1 – Introduction

Advanced Methods for Mapping and Self-localization in Robotics
MPC-MAP

Petr Gabrlik
Brno University of Technology
2025

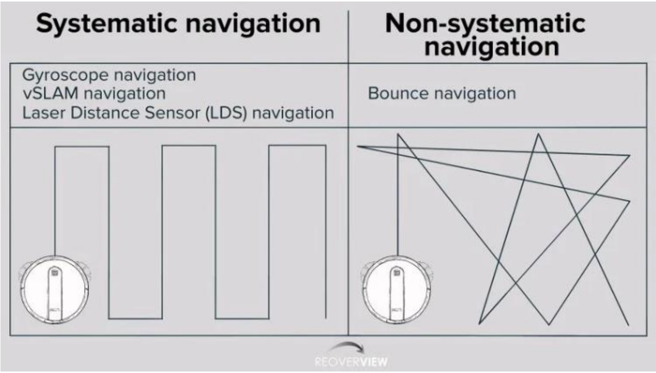
Motivation

The current use of (autonomous) mobile robots

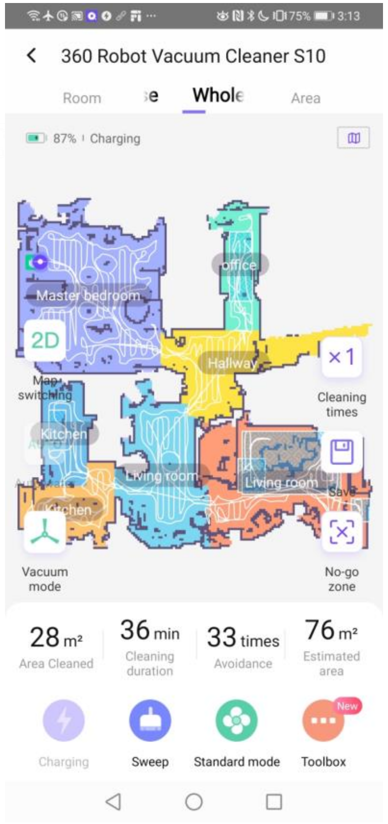
Robot Vacuums

- A widely used type of a consumer-grade robot
- Both *dump* and *high-tech* solutions
- **Environment:** indoor, 2D, uncontrolled
- **Task / navigation goal:** area coverage
- **Localization:** none, encoders, IMU, LiDAR SLAM
- **Perception:** tactile sensors, cameras, LiDAR etc.

Source: iRobot



Source: reoverview.co.uk



Source: digitaltrends.com

Robotic Lawn Mower

- A similar task as a vacuum cleaner
- Both *dump* and *high-tech* solutions
- **Environment:** outdoor, 3D, partially controlled/uncontrolled
- **Task / navigation goal:** area coverage
- **Localization:** none, encoders, IMU, GNSS
- **Perception:** tactile sensors, cameras, LiDAR etc.

Source: wsj.com

Motivation

Warehouse Robots

- Robotic picker, pallet trucks, goods-to-person
- **Environment:** indoor, 2D, controlled/uncontrolled
- **Task / navigation goal**: go to location
- **Localization:** encoders, IMU, LiDAR-based localization in map, indoor localization systems (MoCap, UWB, fiducial markers etc.)
- **Perception:** cameras, depth-cameras, LiDARs etc.

Source: ep-equipment.com

Source: theverge.com

Motivation

Source: kvados.cz

Source: globaltimes.cn

Food Delivery Robots

- A robotic replacement for waiters
- **Environment:** indoor, 2D, uncontrolled
- **Task / navigation goal:** go to location
- **Localization:** encoders, IMU, LiDAR-based localization in map, LiDAR SLAM
- **Perception:** tactile sensors, cameras, depth-cameras, LiDARs etc.

Motivation

Cleaning Robots

- Floor cleaning, UV disinfection
- **Environment:** indoor, 2D, uncontrolled
- **Task / navigation goal:** area coverage, go to location
- **Localization:** encoders, IMU, LiDAR-based localization in map, LiDAR SLAM
- **Perception:** tactile sensors, cameras, depth-cameras, LiDARs etc.

Source: cbc.ca

Source: healthcareitnews.com

Agricultural robots

- Seeding, harvesting, crop maintenance etc.
- **Environment:** outdoor/indoor, 3D, partially controlled/uncontrolled
- **Task / navigation goal:** go to location, area coverage, linear trajectories
- **Localization:** encoders, IMU, GNSS, indoor localization systems, LiDAR-based localization in map, LiDAR SLAM
- **Perception:** cameras, depth-cameras, LiDARs

Source: idnes.cz

Source: latimes.com

Last-Mile Delivery Robots

- Delivering goods to customers
- Operates mainly on the pavements
- **Environment:** outdoor, 3D, uncontrolled
- **Task / navigation goal:** go to location
- **Localization:** encoders, IMU, GNSS
- **Perception:** cameras, depth-cameras, LiDARs etc.

Source: freightwaves.com

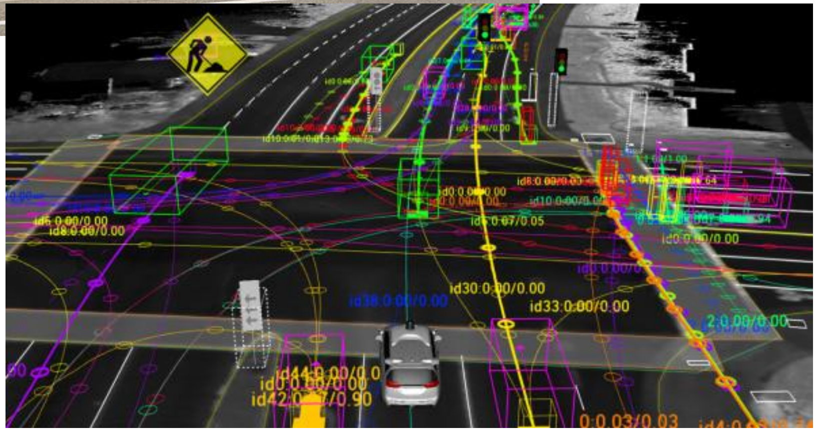
Source: cambridgeindependent.co.uk

Motivation

Self-Driving Cars

- Comprehensive task with human health risks
- **Environment:** outdoor, 3D, uncontrolled
- **Task / navigation goal:** go to location
- **Localization:** encoders, IMU, GNSS
- **Perception:** cameras, depth-cameras, LiDARs, radars

