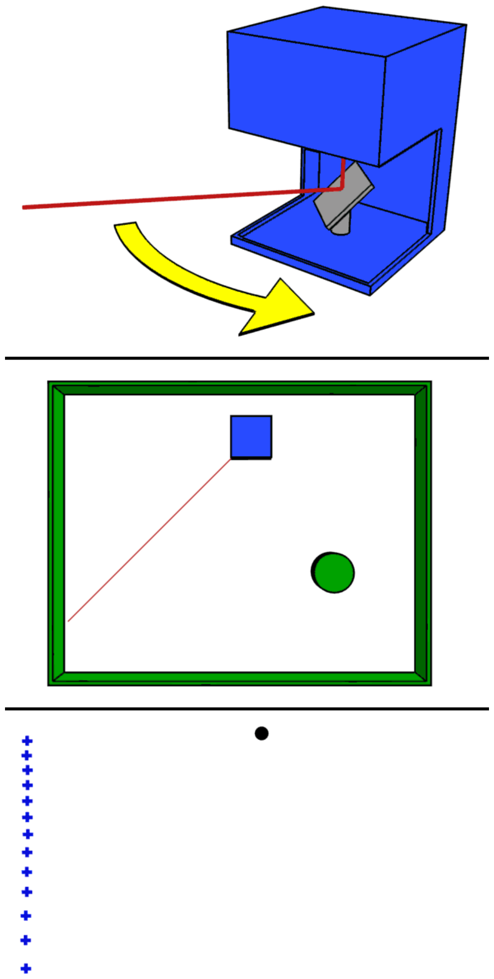
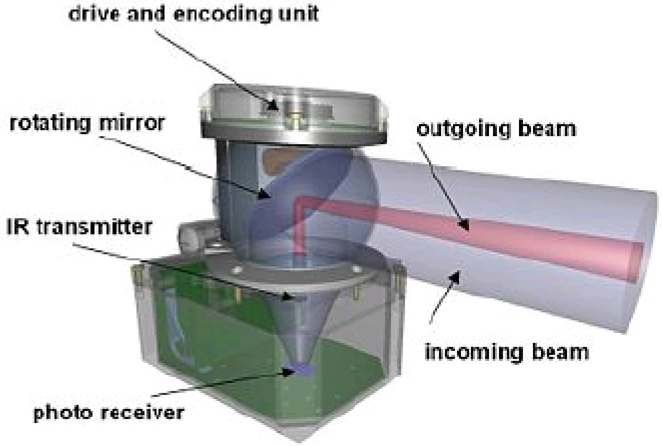
Active ranging – Time of flight