Source: marketwatch.com

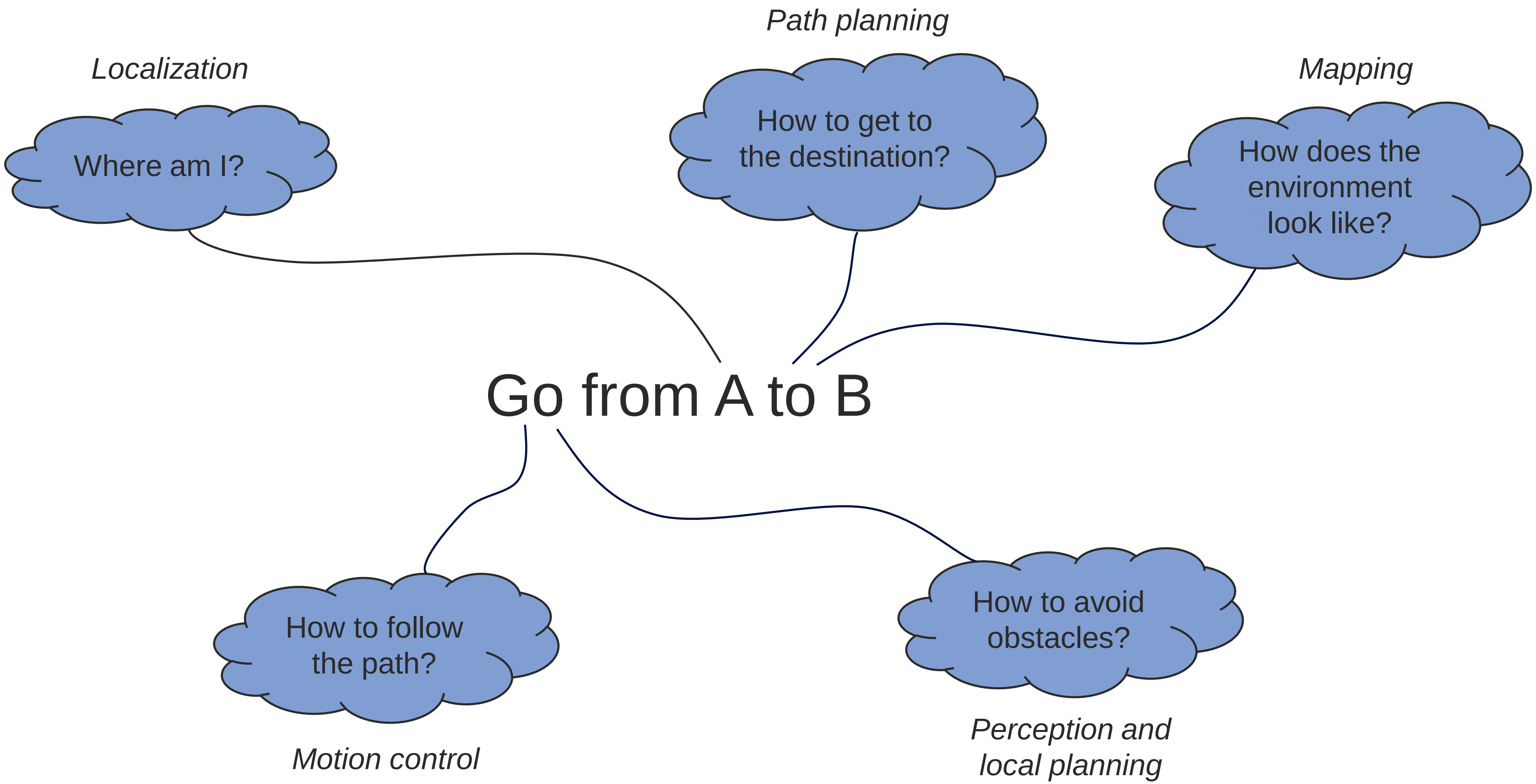


Source: waymo.com

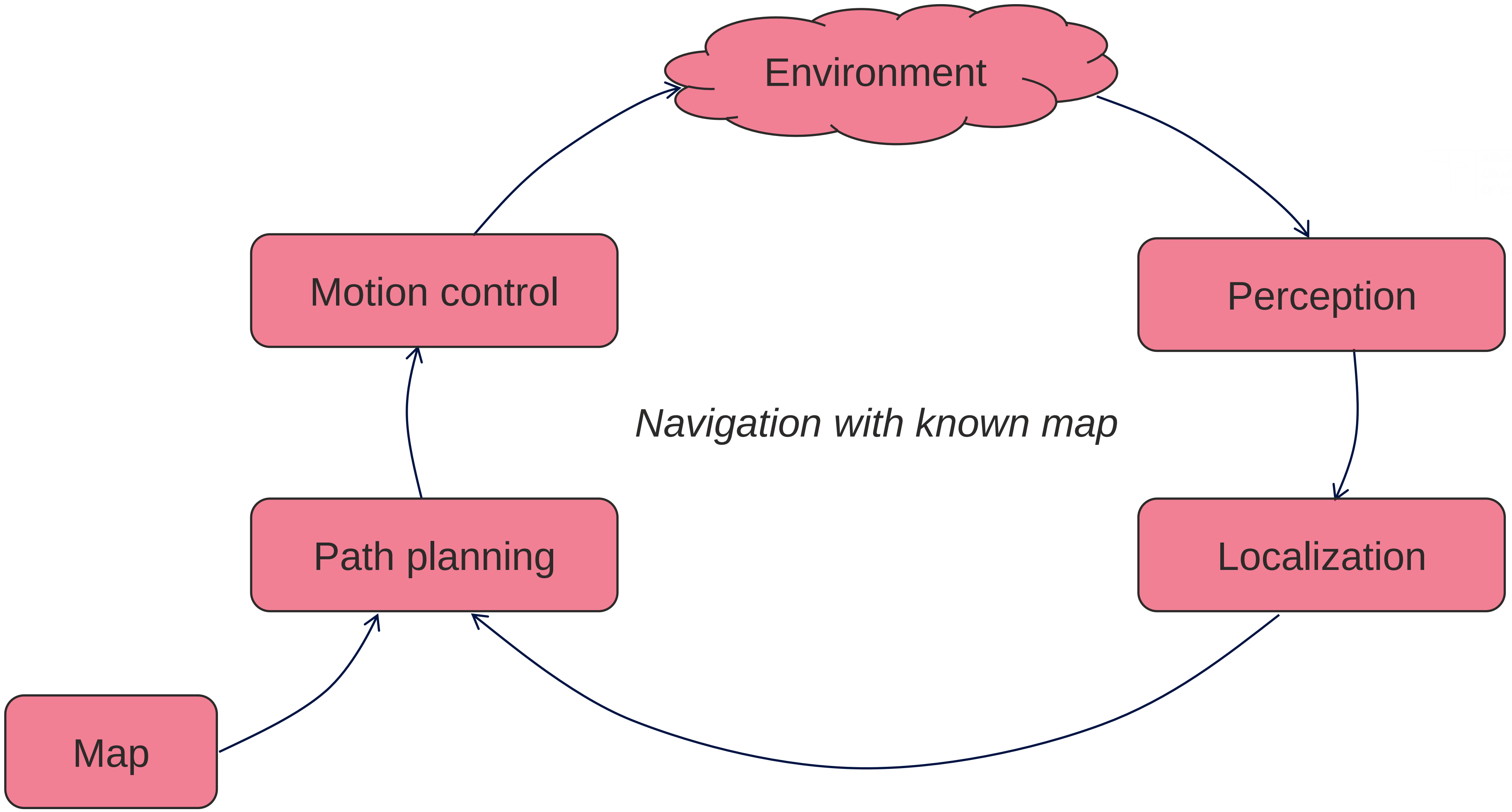
Problem Specification

Fundamental problems in autonomous mobile robotics

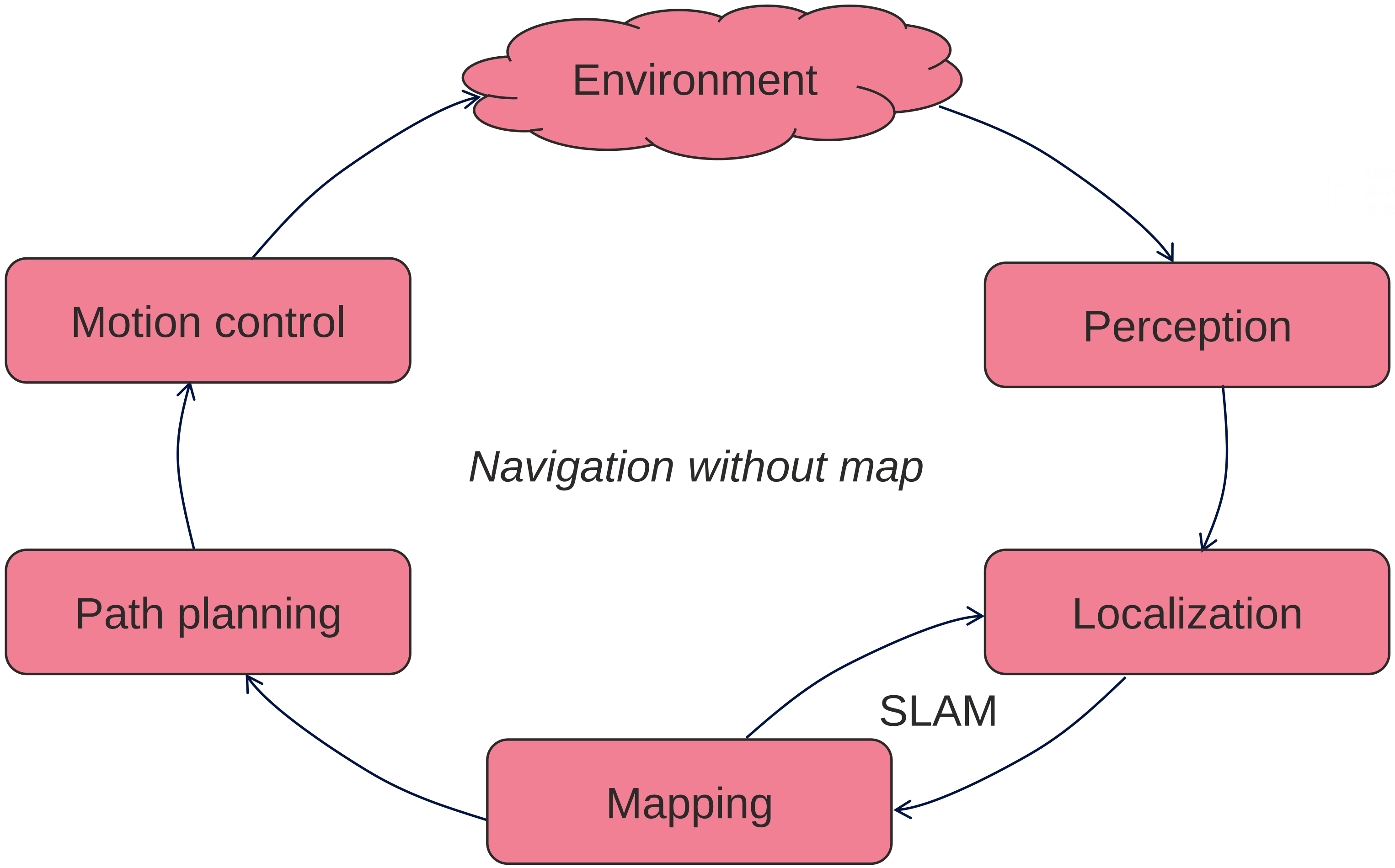
Problem Specification



Concepts


Environment
Motion control
Perception
Navigation with known map
Path planning
Localization
Map

Concepts


Environment
Perception
Localization
Mapping
Path planning
Motion control
SLAM
Navigation without map

Course Details

The goals, lecturers, structure, resources

- **Motivation and goals**
  - Diving into the fundamental problems of mobile robotics.
  - Understand robot navigation: self-localization, path planning, motion control and map building topics.
  - Algorithm-focused course (no complex SW, no HW/robot, no communication..).
  - Practice theory via practical tasks in the simulator.

- **Course parameters**
  - 3 credits (ECTS), ended with classified credit
  - Total work: **72 hrs.** (~24 hrs./credit)
  - Lectures: 7 × 2 hrs. (optional, highly recommended)
  - Labs: 7 × 2 hrs., weekly assignments – individual homework with consultations during lab hours (compulsory)
  - Total individual homework: **58 hrs., ~ 9 hrs./week** (weekly projects, semestral project, self-study)

Lecturers

- **Course supervisor**
  - Ing. Petr Gábrlík, Ph.D.
- **Lecturers**

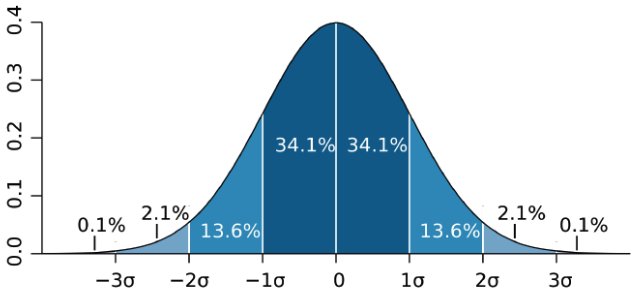
Ing. Petr Gábrlík, Ph.D.
gabrlik@vut.cz
SE1. 112

Ing. Tomáš Lázna, Ph.D.
tomas.lazna@ceitec.vutbr.cz
SE 1.112

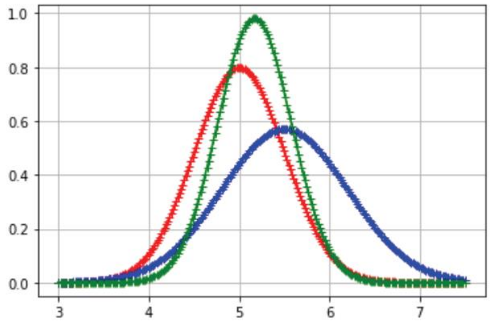
Course Structure

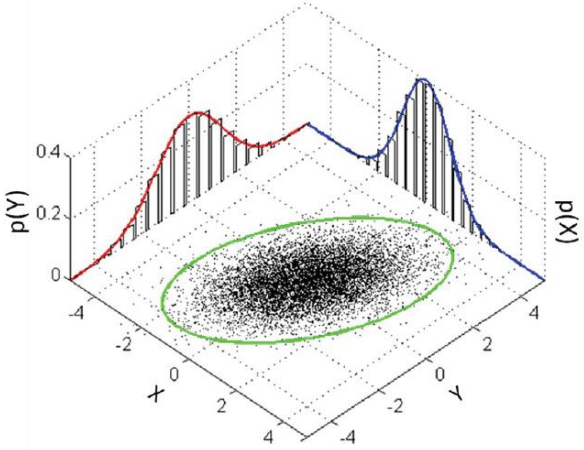
Week	Lecture	Lab	Lab points	Lecturer
1	Introduction	Robot navigation demo	0	Gabrlik
2	Probabilistics Robotics	Uncertainty	10	Gabrlik
3	Kinematics and Motion Control	Motion Control	10	Lazna
4	Particle Filter	Particle Filter	10	Lazna
5	Kalman Filter and EKF	Kalman Filter and EKF	10	Gabrlik
6	Path Planning	Path planning	10	Lazna
7	SLAM	Individual work on project	50	Gabrlik

- Introduction to basic **statistics** and **probability**
- Normal distribution
- Covariance matrix
- Bayes theorem
- Markov localization
- Basic sensors



Source: wikipedia.org





Source: wikipedia.org

$$\mathbf{Cov} = \begin{bmatrix} Cov(X, X) & Cov(X, Y) & Cov(X, Z) \\ Cov(Y, X) & Cov(Y, Y) & Cov(Y, Z) \\ Cov(Z, X) & Cov(Z, Y) & Cov(Z, Z) \end{bmatrix}$$

- **Kinematics** of a differential drive
- Motion model
- How to **follow a path**?