- LiDAR (Light Detection And Ranging)
  - Phase-shift measurement



$$D = \frac{\lambda}{4\pi}\theta$$

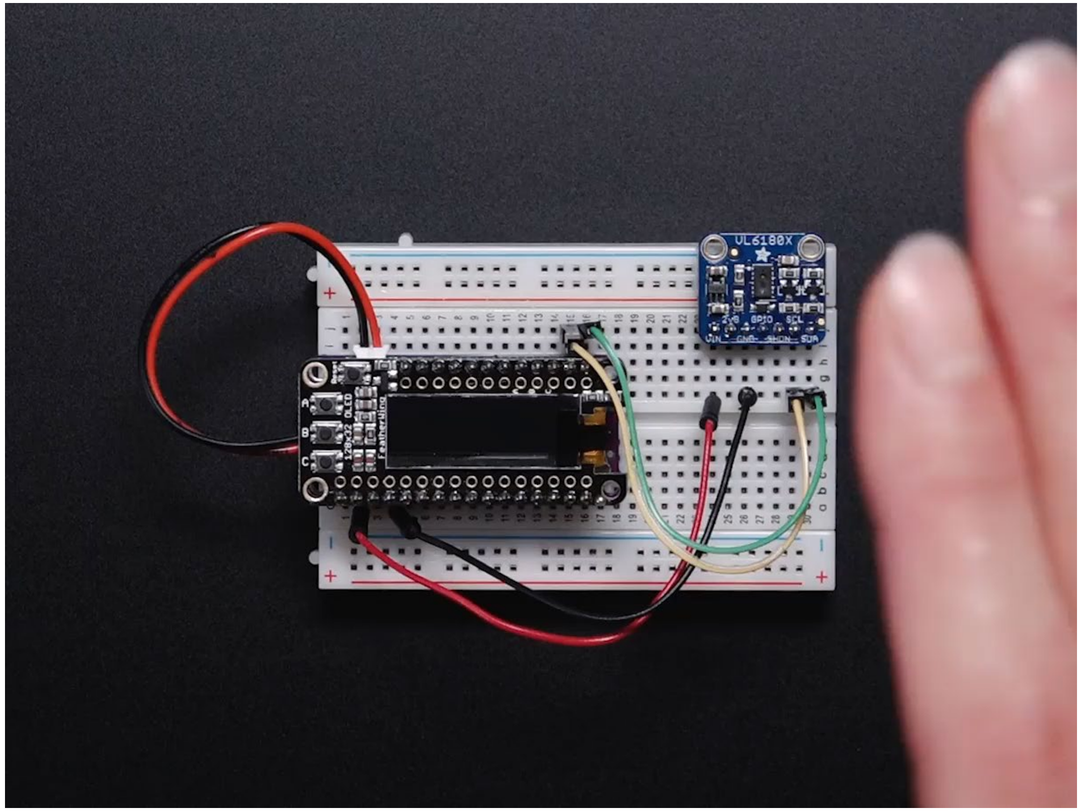




R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to autonomous mobile robots. The MIT Press. Second edition. 2011.
https://home.roboticlab.eu/en/examples/sensor/lidar
https://en.wikipedia.org/wiki/Lidar

Active ranging – Time of flight

- Micro-LiDAR (1D)

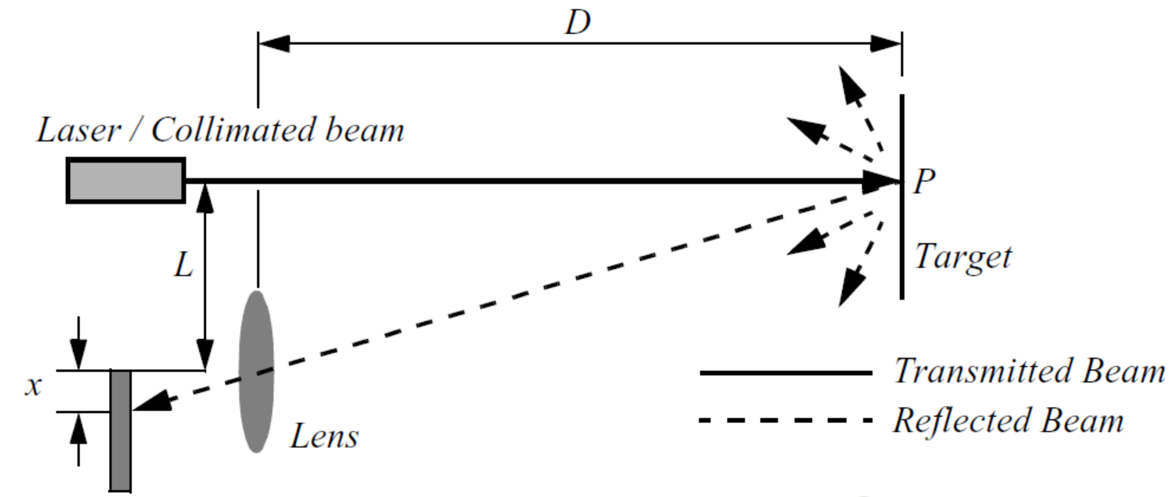


Active ranging – Time of flight

- 3D LiDAR

Active ranging – Triangulation

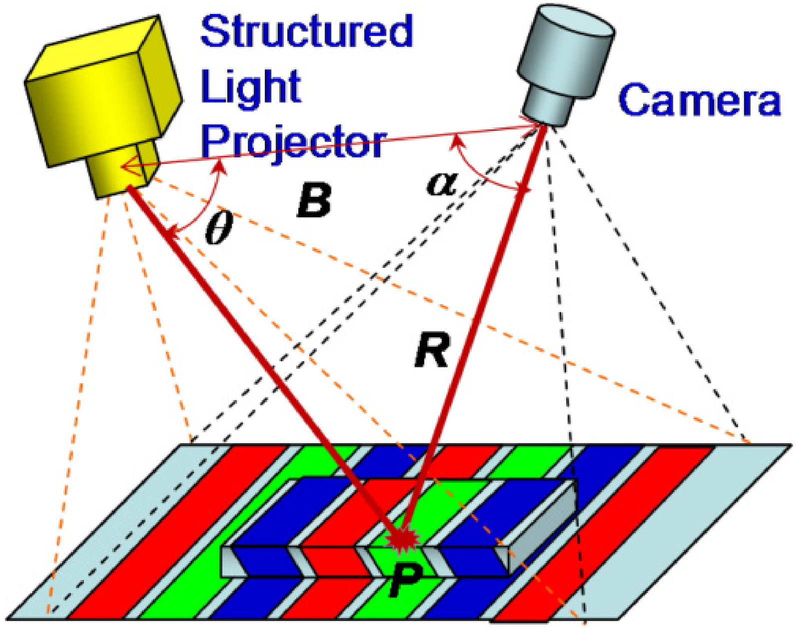
- Optical triangulation (1D)