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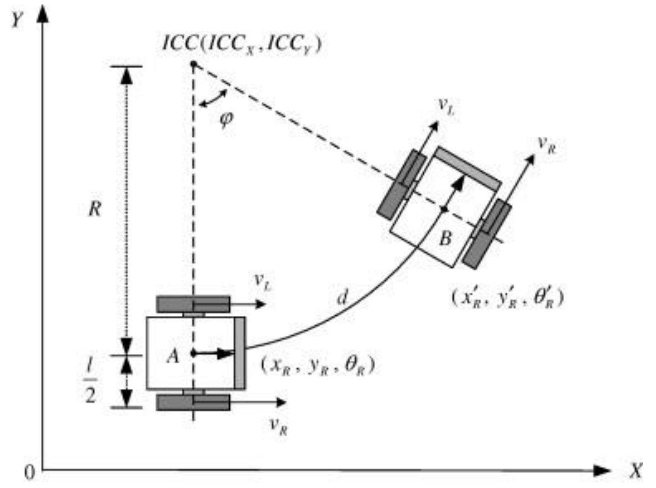

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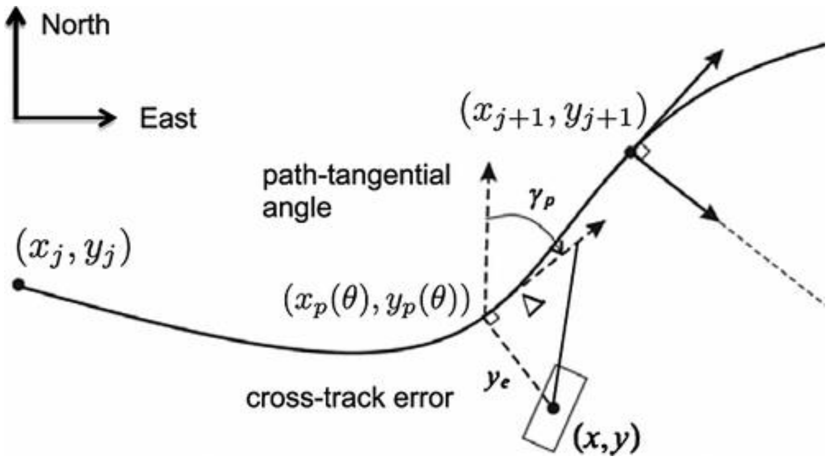
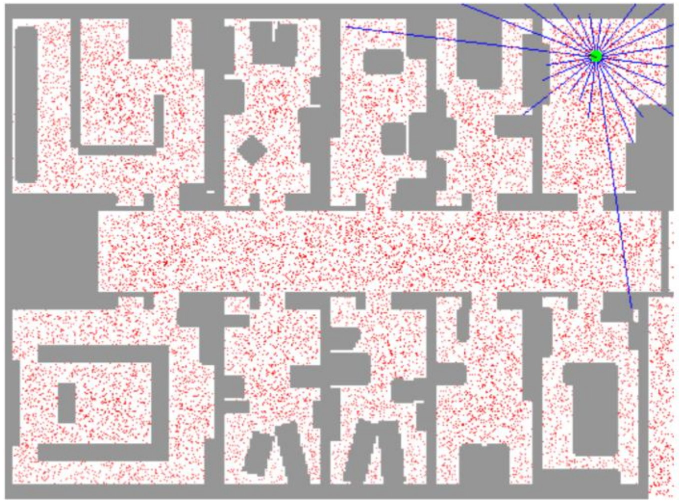


[2]

1. [1] HAN, Soonshin, ByoungSuk CHOI a JangMyung LEE. A precise curved motion planning for a differential driving mobile robot. *Mechatronics* [online]. 2008, **18**(9), 486-494 [cit. 2022-02-04]. DOI: 10.1016/j.mechatronics.2008.04.001
2. [2] FOSSEN, Thor I. a Anastasios M. LEKKAS. Direct and indirect adaptive integral line-of-sight path-following controllers for marine craft exposed to ocean currents. *International Journal of Adaptive Control and Signal Processing* [online]. 2017, **31**(4), 445-463 [cit. 2022-02-04]. DOI: 10.1002/acs.2550
3. https://www.turtlebot.com/

Week 4: Particle Filter (localization)

- Introduction to **Monte Carlo** methods
- What are **particles**?
- Random numbers sampling – a vital element
- Particle filter algorithm – 3 steps:
  - Prediction
  - Correction
  - Resampling
- Application of the PF to the **localization problem**
- Typical issues and how to solve them



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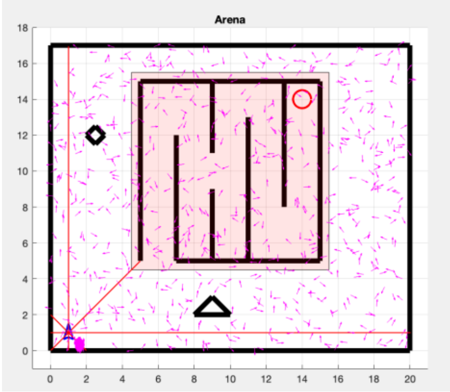
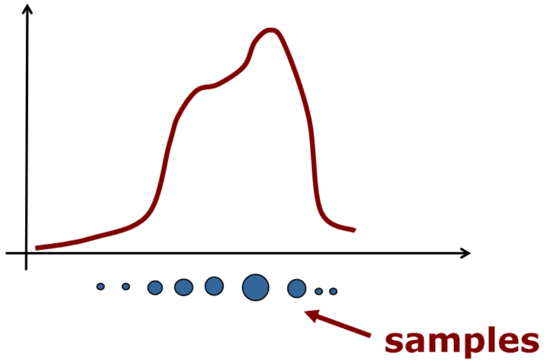


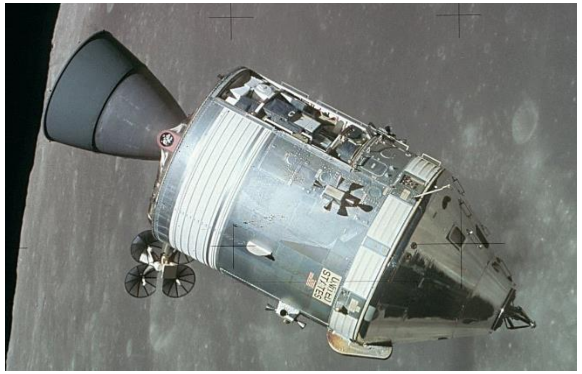


[2]

[1] TRIEBEL, Rudolph. The Particle Filter. In: *Machine Learning for Computer Vision* [online]. Technische Universität München, 2017 [cit. 2021-02-19]. Available at:https://vision.in.tum.de/_media/teaching/ss2017/ml4cv/variationalinference.pdf
[2] STACHNISS, Cyrill. Short Introduction to Particle Filters and Monte Carlo Localization [online]. Uni Freiburg, 2013 [cit. 2021-02-18]. Available at: http://ais.informatik.uni-freiburg.de/teaching/ws13/mapping/pdf/slam10-particle-filter-4.pdf

- An algorithm for ***filtering*** and ***prediction*** in linear systems / ***estimating*** unknown variables.
- Suitable for fusing data from different sensors (different variables and sampling periods).

- Used for ***trajectory estimation*** for the ***Apollo*** program in the ~1960s – one of the very first applications of the Kalman filter [1].
  - Combination of acceleration data and star position observation.



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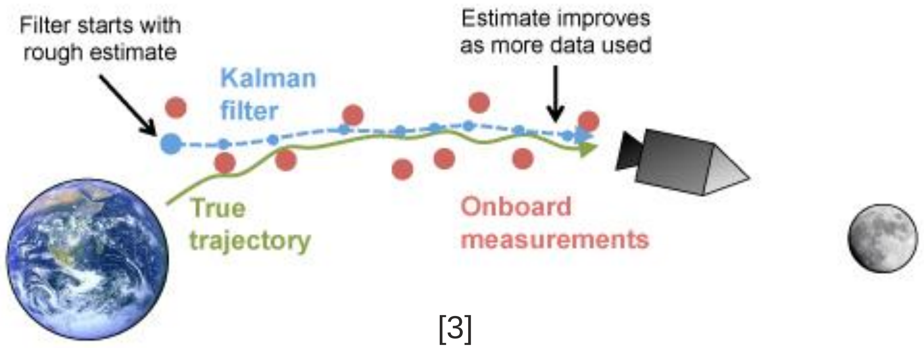
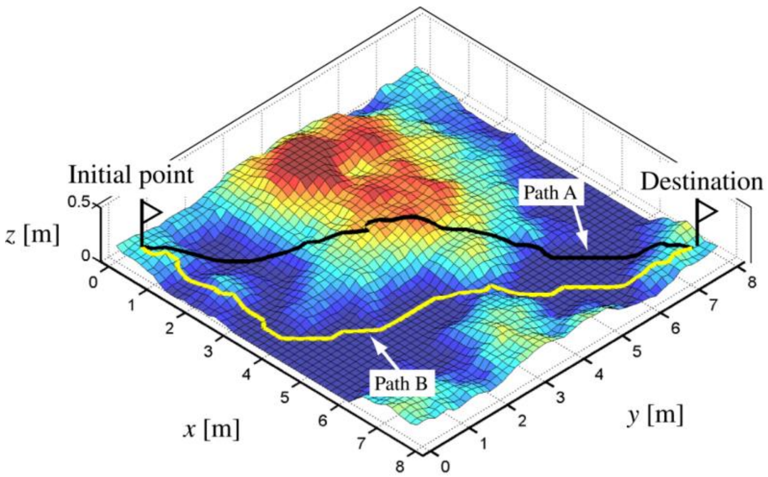


[3]

[1] GREWAL, M. S. and ANDREWS, A. P., 2010. Applications of Kalman Filtering in Aerospace 1960 to the Present [Historical Perspectives]. *IEEE Control Systems Magazine*. June 2010. Vol. 30, no. 3, p. 69–78. DOI 10.1109/MCS.2010.936465.
[2] Apollo command and service module, 2021. Wikipedia [online]. [Accessed 4 March 2021]. Available from: https://en.wikipedia.org/wiki/Apollo_command_and_service_module
[3] Implementations of Kalman Filter From Aerospace to Industry. P2 SMTP LIPI [online]. 2018 [cit. 2021-01-18]. Available at: http://smtp.lipi.go.id/berita633-Implementations-of-Kalman-Filter-From-Aerospace-to-Industry.html

- Configuration space
- Types of planners
- Workspace representation
- Graph-search algorithms: Dijsktra, A*, …
- Avoiding obstacles
- Path smoothing



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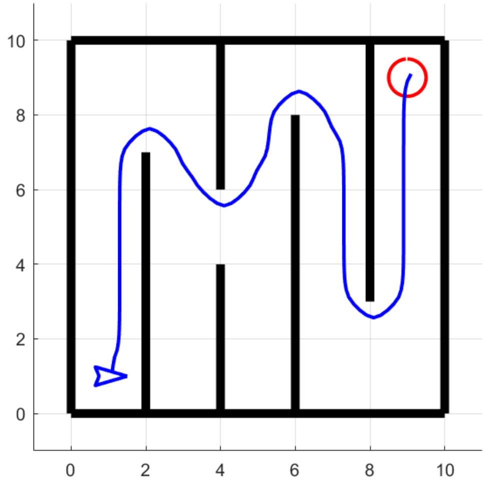
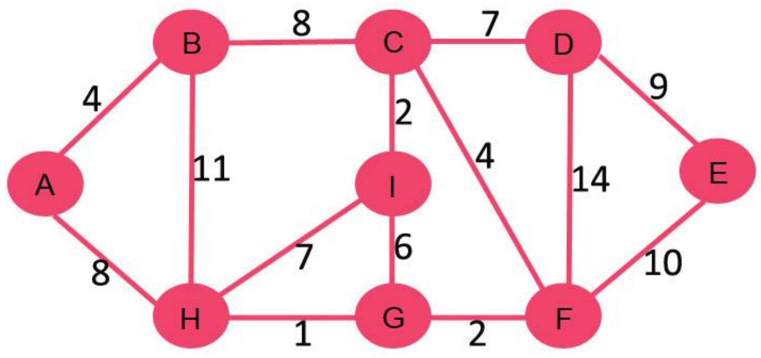




[2]

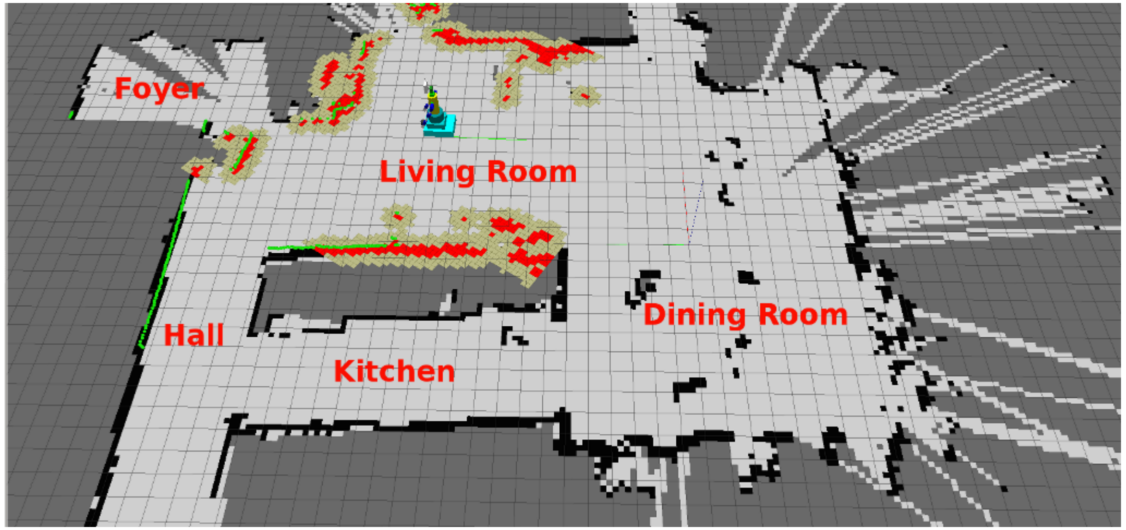
[1] DAHDOUH, Andrew. Graph-Based Path Planning: Dijkstra’s Algorithm. In: *Reality Bytes* [online] 2017 [cit. 2021-02-26]. Available at: https://realitybytes.blog/2017/07/11/graph-based-path-planning-dijkstras-algorithm/
[2] Dijkstra’s shortest path algorithm | Greedy Algo-7. In: *GeeksforGeeks* [online]. 2020 [cit. 2021-02-28]. Available at: https://www.geeksforgeeks.org/dijkstras-shortest-path-algorithm-greedy-algo-7/

- **Simultaneous localization and mapping**
- Both tasks are addressed together
- Comprehensive algorithms
- Essential for indoor autonomous robots