$$D = f\frac{L}{x}$$

Active ranging – Triangulation

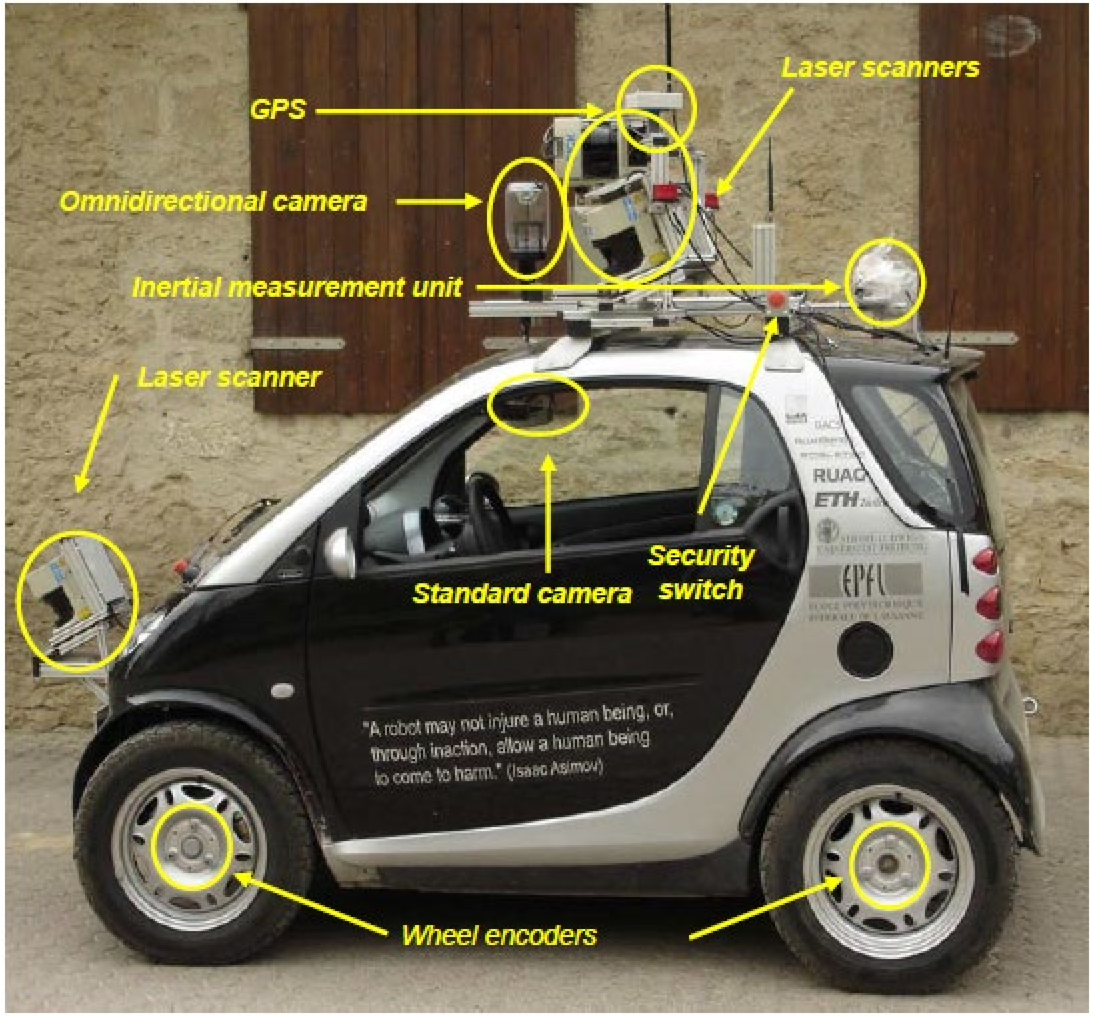
- Structured light camera (3D)



https://doi.org/10.1364/AOP.3.000128
https://www.geeky-gadgets.com/microsoft-sued-over-kinect-xbox-360-motion-controller-patent-infringements-01-10-2012/

Other sensors

- Global Positioning System (GPS)
- Doppler effect sensors
- Tactile/bumper sensors
- Vision sensors
- …



slido

What sensor(s) could be used for a real Micromouse Competition?

ⓘ Start presenting to display the poll results on this slide.