Particles-Based SLAM

Graph-Based SLAM

Kalman-Based SLAM



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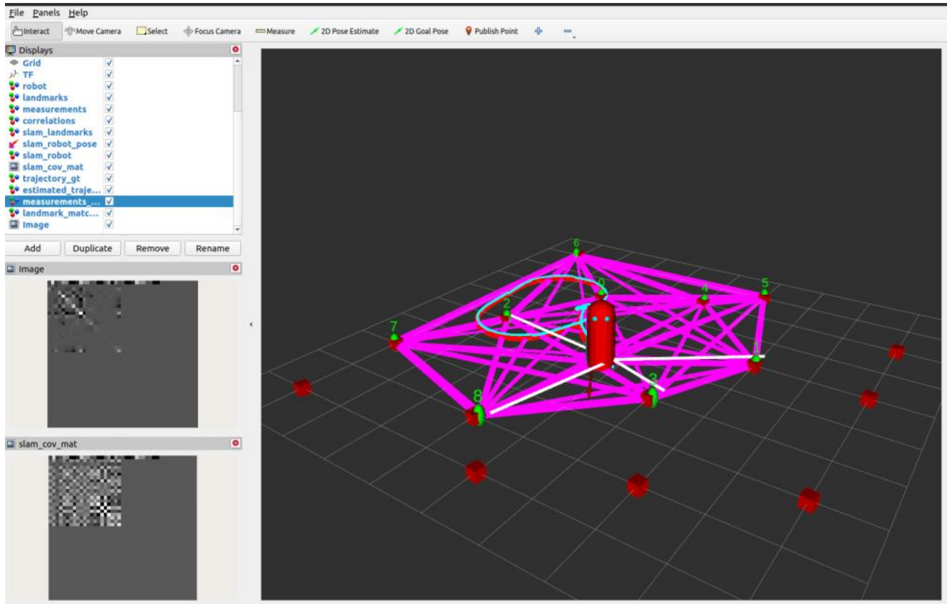


[1] https://sifrobot.com/wp-content/uploads/2020/03/Simultaneous-Localization-and-Mapping-SLAM.png

Weekly Assignments (Labs)

- Weekly assignments in the weeks 2 to 6
- Task assignments available on the GitHub
- For each assignment you will prepare **short, single A4 report** describing your solution
- Each assignment task is documented via **a few sentences** and **image**(s) (if applicable)
- The deadline is next **Wednesday 23:59**
- During the week you can consult your solution with lecturers
- 0 to 10 points per assignment

Overview
Week 2 - Sensor Modeling
Week 3 - Motion Control
Week 4 - Particle Filter
Week 5 - Kalman Filter and EKF
Week 6 - Path Planning
Simulator
Semester Project

MPC-MAP

Week 4 - Particle Filter

The goal of this assignment is to implement a working localization algorithm based on the particle filter.

Create a single A4 report that will describe your approach to the exercise (3-6 sentences for each task and a picture, if it makes sense).

Task 1

Implement the prediction function that takes the particle pose and the control input as arguments and returns the new pose. Apply the probabilistic motion model.

Task 2

Implement the measurement function that takes the map, the particle pose, and the sensor orientations as arguments and return a vector of measured distances without any noise.

You may take advantage of the simulator function `ray_cast` which is used as follows:

```
intersections = ray_cast(ray_origin, walls, dir_rad)
```

The first argument is position of initial point of a ray, the second argument is the description of walls stored in `read_only_vars.map.walls`, and the final argument is direction of the ray in radians. The function returns all intersection of the given ray with the walls.

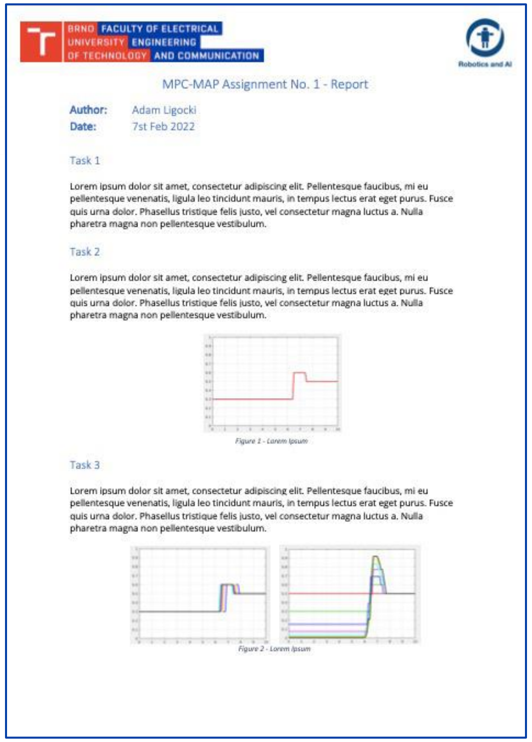
Task 3

Initialize a set of particles at random poses within the map. Implement the resampling algorithm and make the particles converge to the actual agent pose via an appropriate weighting function (apply the outcomes of the previous task). You should be able to present a screenshot with a cluster of particles gathered around the agent. You may need to move the agent to make the particles converge.

Submission

Send the report and all related MATLAB scripts to tomas.lazna@ceitec.vutbr.cz. MATLAB script must be executable without any errors and has to generate all graphical outputs that are in the report. Deadline: 5 March 2023, 23:59.

Assignment (GitHub)



BRNO UNIVERSITY OF TECHNOLOGY FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
Robotics and AI

MPC-MAP Assignment No. 1 - Report

Author: Adam Ligocki
Date: 7st Feb 2022

Task 1

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Task 2

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Figure 1 - Lorem ipsum

Task 3

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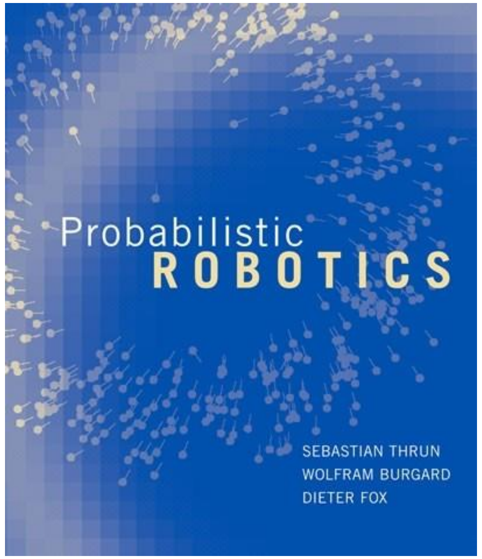
Figure 2 - Lorem ipsum

Report (pdf)

Study Resources

- Lectures
- Labs / Consultations
- GitHub repository: https://github.com/Robotics-BUT/MPC-MAP-Student
- Sebastian Thrun: Probabilistic Robotics* (Book) [1]
- Sebastian Thrun: Artificial Intelligence for Robotics (Udacity course)



[1]

[1] THRUN, Sebastian, BURGARD, Wolfram and FOX, Dieter, 2005. Probabilistic Robotics. 1st edition. Cambridge, Mass: The MIT Press. ISBN 978-0-262-20162-9.

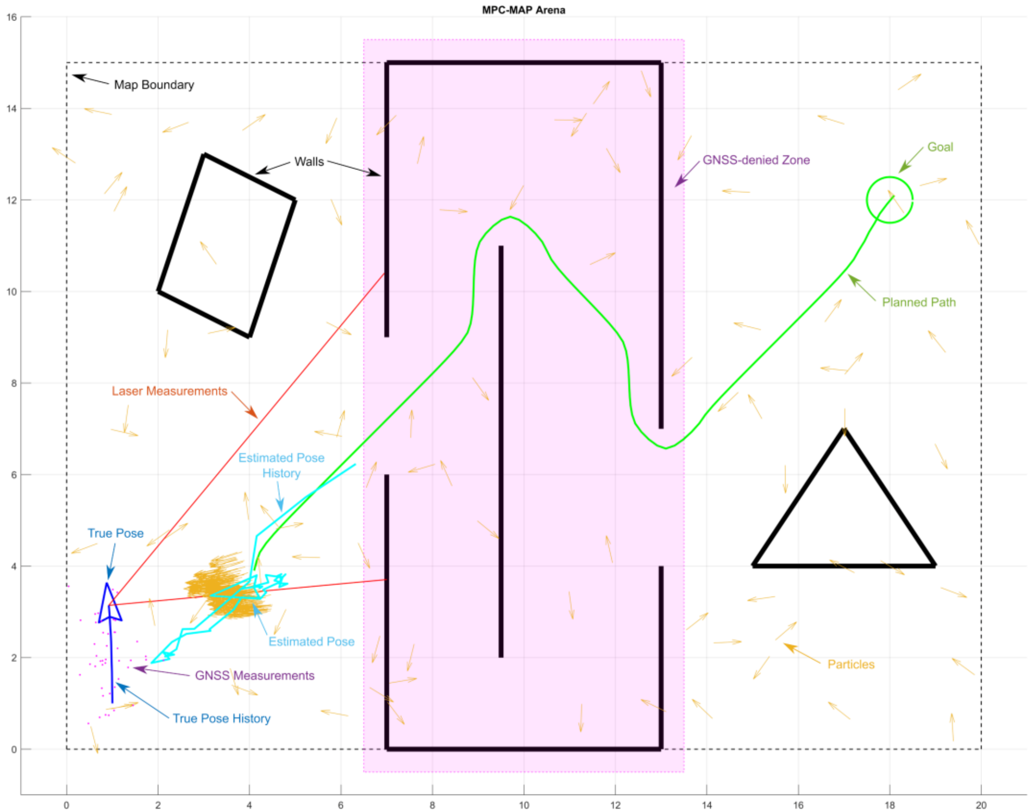
* An early book version is available online, the hardcover is available in the FEEC BUT library.

Simulator

Lightweight, MATLAB-based robot simulator

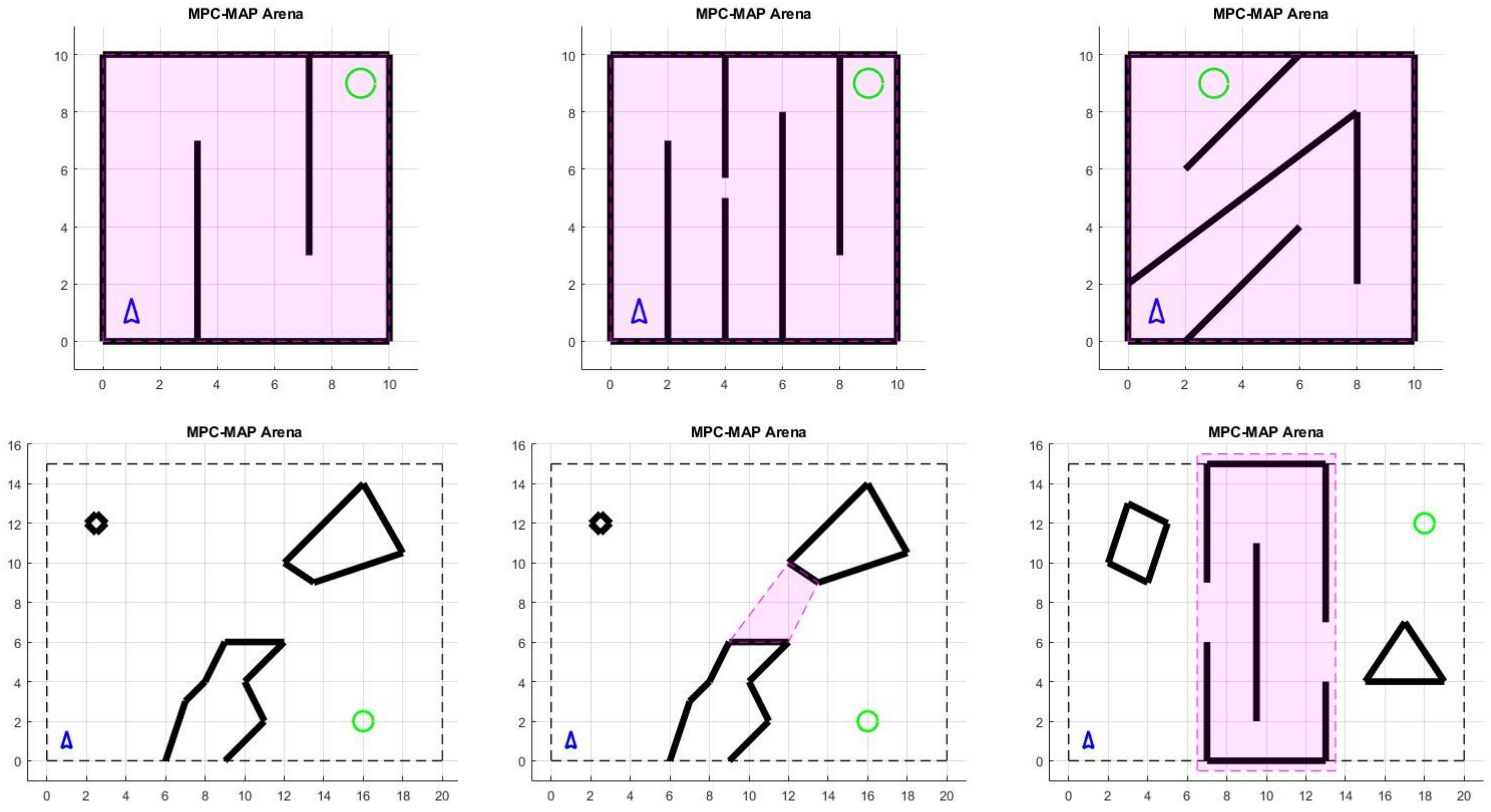
Simulator

- Both the **weekly assignments** and the **semestral project** are implemented in **MATLAB**
- **Custom-build**, lightweight **robot simulator**
- The robot (the blue arrow) is controlled via linear/angular speed
- Two sensors available: 8-way lidar, GNSS receiver
- The goal is to navigate the robot to the goal location
- Robot can not hit the walls and leave the map
- Numerous maps are available
- A simulation loop is prepared to be filled with **your custom functions** for **localization**, **path planning**, **motion control** etc.
- The simulator is available on GitHub



The simulation visualization

Simulator


MPC-MAP Arena
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MPC-MAP Arena
0 2 4 6 8 10
0 2 4 6 8 10 12 14 16 18 20
0 2 4 6 8 10 12 14 16

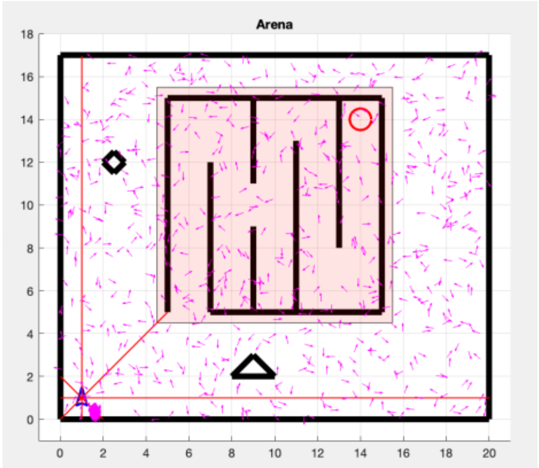
Semestral Project

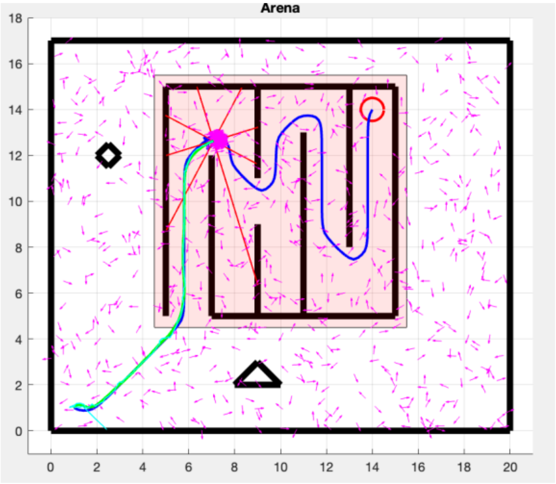
The final project addressing a complete navigation problem

Semestral Project – Goals

- The semestral project **connects all the functions prepared within weekly assignments together**
- The goal is to **navigate the robot to the goal** location:
  - With the minimal number of iterations
  - For diverse maps (incl. indoor, outdoor, combined)
  - For different start poses and goal locations
  - Without hitting walls and leaving the map

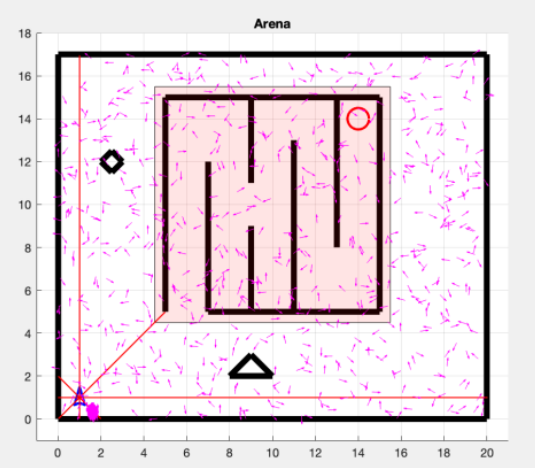
- A detailed semestral project assignment will be available on GitHub during the semester



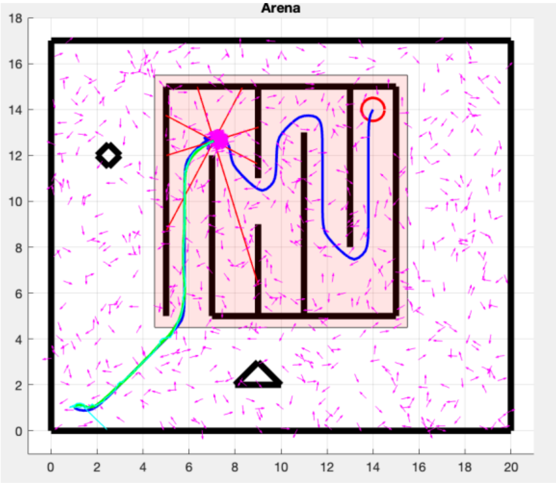


Semestral Project – Evaluation

- The project deadline: **8th week** of the semester, **Sunday 23:59**
- Your solutions will be tested and evaluated by repeated runs with different simulator settings (up to 100 runs)
- The solution (code quality, algorithms, ideas) will be evaluated as well



- Scoring – up to **50 points**:
    - Reaching goal probability: 0 to 15 points
    - Number of iterations: 0 to 15 points
    - Technical solution: 0 to 20 points

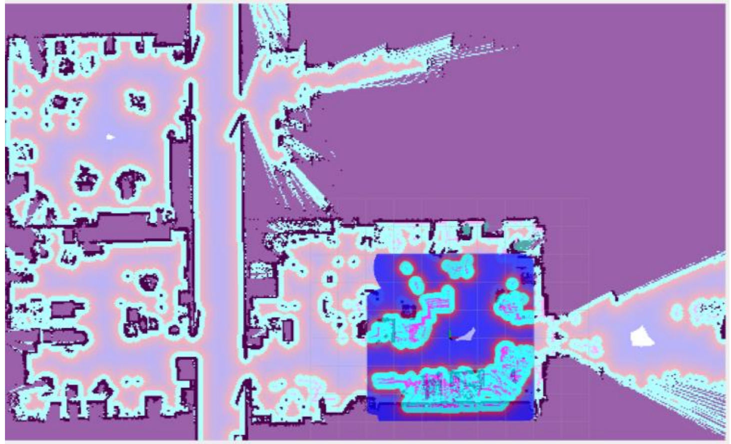


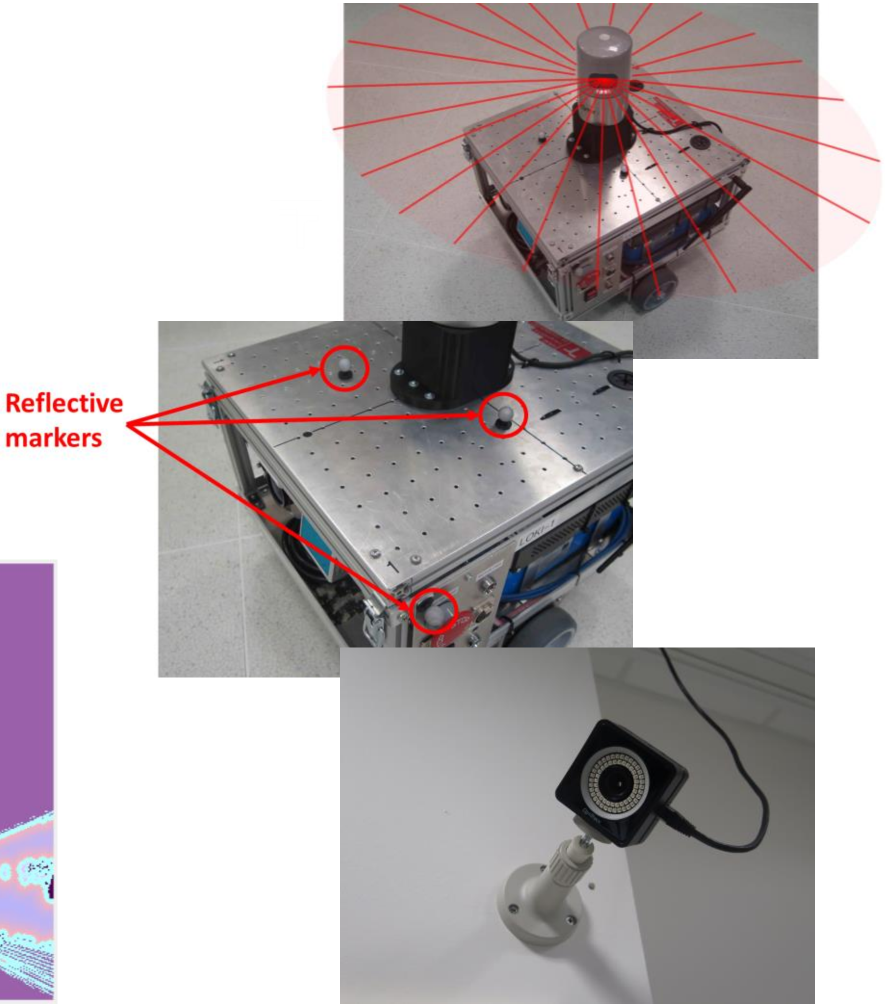
Live Demonstration

A live demo illustrating the concepts and algorithms

Live Demonstration

- **Loki** mobile robot
  - Custom build platform for the research and development
  - Differential drive
  - ROS2 based, incl. Nav2 stack
  - Sensors: encoders (odometry), 3D LiDAR, MoCap, IMU





Petr Gabrlik
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Faculty of Electrical Engineering and Communication
Department of Control and Instrumentation

Robotics and AI Research Group